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Solar photovoltaic systems for the Short Sea Shipping's compliance with decarbonization regulations in the European Union

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ABSTRACT

Carbon Intensity Indicator (CII) regulation came into force In January 2023 as one of the main International Maritime Organization's measures to reduce Greenhouse Gas (GHG). Short Sea Shipping (SSS) demand significant electricity supply by reaching up to 30% of total on-board power. This paper addresses SSS-fleet compliance with CII regulation, Market and Goal-Based Measures imposed by the European Union (EU) through solar photovoltaic systems (PV) for on-board electricity production. The paper analyses the techno-economic feasibility of this solution from the shipowners' standpoint in the medium-term. To meet this aim, a SSS Car-carrier between Canary Islands and Iberian Peninsula is assessed by simulating PV performance, vessel's technical implications, and economic consequences of GHG mitigation in the context of the EU. The results reveal that PV reduces fuel consumption for electricity generation by 15.5% