Transportation Research Part D 94 (2021) 102775

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Specific environmental charges to boost Cold Ironing use in the European Short Sea Shipping

Alba Martínez-López [a,*], Alejandro Romero-Filgueira [b], Manuel Chica [a]

[a] Department of Mechanical Engineering, University of Las Palmas de Gran Canaria, Spain
[b] Oceanic Platform of the Canary Islands (PLOCAN), Telde, Spain

ARTICLE INFO

Keywords:
Cold Ironing
On shore power supply
Short sea shipping
Internal rate of return
Sensitivity analysis

ABSTRACT

Through Directive 2014/94/EU, European Union (EU) has required European ports to provide facilities to enable Cold Ironing (CI) use by 2025. This new reality advances a stricter normative in terms of port emissions. This paper introduces a calculation method to estimate a specific environmental charge in ports to incentivize CI use in Short Sea Shipping. The impact of this charge on the economic performance of the vessel's operators is assessed through Internal Rate of Return of the CI retrofitting investment in vessels. The calculation method assumes a pollutant differentiation system by considering kinds of vessel, technical features, port localization and hinterlands populations. Results show that, only when the generation of on-shore electricity is dominated by sustainable sources, the environmental charge is effective to stimulate the CI retrofitting of vessels in adverse scenarios. Sensitivity analyses determine that low gross tonnages' vessels with longer berthing times take greater advantage from CI use.

1. Introduction

Cold Ironing (CI) is the process to supply on shore electric power to vessels at berth. Thus, vessels' electricity consumption during berthing is met by plugging-in vessels to the on-shore electricity network. Consequently, the auxiliary engines of the vessels, which usually supply the electricity to keep the vessel's operation, are switched off at berthing and this leads to emission savings by not burning fuels from the engines. The electricity supply always produces pollutant emissions during generation (land-based sources), however the advantages of CI use rely on relocating the emission source outside ports. The potential benefits of CI increase when considering port location and its activity pressure. The vessels' emissions, in terms of NOx and SOx, have a direct impact on citizens, thus, port vessel activity is especially harmful due to the existence of significant population centres in the port's hinterlands.

Even though, the CI alternative has been addressed by previous works, most of them have focused their analysis on the port standpoint (facilities investment) by assuming that the main role of the ports is ensuring the general interest. Significant insights were achieved from models able to estimate the environmental advantages after the installation of CI facilities in the ports. However, in most cases the environmental benefits were assessed through analysis of investment projects for the ports, where the vessel's perspective was scarcely tackled beyond their willingness to use CI (penetration rates).

This paper introduces a different approach to CI, since it does not only assume port pollutant emissions as an additional cost for vessels through an environmental charge, but also examines the impact of a charge on Short Sea Shipping (SSS) vessel operators'

* Corresponding author at: University School of Industrial and Civil Engineering, Campus of Tafira, Las Palmas de Gran Canaria, Las Palmas, Spain.

E-mail address: alba.martinez@ulpgc.es (A. Martínez-López).

https://doi.org/10.1016/j.trd.2021.102775

Available online 25 March 2021

economic performance under different scenarios. Furthermore, the paper provides useful information about the influence of different variables on the expected results: the port electricity price, fuel cost, capital costs, time invested in switching vessels and environmental charges.

The European Union (EU) has urged the International Maritime Organization (IMO) to implement global instruments for the internalization of external costs by maritime transport (Directive 2009/29/EC, recital3). In fact, in 2017, the European Parliament decided to include 'shipping for 2023' in the EU's Emissions Trading System (EU ETS) if the IMO strategy was insufficient. This concern is collected in the current White Paper on Transport (2011), the European policy driver (COM (2011) 144 final), that establishes avoiding smart pricing and tax distortions through the internalization of external costs for all modes of transport. Among other solutions for greener port operation, two required significant port investments: Onshore Power Supply (OPS) and Liquefied Natural Gas (LNG) bunker facilities.

Through Directive 2014/94/EU, the EU has forced on European ports to provide facilities to enable OPS use by 2025. However, despite this political instruction, significant public investment to provide OPS facilities in port, and the broader sustainability advantages regarding other solutions (the elimination of port waste, noise, vibration etc.) CI use is voluntary in the EU. Thus, the current European regulation (Directive 1999/32/EC; Directive 2005/33/EC) has relied the responsibility of using green alternatives on the ship operators' willingness.

This attitude contrasts with EU policy towards other transport modes, where a consistent application of the 'polluter pays' and 'user pays' principles is collected from the European Policy (White Paper on Transport, 2011), shown in the Regulation (Directive 1999/62/EC amended by Directive 2011/76/EU and COM (2017) 275 final, ANNEX 1), and is implemented through taxes and charges (Schroten et al., 2019).

In the light of foregoing, a progressive rising in the environmental exigency is expected in the EU for the maritime transport in general, and for the port operative, in particular. Thus, similar treatment to road transport seems reasonable for the seaborne sector in the near future: including compulsory external-cost charging to reflect the environmental burden from the vessels activity in port. These burdens are dependent on vessel technology, but also on the location and density of port populations. Taking European road transport as a reference, infrastructure charges must include a precise external cost calculation, where the aforementioned features are taken into account, to maintain the proportionality of the charging system and promote sustainable port operations. From this assumption, this paper tackles the possible internalization of the air pollution costs in port through applying environmental charges to the vessels, being these ones based on the additional pollution generated by not using CI in the EU ports.

This paper is organized as follows. The next section reviews European regulations on port sustainability, and in section 3, the main findings from relevant research in CI use are briefly presented. Section 4 and 5 introduces the calculation method and the application cases, respectively. Finally, section 6 presents the results obtained for application cases, while the main findings of this paper are drawn in the conclusion section.

2. Current European port initiatives

In the European Union (E.U.), since 2010 the Community ports demand a maximum limit of 0.1% sulphur by weight for marine fuels used by inland waterway vessels and ships at berth (Directive 2005/33/EC amending Directive 1999/32/EC). Despite this restriction, the Commission in 2006 recognized that the regulation established to date was insufficient to maintain port air quality. Consequently, it recommended Shore-Side Electricity (SSE) use by ships at berth in Community ports (Recommendation 2006/339/EC), since it provides additional benefits, such as noise reduction, especially for those ports situated near residential areas. The COM 2013(295) pointed out the need for stricter requirements on environmental performance in ports.

In a further step, Directive 2014/94/EU demands an adaptation of port facilities to be included in national policy frameworks, which will involve member states investing to ensure an SSE supply for vessels, especially in TEN-T Core Network ports, by 31 December 2025. In parallel, Regulation (EU) (2017/352) has stated the intention to define common criteria (among European Commission and member states) for voluntary environmental charging. However, this Regulation also gives freedom for ports to establish their own environmental charging system, and this has generated a multitude of solutions that have been adopted by ports (Sornn-Friese et al., 2021). European ports have based their business strategies on encouraging ship operators to use CI by making it more attractive: the national governments are supporting port infrastructure investments, and even operation costs. In order to coordinate implementation across ports the EU Commission's Directorate-General for Mobility and Transport (DG MOVE) conducted a study in 2017 about port infrastructure charges from sustainability criteria (European Commission, 2017). Among the conclusions, significant reductions in port dues (up to 50% applied as environmental charging for CI use) are necessary to maintain ship operators' interest in CI use.

In the same line, the Green Guide (ESPO, 2012) and the ESPO Environmental Report (2019), which have both been published by the European Sea Ports Organization (ESPO), specifically encourage port authorities to be proactive in air quality management by including OPS facilities as ''soft infrastructures''(TEN-T policy) and it argued that bonuses or reductions in port dues should be considered for a short run in order to stimulate CI usage.

Most environmental schemes applied by European ports are based on environmental indexes or certifications (Energy Efficiency Design Index-EEDI-, Environmental Ship Index-ESI, Green Award- European Commission, 2017-), or even on the accomplishment of "Guidelines of good environmental practices" at national level, (such as Spain's Royal Legislative Decree 2011/2). In this way certificated vessels can obtain rebates on base port dues.

The implementation of environmental schemes in EU ports (mostly rebate schemes), is not conditioned by the port size. However, the large ports, due to their greater financial capacity, can more easily put in place an environmental charging scheme (European

Commission, 2017).

Oslo, Marseille and Gothenburg, among others, apply environmental differentiations in port charges that are based on a reduction for those vessels that use CI. The port of Stockholm, for example, not only applies these reductions but also offers a grant of SEK 1 million (99,000€) for the retrofit of Ro-Pax vessels that regularly call in port (Ports of Stokholm, 2020).

3. Main insights from previous research

Academic studies about the feasibility of CI have not only analyzed the EU co-funding for port investments without taking into consideration additional port charges for the vessels (Innes and Monios, 2018; Zis, 2019), but some have also suggested compensating ship operators for lost time during the CI connection/disconnection (Zis et al.,2014). Most studies about On-Shore Supply Energy assess the societal benefits, this is, by monetizing the health impact, and the payback period on port investment by considering different penetration rates in vessel use (Zis et al.,2014; Ballini and Bozzo, 2015; Innes and Monios, 2018; Zis, 2019; among others). Even though, the environmental effects of CI are highly dependent on the regional features of the electricity grid (especially, electricity generation share by renewable energies sources -RES-, Winkel et al.,2016), these proved to be majority positive when the external costs are evaluated from the on-shore standpoint (Ballini and Bozzo, 2015; Innes and Monios, 2018; Zis,2019; Winkel et al., 2016). In contrast, Winkel et al.'s (2016) results were remarkable: they found that investment in CI does not lead to health benefits if the electricity grid is predominantly supplied by burning oil, in such a way the CI is even, a less suitable alternative than burning fuel in ship engines (many of Islands states' cases).

Focusing on the ship operators' perspective, Zis (2019) concludes that CI investment is not beneficial for vessels in the lifecycle (10 years) when the fuel cost is very low, but in other cases the investment would be interesting. Innes and Monios (2018) include a brief analysis about the CI convenience for the vessels. Again, their paper presents CI as a beneficial solution for ship operators by considering the unitary price of electricity against fuel price (yearly savings in operational costs). However, in 2017 the European Commission presented a report (European Commission, 2017) whose results were less favourable. The report concluded that for 25,000 GT Ro-Ro vessels (30 calls/year) the yearly costs for CI were higher when compared to on-board electricity production and only rebates up to 50% of port dues made payback possible within 10 years. Among the reasons for this, one can be remarked: the current on-board electricity is tax free (Kumar et al., 2019), whereas the electricity supplied from ports is taxable under EU regulations. Consequently, tax reduction on the electricity provided in port was the main fiscal incentive proposed by previous research to boost CI use (Ballini and Bozzo, 2015; Winkel et al., 2016). Thus, some member states already apply a reduced tax rate for this supply, which has been temporarily permitted by the EU.

Spengler and Tovar (2021) concluded that the composition of port traffic, especially the kind of vessels, plays a major role in the potential of CI for the reduction of externalities. Beyond the kind of fleet, Sciberras et al. (2017) noted the importance of the vessels' operational and technical profile on emission reductions when abatement technologies, like CI, are evaluated.

In this regard, there is a wide consensus about the main potential benefiters of the CI use: Cruise ships, Ro-Ro vessels (Winkel et al., 2016; Innes and Monios, 2018) and container vessels (Winkel et al., 2015) with special mention to those vessels with reefer cargoes (Zis et al, 2014). This is so, not only due to their environmental effects (high energy consumptions in port with medium berthing times), but also because these ship types regularly call at the same ports. This, along with the high environmental impact of NOx and SOx emissions on citizens due to high operation frequency lead to that the CI is an interesting abatement system for the Short Sea Shipping (SSS). This reality has motivated the European projects like ELEMED (Mertikas et al., 2018), which has analyzed the impact of CI on the East Mediterranean corridor (i.e. Greece, Cyprus, and Slovenia; see Mertikas et al., 2018).

4. Method

In order to accurately assess the impact of CI on shipping lines' activity, the following sections introduce a calculation model able to quantify its performance in monetary terms.

4.1. Environmental impact of cold Ironing

This section presents formulas for calculating the air pollution performance of SSS vessels in port under two circumstances: the on board conventional generation of electricity and CI use. Even though the cold ironing is just an alternative for the berthing time of the vessels, in order to offer a wider knowledge of the pollution in port, the air pollution generated during the manoeuvring of the vessels is also evaluated. Thus, equations (1) and (3) provide the yearly environmental cost (€/year) for conventional vessel operation (on-board electricity generation) during the manoeuvring (ECM_q, $\forall q \in$ Q) and berthing stage *(*ECB_q, $\forall q \in$ Q*)* on a SSS line.

$$\mathrm{ECMq} = N \times \sum_{k=1}^{2} (ECMqk) \forall q \in \mathrm{Q} \tag{1}$$

$$\mathrm{ECMq,k} = \sum_{u=1}^{5} (EFMuq \times (MT) \times UCukv) \forall q \in \mathrm{Q} \wedge \forall k \in \mathrm{K} \wedge \forall v \in \mathrm{V} \tag{2}$$

$$\mathrm{ECBq} = N \times \sum_{k=1}^{2} (ECBqk) \forall q \in \mathrm{Q} \tag{3}$$

$$\mathrm{ECBq,k} = \sum_{u=1}^{5} (EFBuq \times (BTq) \times UCukv); \forall q \in \mathrm{Q} \wedge \forall k \in \mathrm{K} \wedge \forall v \in \mathrm{V} \tag{4}$$

Likewise, equation (5) (ECG_q, $\forall q \in \mathrm{Q}$) offers information about the yearly environmental costs during berthing when the vessel is plugged into the electricity grid (the CI option).

$$\mathrm{ECGq} = N \times \sum_{k=1}^{2} (ECGqk) \forall q \in \mathrm{Q} \tag{5}$$

$$\mathrm{ECGq,k} = \sum_{u=1}^{5} (EFGuk \times (BTq + CT) \times PBq \times UCukv); \forall q \in \mathrm{Q} \wedge \forall k \in \mathrm{K} \wedge \forall v \in \mathrm{V} \tag{6}$$

These expressions (1–6) quantify in monetary terms the impact of the pollutants ($\mathrm{U} = \{1, \dots, u\}$): NO_x (ozone precursors), SO_2 (acidifying substances), $PM_{2.5}$ (particular matter mass), PM_{10} and the greenhouse gases CO_2) that are emitted to the air by different SSS ($\mathrm{Q} = \{1, \dots, q\}$, container and Roll-on, Roll-off vessels) by operating in several ports ($\mathrm{K} = \{1, \dots, k\}$).

Due to the features of the electricity grid, equation (6) integrates, besides the yearly trips of the shipping lines (N), the time (hours) invested in the various stages (*MT*-manoeuvring time-, BTq; $\forall q \in \mathrm{Q}$ -berthing time-), emission factors, unitary costs for the pollutants, the required shore power for operating during the berthing (PB_q; $\forall q \in \mathrm{Q}$) and the connection lag time (*CT*).

The unitary cost of pollutants (UC_{ukv}; $\forall u \in \mathrm{U} \wedge \forall k \in \mathrm{K} \wedge \forall v \in \mathrm{V}$) involve the average 'damage cost' for transport emissions (€/kg) by taking into account the geographical location of the port ($\mathrm{K} = \{1, \dots, k\}$) and the population density of its hinterlands ($\mathrm{V} = \{1, \dots, v\}$). For European cases this information is regularly published by the European Commission in the *Handbook on the external costs of transport* (last updated in 2019; Van Essen et al., 2019) for every country. Successive updates can be estimated through the national Consumer Price Index -CPI- for every country (e.g. the National Statistics Institute of Spain, the National Institute of Statistics and Economic Studies of France, etc.).

The emission factors for the vessels during port operations: manoeuvring (EFM_{uq}; $\forall u \in \mathrm{U} \wedge \forall q \in \mathrm{Q}$ see equation (2)) and berthing (EFB_{uq}; $\forall u \in \mathrm{U} \wedge \forall q \in \mathrm{Q}$ see equation (4)) are highly dependent on the kind of engines and power demanded by each operational stage. These emission factors (kg/h) have been obtained through the calculation tools developed by Kristensen and Bingham (2020) (available at: https://gitlab.gbar.dtu.dk/oceanwave3d/Ship-Desmo) for container vessels and Ro-Pax vessels (Kristensen and Psaraftis, 2016). On the other hand, the emission factors relating to the electricity grid (EFG_{uk}; $\forall u \in \mathrm{U} \wedge \forall k \in \mathrm{K}$, see equation (6)) are a direct consequence of the dominant sources in land generating plants. Consequently, the location of the port and the relative weight of the renewable sources in the land based energy mix are the main drivers of these emission factors (kg/kW.h).

For the European application cases, the emission factors of the electricity grid (EFG_{uk}; $\forall u \in \mathrm{U} \wedge \forall k \in \mathrm{K}$) can be obtained per country and year through the European Pollutant Release and Transfer Register -E-PRTR- (Regulation (EC) No 166/2006) along with the Energy Statistics published by EUROSTAT (EU Commission, DG Energy, Unit A4, 2020). Despite the fact that the E-PRTR contains a register for 91 different pollutants, the particulate matters $PM_{2.5}$ are not specifically provided. Due to the significant impact of this pollutant on human health (in 2016 about 412,000 premature deaths in Europe were due to long-term exposure to this pollutant -European Environment Agency, 2019-), the $PM_{2.5}$ amount is estimated through its relationship with the PM_{10} (see Table 1), since this information is offered by E-PRTR.

EUROSTAT (EU Commission, DG Energy, Unit A4, 2020) collects information about Gross Electricity Generation, by fuel or product, as well as by type of generation. In this case, the calculation of the weight of the source in an electricity grid can be calculated for every country and year by making it possible to estimate the $PM_{2.5}$ amount from PM_{10} information. However, this information is not available for smaller geographical levels than a country in EUROSTAT.

Thus, for application cases to regions or provinces, the official data from local institutions must be consulted. The E-PRTR- (Regulation (EC) No 166/2006) not only offers information per kind of economic sector (NACE) and industrial activity but also desegregated information beyond the national level.

4.2. Environmental charge and port dues

From 2025 onwards European Union ports belong to TEN-T Core Network will be able to supply on-shore electricity to vessels (Directive 2014/94/EU) and, as a consequence, stricter and harmonized legislation about port emissions is expected to ensure the internalization of external costs.

Table 1
Emission factors $PM_{2.5}/PM_{10}$ for source category in energy industries (g/GJ).

Hard Coal	*Brown Coal*	*Natural Gas*	*Derived Gases*	*Heavy fuel Oil*	*Other Liquified fuels*	*Biomass*
'9/20'	'9/20'	'0.9/0.9'	'5/5'	'18/13'	'2/1'	'38/33'

(Source: European Environment Agency, 2009*).*

Thus, in the short to medium term, a normative evolution in ports towards environmental principles-core calculation principles - which govern current EU road transport (ownership taxes and infrastructure charges, Shroten et al., 2019-) can be justified. This is a compulsory EU charging scheme for infrastructure use based on a charges variation according to the environmental performance of vessels in port.

As with the road charging schemes for HGV in the trucking (Directive 1999/62/EC amended by Directive 2011/76/EU and COM (2017) 275 final, ANNEX 1), the amount of external cost charge should be calculated considering the emissions excess of the used technology over those emitted by the most sustainable technology (pollutant differentiated charging, see equations 1–6). By default, CI emissions (see equations (5) and (6)) can be assumed as the reference values for minimum emission levels in port. Therefore, whereas for vessels plugged into the electricity grid the external-cost charge is minimum, on-board supplied vessels should pay a variable charge for the extra emissions above CI emission levels. Even though the amount of charge is dependent on port location (linked to the local value for monetary cost of air pollutants- unitary costs- and port hinterland population density) the charging structure will be expectedly common and harmonized for all member states, based on vessel size and their environmental technology.

In this regard it is interesting to bear in mind that, whereas basic port dues (infrastructure charges) must be levied to recover the construction, maintenance, and operation costs of facilities (current European port dues include no external cost calculation by law), the proposed environmental charge should cover the burdens on the environment that are caused by vessels' air emissions in port (see equations 1–6). Consequently, due to the significant port investment required to provide CI facilities ($2mill for a container terminal of a 1.3 million TEU, -Zis, 2019- €7.4 million for Aberdeen port -Innes and Monios, 2018), in a next step, a careful review of base port dues should be undertaken to ensure the recovery of these investments in the charging structure.

4.3. Port times

The time reduction in port operations has proven to be a mitigation system pollutant system by itself, especially in SSS (Johnson and Styhre, 2015), where the high frequency of calls and the usual night-time inoperability (often berthing periods from 23 pm to 7 am) lead to a high relative weight of the port time on whole vessels activity. In this regard, it is important to consider that, beyond the environmental perspective, port times often condition not only SSS operational costs (operation port costs can reach 46% of total costs, Martínez-López et al., 2016), but also its competitiveness as a feasible alternative to unimodal transport (Suárez-Alemán et al., 2014).

However, additional berth time due to on-shore connection/disconnection is not yet officially inventoried, and published information in this regard ranges from 10 min to two hours (Zis, 2019), and can reach six hours if any problem exists (Tseng and Pilcher, 2015). Among other reasons, this variation is due to vessels' dependence on the port operator's skills, service demand and limitation of facilities. Consequently, the expected connection lag times due to CI use must be incorporated into any calculation of CI performance since this extra time could make the on-shore power alternative for short call vessels unfeasible (Zis et al., 2014).

Accepting that CI assessment is a very young approach, one hour of connection/disconnection lag time (*CT*, see equation (6)) can be assumed to be a realistic value when the ports under study do not offer this information. Likewise, when the time invested in the manoeuvring stage (*MT*) is unknown, 30 min can be taken as a probable time-frame (Zis et al., 2014). Finally, for vessels operating under SSS conditions the inoperative night-time -hotelling stage - must be added to the berthing time in the annual analysis. Expressions published by Martínez-López et al. (2015), could be used to estimate loading/unloading times (TB_q; $\forall q \in$ Q) when these times are unavailable.

4.4. Capital costs for CI outfitting of SSS vessels and their operational costs in port

According to the International Maritime Organization-IMO-, 2017 the required capital cost –CAPEX- for CI retrofitting of Reefer and Ro-Pax vessels is dependent on the vessel's size. In such a way, the CAPEX range 50,000–350,000$ is for 1000–5000 GT Feeder vessels whereas for 10,000–25,000 GT Ro-Pax vessels the range is 100,000–400,000$. Even though a direct relationship between GT and electricity power installation does not exist, this information can be taken as a first approach (see equations (7) and (8), monetary conversion December 2017: 1€=1.19US$) due to its correct match with real cases (information provided by the repair shipyards in Las Palmas de Gran Canaria for implementing on-board Shore-power systems on a 12,895 GT Ro-Pax vessel: ''Volcán de Taburiente''-IMO: 9348558-in 2020).

$$CAPEX_{feeder} = 63.025\ GT\text{-}21008\ (€) \quad 1000 \leq GT \leq 5000 \tag{7}$$

$$CAPEX_{ro\text{-}pax}=16.807\ GT\text{-}84034\ (€) \quad 10{,}000 \leq GT \leq 25{,}000 \tag{8}$$

There is a high level of heterogeneity among ports for commercializing electricity. Most have a specific agreement between the electricity supply company and the shipping company for SSS (e.g. Gothenburg, Sweden). However, there are cases where the port plays the role of an intermediate institution, especially when terminals and connection points are shared by ships from several shipping companies. In other cases, port authorities establish maximum prices for the electricity supply (e.g. Melilla port, Spain). In this way, the electricity price is often conditioned by the supply system: high or low voltage.

4.5. Internal rate of Return (IRR) for shipping companies

In this section IRR is considered as an evaluation tool to analyze investments in CI retrofitting of the vessels. Equation (9) shows the IRR expression due to CI installation and its operation:

$$Nb.CAPEXq = \sum_{t=1}^{T} \left(\frac{\Delta(CFq)t}{(1+IRR)t} \right) \forall q \in Q \tag{9}$$

The first element in this equation involves the required capital costs (*Nb. CAPEX*, see Appendix A) for all vessels of the fleet, in a particular SSS service, whereas in the second one the difference between the Net Cash Flow, both with and without CI installation, is considered ($\Delta(CF_q)_t$; $\forall q \in$ Q $\wedge$ $\forall t \in$ T see Appendix A), for every year (t) of the vessel lifecycle (T = {1, …, t}).

$$\Delta(CF_q)_t = \left(CIT + ECCI_q - ECOB_q - \left(ECB_q - ECG_q\right)\right)t \forall q \in Q \wedge \forall t \in T \tag{10}$$

Expression (10) collects the key variables in the Net Cash Flow difference for the operative alternatives during the berthing time: the costs of the lag connection/disconnection time (CIT), the electricity cost for CI ($ECCI_q$ $\forall q \in$ Q) and on-board supply ($ECOB_q \forall q \in$ Q) during the berthing time. Finally, the environmental charge (ECB_q-ECG_q; see equations (3) and (5)) is also integrated. Furthermore, equation (10) must include the financing costs (repayment of capital and interest) when retrofitting is paid through a loan.

No port charge rebates have been assumed for CI in this analysis, nor are public supports for retrofitting vessels included; consequently, this evaluation provides information about the environmental charge's capacity to incentivize CI use by itself. Moreover, even though the additional time in port involves broad scope for a regular shipping line company, a first approach can be made from port duties due to excess time.

5. Application cases

The selected case studies attempt to be representative enough to obtain significant findings through comparing CI performance not only in different frameworks, but also through different fleets. In such a way as the selected case studies are application cases where the expected benefits from CI use could reach maximum levels. This aim involves analysing the most demanding SSS lines: high frequency transport services (five calls/week) and operating with high electricity requirement vessels in port: Ro-Pax vessels (Winkel et al., 2016; Innes and Monios, 2018) and Feeder vessels with reefer containers (Zis et al, 2014, Winkel et al., 2015).

The analysis considers the fleets shown in Table 2; optimized container vessel (capacity to 185 reefer container) (Martínez-López et al., 2018) and conventional Ro-Pax vessels, by operating both under SSS conditions. Paying attention to the vessels' electricity balance, the most demanding operation stage is manoeuvring. This is so because this stage demands an additional electricity power to supply, besides the steering and mooring systems, the bow thrusters (see Table 2). This fact, along with the time invested in manoeuvring the whole time in SSS, forces us to include this operational stage in the analysis.

Container vessels' electricity plants are designed to meet all reefer containers' cargo units' demand (most demanding needs of electricity power). Likewise, the engine room arrangement for Ro-Pax vessels is designed around two main engines, (with two main engine driven alternators; Power take off (PTO) in their gearboxes), which move two propellers. This propulsion configuration, together with two bow thrusters' installation, significantly improves the manouvering capacity of these vessels, but also increases their

Table 2
Technical features of the fleets considered for the application cases.

		Feeder Vessel (reefer)**	Ro-Pax Vessel***
Technical Features	Cargo units	184 (reefer containers)	Pax: 1000 Lane length for trailers:1600 m Cars:160 Reefer [container plugs]:100
	Lbp(m)	78.15	153.25
	B(m)	14.46	28.65
	D(m)*	7.41	13.85
	GT	2456	26,916
	Service Speed (kn)	19.49	23
	Main Engine (kW)	7000	2 × 15,600
	Type of Main Engine	Tier III (MGO)	Tier III (MGO)
	Auxiliary engines (kW)	2 × 662	3 × 1254
	Power take off -PTO- (kW)	1500	2 × 1000
	Bow thruster (kW)	350	2 × 1000
Electricity demand	Manouvering (kW)	1620	4936
	Berthing (kW)	1200	1880
Electricity support	Manouvering	PTO + 1 auxiliary engine	2 PTO + 3 auxiliary engines
	Berthing	2 auxiliary engines	2 auxiliary engines
Maritime-Route 1		***Vigo(Spain)-St.Nazaire (France)***	
Maritime-Route 2		***Las Palmas (Gran Canary island)-Huelva (Spain)***	
Maritime-Route 3		***Las Palmas (Gran Canary island)-Sta.Cruz de Tenerife (Tenerife island)***	

*Depth to upper continuous deck for Ro-Pax vessel.
**More technical features in Martínez-López et al., 2018.
***More technical features on base vessels: ''Sorolla''(http://www.hjbarreras.es/?page=lis-ferries&idp=10) and ''Martí i Soler''(http://www.hjbarreras.es/?page=lis-ferries.2&idp=35)

electricity demands (see Table 2).

Finally, the Ro-Pax vessels assumed in the application cases require sufficient energy to feed in port: plugging capacity for 100 reefer cargo units, high capacity for cold storage warehouses, air conditioning systems, two Stern Ramp-Doors and one Movable Car-deck in the garage.

It is necessary to bear in mind that the vessels' boiler emissions have not been considered in the analysis, since shore power is not an alternative for their activity (Zis et al, 2014; Zis, 2019). Consequently, even though the vessel is plugged into the land grid during the berthing stage, the vessels' boilers are working to provide the necessary steam for the fuel tanks' heating coils (among other uses).

Table 2 also shows the maritime routes selected for the study cases. These routes involve ports that pertain to electricity grids with large differences in terms of sustainability. The first one, between Vigo in the North West of Spain and St. Nazaire in Brittany (France), was selected mainly due to the different environmental footprint of the electricity grids of both countries (see Table 3 in the results section). Additionally, this route currently operates as a European Motorway of the Sea (MoS), and so has been a frequently studied route for optimizing fleets in the past (Martínez-López et al., 2015; Martínez-López et al., 2018.). This permits to broaden the analysis by including unconventional ships (optimized feeder vessels) versus conventional vessels'. Case study 2, between the Canary Islands (Las Palmas port) and the Iberian Peninsula (Huelva, Spain) represents a common shipping route between continental Europe and its islands. Each island is supplied by its own electricity generation plants and therefore the sustainability of its grid is completely different from the continent (see Table 3). Finally, case study 3, between two of the Canary archipelago islands (Las Palmas and Sta. Cruz de Tenerife), introduces one of the most frequent maritime routes in Europe (inter island) but with the singularity of a scare share of renewable energy sources (RES level) in their electricity generation.

The operation times in port were estimated through expressions published by Martínez-López et al. (2015) for SSS vessels (Feeder and Ro-Pax vessels). The results were tested with real values from Las Palmas port (an average loading/unloading time of 3.5 and 2.3 h for Feeder and Ro-Pax respectively, and 30 min for the manouvering stage). Additionally, a hoteling time of 8 h per day (from 23 pm to 7 am) was assumed for every shipping line.

Despite the fact that some of the study ports are involved in CI projects (such as the Core LNGas hive project: http://corelngashive.eu/en/) none of them currently have permanent on-shore supply facilities for SSS traffic. Thus, 1 h as a connection/disconnection lag time was assumed for all cases. Additionally, since the Spanish ports are not autonomously able to decide their port dues (they are governed by the Royal Legislative Decree 2011/2 at national level), it seems reasonable to assume, for the electricity, the maximum unitary costs that are currently imposed by Melilla port (one of the first ports in Spain with on-shore supply facilities): 0.065€/kWh for large consumers (120.000kWh/three months) and 0.167€/kWh for the remaining cases (2017 service tariffs, https://www.puertodemelilla.es/index.php/servicios/tasas-y-tarifas).

Regarding on-board electricity supply, the 2017 Gibraltar price for LSMGO (0.1% Sulphur content MGO) will be applied as a base price for the routes between the Canary islands and the south of the Iberian Peninsula: 574$/mt (December 2017- https://shipandbunker.com/prices/emea/medabs/gi-gib-gibraltar#LSMGO-); whereas the 2017 Rotterdam price 532.50$/mt (December 2017 https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#LSMGO) will be considered for the route between the north of Spain and France.

Finally, the application cases have assumed a 10 year lifecycle for the analysis of the investment project (the repayment period for the investment). In all cases, the cost due to excess time in port has been estimated on the basis at extra port dues.

6. Results

Despite the difference in maritime distances, the same operation features (five calls per week, see Tables 5 and 6) for transport services have been taken for all case study routes in order to simplify their comparison and determine the influence of the electricity grid and the kind of fleet on CI performance.

6.1. Estimation of emission factors for the electricity grids in the application cases

EUROSTAT (EU Commission, DG Energy, Unit A4, 2020) information about Gross Electricity Generation per type of generation was used for the French and continental Spain electricity grid, while information for the islands was taken from the Energy yearbook of the Canary Islands (Government of the Canary Islands, 2018). This information (see Table 3), together with the relationship between $PM_{2.5}$

Table 3
Gross Electricity Generation, by fuel in 2017 (%).

	Hard coal	*Brown coal*	*Oil and petroleum products*	*Natural gas and manufactured gas*	*Solid biofuels and renewable wastes*	*Renewable*	*Nuclear*	***Main Activity Electricity Only Plants [TWh]***
SPAIN	15.44%	0.93%	5.72%	23.68%	1.86%	31.31%	21.06%	239.59
FRANCE	2.28%	0.00%	1.24%	7.64%	1.01%	16.84%	70.98%	530.76
GRAN CANARY ISLAND	0.00%	0.00%	91.86%	0.00%	0.00%	8.14%	0.00%	3.48
TENERIFE ISLAND	0.00%	0.00%	92.27%	0.00%	0.24%	7.49%	0.00%	3.53

(Data Source: EUROSTAT, 2020; Government of the Canary Islands, 2018).

Table 4
Average emission factor for European grids in 2017.

	NO_x (g/kW.h)	SO_2 (g/kW.h)	$PM_{2.5}$(g/kW.h)	PM_{10}(g/kW.h)	CO_2(g/kW.h)
SPAIN (continental)	0.567	0.402	0.012	0.013	291.369
FRANCE	0.066	0.042	0.001	0.001	4.301
GRAN CANARY ISLAND	1.796	0.785	0.030	0.015	656.034
TENERIFE ISLAND	2.344	0.762	0.033	0.016	645.609

(Data Source: European Environment Agency, 2009; E-PRTR, 2017, EUROSTAT, 2020; Government of the Canary Islands, 2018*).*

Table 5
Emission reduction by CI use in feeder vessels.

			Vigo-St. Nazaire		Las Palmas -Huelva		Las Palmas -Sta. Cruz de Tenerife	
N (yearly_trips)			476		476		476	
Calls per week and direction			5		5		5	
Number of vessels (Nb)			3		4		1	
Maritime distance (Nautical Miles)			464		702		53	
			Vigo	**St. Nazaire**	**Las Palmas**	**Huelva**	**Las Palmas**	**Sta. Cruz Tenerife**
Feeder	Manouvering emissions per trip and port-ECM_{1k}-(€/trip)		111.94	246.41	157.40	111.94	157.40	111.94
	Manouvering emissions per trip (€/trip)		358.35		269.34		269.34	
	Manouvering emissions per year-ECM_1-(€/year)		170576.54		128205.88		128205.88	
	On-board power supply	Berthing emissions per trip and port-ECB_{1k}-(€/trip)	435.60	882.76	611.50	435.60	611.50	435.60
		Berthing emissions per trip(€/trip)	1318.36		1047.10		1047.10	
		Berthing emissions per year-ECB_1-(€/year)	1135935.53		902214.20		902214.20	
		Port emissions per trip (€/trip)	1676.71		1316.44		1316.44	
		Port emissions per year (€/year)	**1306512.07**		**1030420.08**		**1030420.08**	
	On-shore power supply	Berthing emissions per trip and port-ECG_{1k}-(€/trip)	201.38	79.62	474.78	201.38	474.78	447.30
		Berthing emissions per trip (€/trip)	281.00		676.16		922.08	
		Berthing emissions per year-ECG_1-(€/year)	133754.15		537175.34		742583.35	
		Port emissions per trip (€/trip)	639.35		945.50		1.191.42	
		Port emissions per year (€/year)	**370533.14**		**665381.22**		**870789.22**	
	Save emissions by on-shore power supply per year (€)		**935978.93**		**365038.86**		**159630.85**	
	Emissions reduction by on-shore power supply per year (%)		**71.64%**		**35.43%**		**15.49%**	

and $PM_{10,}$ offered by the E-PRTR (see Table 1), has permitted to obtain the emission factors of these pollutants (see Table 4).

Finally, the pollutant emissions of the electric power generating plants (main activity-NACE: 35.1- electric power generation, transmission, and distribution-) not just for the countries (France and Spain), but also for the islands, has been taken from the E-PRTR (Regulation (EC) No. 166/2006).

In light of the above, Table 4 shows the estimated emission factors for the European grids considered in the application cases: Spain, France, Gran Canary island and Tenerife island (EFG_{uk}; $\forall u \in \mathrm{U} \wedge \forall k \in \mathrm{K}$).

6.2. Environmental charges

Tables 5 and 6 offer the savings in emissions by onshore power supply per year. This saving is assumed to be the amount of environmental charge that should be paid by vessel operators when CI is not used in the applications cases.

The quantification in monetary terms of port emissions for on-board power supply and the CI alternative shows, as expected, that the 'advantage ranking' for CI use is strongly conditioned by the sustainability of the port's electricity grid energy mixes. Thus, regardless of the kind of vessel, the maritime routes through St. Nazaire reach the highest emissions reduction versus on-board supply (see Tables 5 and 6), since above an 80% energy mix for grid generation in France (see Table 3) is from no air emitted sources (i.e. nuclear and renewable energy).

This initial advantage for CI use via the Vigo-St.Nazaire route (northern Spain and France) falls by almost one-half when the French port is replaced by an insular port (Las Palmas de Gran Canaria) from the south of the Spanish peninsular (Huelva, see Tables 5 and 6), by achieving an 80% decrease in the initial advantage, when both involved ports are insular ports (Las Palmas-Sta. Cruz de Tenerife, see Tables 5 and 6). Again, the share of renewable and nuclear sources in the electricity grid generation explains this reality (the RES contribution to the energy mix of continental Spain is almost 50%; while it is scarcely 8% in insular grids, see Table 3).

Tables 5 and 6 show Feeder fleets have an additional advantage over Ro-Pax for CI use mainly due to the longer port times for feeder berthing. This operative feature leads to a lower sensitivity of this fleet to lag connection/disconnection times in comparison to the Ro-Pax vessels. Thus, despite their lower energy requirements in port (1200 kw versus 1880 kw for Ro-Pax, see Table 2), the feeder fleet

Table 6
Emission reduction by CI use in Ro-Pax vessels.

			Vigo-St. Nazaire		Las Palmas -Huelva		Las Palmas -Sta. Cruz de Tenerife	
N (yearly_trips)			476		476		476	
Calls per week and direction			5		5		5	
Number of vessels (Nb)			3		4		1	
Maritime Distance (Nautical Miles)			464		702		53	
			Vigo	**St. Nazaire**	**Las Palmas**	**Huelva**	**Las Palmas**	**Sta. Cruz Tenerife**
Ro-Pax	Manouvering emissions per trip and port-ECM_{1k}-(€/trip)		286.74	605.33	402.94	286.74	402.94	286.74
	Manouvering emissions per trip (€/trip)		892.07		689.68		689.68	
	Manouvering emissions per year-ECM_1-(€/year)		424623.52		328287.88		328.287.88	
	On-board power supply	Berthing emissions per trip and port-ECB_{1k}-(€/trip)	406.67	608.38	592.08	406.67	592.08	406.67
		Berthing emissions per trip (€/trip)	1015.05		998.75		998.75	
		Berthing emissions per year-ECB_1-(€/year)	1065296.48		1048194.01		1048194.01	
		Port emissions per trip (€/trip)	1907.12		1688.43		1688.43	
		Port emissions per year (€/year)	**1489920.00**		**1376481.89**		**1376481.89**	
	On-shore power supply	Berthing emissions per trip and port-ECG_{1k}-(€/trip)	228.89	82.55	532.83	228.89	532.83	496.72
		Berthing emissions per trip (€/trip)	311.44		761.72		1.029.55	
		Berthing emissions per year-ECG_1-(€/year)	252019.93		700096.69		966074.57	
		Port emissions per trip (€/trip)	1203.51		1451.40		1719.23	
		Port emissions per year (€/year)	**676643.44**		**1028.384.56**		**1294362.44**	
	Save emissions by on-shore power supply per year (€)		**813276.56**		**348097.33**		**82119.45**	
	Emissions reduction by on-shore power supply per year(%)		**54.59%**		**25.29%**		**5.97%**	

Table 7
Internal Rate of Return for vessel operators.

	Vigo-St. Nazaire		Las Palmas -Huelva		Las Palmas -Sta. Cruz de Tenerife	
N (yearly_trips)	476		476		476	
Calls per week and direction	5		5		5	
Number of vessels (Nb)	3		4		1	
Maritime distance (Nautical miles)	464		702		53	
Vessel	**Feeder**	**Ro-Pax**	**Feeder**	**Ro-Pax**	**Feeder**	**Ro-Pax**
Retrofitting investment(€)	−401,344	−1,105,030	−535,126	−1,473,373	−133,781	−368,343
Net cash flow difference $_{first\ year}$(€)	1,048,668	863,099	531,201	526,831	326,512	281,400
IRR(%)	**261**	**78**	**99**	**34**	**244**	**76**

Table 8
Scenarios for the deterministic sensitivity analysis.

	Base scenario	Pessimistic scenario
Unitary cost for on-shore electricity supply (€/kW.h)	0.065	0.12
LSMGO (0.1% S) (€/mt)_Rotterdam	447.06	310.08
LSMGO (0.1% S) (€/mt)_Gibraltar	482.35	337.81

Table 9
Sensitivity analysis.

	Vigo-St. Nazaire				Las Palmas -Huelva				Las Palmas -Sta. Cruz de Tenerife			
	Feeder		Ro-Pax		Feeder		Ro-Pax		Feeder		Ro-Pax	
Probabilistic Analysis	IRR_mean = 510%		IRR_mean = 90%		IRR_mean = 90%		IRR_mean = (−7)%		IRR_mean = 128%		IRR_mean = (3%)	
Deterministic Analysis	Base case	Pessimistic scenario	Base case	Pessimistic scenario	Base case	Pessimistic scenario	Base case	Pessimistic scenario	Base case	Pessimistic scenario	Base case	Pessimistic scenario
IRR	816%	328%	205%	–	276%	–	67%	–	758%	–	199%	–

mainly benefits in the case studies.

Even though in all case studies CI use has proved to be more sustainable than on-board electricity supply (positive emission reductions in all cases), the scarce contribution of RES in electricity production in Tenerife's grid (see Table 2) leads to the fact that plugging-in vessels in Sta. Cruz de Tenerife is currently less environmentally friendly than on-board supply when a single trip is evaluated (447.30€/trip versus 435.6€/trip, see Table 5). This reality might even rule out the CI alternative for Ro-Pax vessels in Sta. Cruz de Tenerife since, aside from the low sustainability of the grid, their short berthing times are significantly penalized by the connection/disconnection lag times of CI use (496.72€/trip versus 406.67€/trip, see Table 6). In such a way, only when hoteling time (inactive time in port from 23 pm to 7 am) is considered in the analysis, the environmental balance becomes favourable to CI use in Sta. Cruz de Tenerife. These results quantitatively confirm the previous 'voices of caution' about the convenience and expected performance of CI on the islands (Winkel et al., 2016.) by operating through vessels with short calls (Khersonsky et al 2007; Zis et al., 2014).

It is interesting to note that, even though manoeuvring emissions have limited influence over on-board power supply (13–20% of whole port emissions), the relative weight of the manoeuvring stage emissions (ECM_1 see Tables 5 and 6) significantly increase on the whole port emissions when CI is used (port emissions per year in on-shore power supply) by reaching overcoming 50% in Vigo-St. Nazaire (see Tables 5 and 6). This suggests the need to implement additional mitigation systems during the manoeuvring time (Sciberras et al., 2017) aside from Tier III engines (see Table 4).

6.3. *Internal rate of Return (IRR)*

Table 7 shows the IRR of investment in CI retrofitting for the vessels (see Table 2) in the shipping lines taken as case studies. When the IRR is analyzed, the feeder vessels continue to be those that most benefit from CI retrofitting. Besides the environmental charge savings per air emissions (see Tables 5 and 6), the advantage for the feeders is due to their lower size (gross tonnage, see Table 2). This directly influences the cost per extra unit of time in port (ship duty) and indirectly on the retrofitting investment (see Table 7 and equations (7) and (8)).

The IRR achieved in all cases has proven to be sufficiently interesting to encourage CI investment from a vessel operator's perspective. It is remarkable that even the Las Palmas-Sta. Cruz de Tenerife shipping line, with low savings in terms of the environmental charge (limited emission savings, see Tables 5 and 6), would benefit from CI use. This is because of a reduced initial investment in retrofitting a single vessel along with lower operational costs, since the base cost for the on-shore electricity in 2017 (0.065€/kWh) offers, in itself, a more competitive alternative than LSMGO (0.1% sulphur content MGO of 482,35€/mt, Gibraltar in 2017) for electricity generation in port.

Fig. 1. Sensitivity chart in the probabilistic analysis.

Paying attention to the net cash flow difference per CI use in the first year (ΔCF_1, see equation (9)), in all cases it is positive, and even in some cases exceeds the initial investment (see Table 7). Despite no loan being considered, the maximum payback period for the investment is four years (for the Ro-Pax service between Las Palmas and Huelva). Consequently, the environmental charge under the conditions assumed for the application cases, proves to be a useful tool for CI promotion from the ship-owner standpoint.

6.4. *Sensitivity analysis*

Considering the favourable IRR results obtained in the application cases (base estimations), a sensitivity analysis is necessary to know not only the robustness of this first approach, but also its dependence on the variables involved. Since results achieved from the application cases (base scenarios) have been positive, those are assumed to be optimistic scenarios in the sensitivity analysis (see Table 8). More 'unfavourable' frameworks were then defined, by assuming lower values for bunkering. Moreover, higher values for on-shore electricity costs were also taken to characterize pessimistic scenarios. The aforementioned values are the highest or lowest recorded, from the same sources, in the base cases (see Table 8).

Table 9 shows the results of the sensitivity analysis when a loan for over 70% of the retrofitting investment is requested, for a payback period of five years with a 6% interest rate. Aside from the base cases (optimistic scenario), the deterministic analysis shows the results achieved for pessimistic scenarios (see Table 8). In this latter case, only the feasibility of the feeder service between Vigo-St. Nazaire is ensured, since negative values for IRR were found for the other shipping lines in pessimistic scenarios (see Table 9).

In order to provide a broader perspective, a probabilistic analysis was carried out through 'Montecarlo simulations' by taking values for the core variables (see Fig. 1), according to probability functions. These functions (triangular distributions) have taken a 20% range for the most and least probable values from the base cases.

Thus, for the variables of Table 8 medium values were assumed as base cases, while for the other variables the base values are those of the application cases (see section 4). The mean values for the IRR distributions obtained from the simulations (at a 95% confidence level) are collected in Table 9. These results suggest the unfeasibility of CI retrofitting for Ro-Pax services between Las Palmas-Huelva and inter islands (Las Palmas-Sta. Cruz de Tenerife). The sensitivity chart (see Fig. 1), that shows the contribution of variance for the IRR results, provides evidences that the incidence of a specific environmental charge is actually useful when the environmental benefit is significant (Vigo-St.Nazaire routes). However, in contexts of moderate emission savings (Huelva-Las Palmas) the 'charge incentive' is insufficient in itself to make a CI investment feasible, since the operational cost difference (on-shore electricity versus bunkering cost) is the most influential parameter on the feasibility of these scenarios.

The sensitivity analysis confirms the initial findings about the lower incidence of the lag connection/disconnection times for the Feeder vessels. The sensitivity chart (see Fig. 1) evinces the lower relative weight of ship duties (that collect the extra time value) on IRR variance for feeder vessels in relation to Ro-Pax fleets.

7. Conclusions and further research lines

The obligation to provide CI facilities in the main EU ports from 2025 (Directive 2014/94/EU) suggests a change towards the harmonization of environmental charge schemes for port emissions. This work assumes, as a first step, a similar evolution of the environmental port normative to that of road transport in the EU (Directive 1999/62/EC amended by Directive 2011/76/EU and COM (2017) 275 final, ANNEX 1), through an external cost charge based on a differential system related to the most sustainable technological alternative. Thus, an environmental charge - linked to the emission difference between CI use and on-board electricity supply - should be paid by the vessels in port, in order to incentivize vessels retrofitting with CI to address the harm caused from pollution in both social and economic terms.

In the light of foregoing, this work introduces a method that is able to quantify the environmental charges for SSS fleets operating on a specific route. Moreover, the paper presents the economic impact of that environmental charge, when the fleet retrofits CI, by employing IRR assessment for the vesselś operator investment.

The method has been applied to several European routes (European electricity grids diversity) where Feeder and Ro-Pax vessels operate. Even though the results were obtained from specific application cases, these are sufficiently representative to enable the extrapolation of the presented findings to similar frameworks. Thus, the results indicate that the environmental charges would contribute to strengthening the feasibility of CI retrofitting for those SSS vessels that operate on routes where CI offers a significant emission saving (environmental charge savings). Moreover, that feasibility would be little conditioned by the framework parameters (bunkering cost and unitary electricity price) on these routes. The opposite of this is expected on routes whose ports offer CI services with low environmental benefits in relation to on-bord electricity supply. In this latter case, the feasibility of CI retrofitting on vessels is highly dependent on the operation costs (bunkering versus on-shore electricity price) regardless of environmental charges application. Consequently, ports located in regions with high share of RES on the on-shore electricity generation would take wide advantages from the introduction of an environmental charge, whereas those ports whose electricity grids are still highly dependent on fossil fuels could even be penalized by CI use regardless of environmental charge application. Nevertheless, additional externalities (such as noise pollution, port waste generation, vibration, etc) should also be considered in further approaches to environmental charge calculations to provide more accurate evaluations. Likewise, the societal impact of the environmental charge should be included by authorities and policy makers in CI cost-benefit analysis, when this is evaluated as a whole (European Commission, 2015).

The analysis also shows that feeder vessels with longer berthing times per call and lower gross tonnage, in relation to Ro-Pax vessels, would be the most to benefit from CI use with environmental charge application, as it involves lower investment costs for retrofitting and lower sensitivity to the additional time for connection/disconnection in port.

Even though the calculation method for environmental charge introduced by this paper estimates the level of differentiated pollutant emissions (pollutant differentiation system), following the evolution of road transport as an example, a simplified application in Tier system way is expected (Euro categories for trucks) in a first step. This reality drives the future research lines. Thus, one of them must tackle the environmental categorization of vessels by considering the ESI (IAPH' initiative) as an initial indicator. To this aim, aside of including $PM_{2.5}$ and PM_{10} emissions in the ESI calculation, the current IMO required levels should be replaced by CI emissions in the ESI expressions. Thus, the calculation of the environmental charge could be addressed from an adaptation of the method proposed in this study through the inclusion of a modified ESI indicators.

Finally, the consequences of the application of environmental

Acknowledgements

The authors gratefully acknowledge the very helpful comments made by the anonymous reviewers of this journal. The authors also wish to acknowledge funding received from 'Canary smart specialization strategy programme RIS-3, 2020' co-funded by European Regional Development Fund (2014-2020).(REPORT project, grant agreement no. ProID2020010056).

Appendix A

Subscripts:

K = {1, …, k}: Ports for linear shipping line: Vigo, St.Nazaire, Las Palmas de Gran Canaria and Sta. Cruz de Tenerife. These ports articulate the lines: Vigo(Spain)-St. Nazaire(France); Las Palmas de Gran Canaria(Gran Canary island)-Huelva (Spain) and Las Palmas de Gran Canaria (Gran Canary island)- Sta. Cruz de Tenerife (Tenerife island).

Q = {1, …, q}: Kind of vessel: feeder vessel and RO-PAX

U = {1, …,u}: Kind of emission pollutants: NO_x, SO_2, $PM_{2,5}$, PM_{10} and CO_2;

V = {1, …,v}: Classification of ports according to the population of their hinterlands: metropolitan zone (over 0.5 million inhabitants) and urban zone.

T = {1, …, t}: Every year that is considered in the investment project for the CI retrofitting of vessels in their lifecycle.
Variables:
BT_q: Berthing Time (h). This time is the loading/unloading time. $\forall q \in Q$
$CAPEX_q$: Capital cost for CI retrofitting (€). $\forall q \in Q$
CIT: the yearly cost for the lag connection/disconnection time (€),
$(CF_q)_t$: Net Cash flow (€); $\forall q \in Q \wedge \forall t \in T$
CT: Lag connection time (h).
ECB_{qk}: Environmental costs during berthing, for every kind of vessel and port (€);
$\forall q \in Q \wedge \forall k \in K$
$ECCI_q$: Annual electricity costs for CI (€) ($\forall q \in Q$)
ECG_{qk}: Environmental costs of on-shore power use during berthing, for every kind of vessel and port (€);
$\forall q \in Q \wedge \forall k \in K$
ECM_{qk}: Environmental costs of manouvering, for every kind of vessel and port (€);
$\forall q \in Q \wedge \forall k \in K$
$ECOB_q$: On-board supply of electricity, costs per year (€); $\forall q \in Q$
EFB_{uq}: Emission factors for every kind of vessel and pollutant during berthing. (kg/h) $\forall u \in U \wedge \forall q \in Q$
EFG_{uk}: Emission factors of the electricity grid for every kind of pollutant and port during berthing. (kg/kW.h) $\forall u \in U \wedge \forall k \in K$
EFM_{uq}: Emission factors for every kind of vessel and pollutan during manouvering. (kg/h) $\forall u \in U \wedge \forall q \in Q$
MT: Manouvering Time (h). This variable collects the pilot and towing time, when necessary.
N: Number of annual trips by a shipping line.
N_b: Number of vessels that offer a particular SSS line.
PB_q: Required power to carry out the loading/unloading operations for every kind of vessel (kW). $\forall q \in Q$
UC_{ukv}: Unitary costs for every kind of pollutant and port (€/kg). $\forall u \in U \wedge \forall k \in K \wedge \forall v \in V$

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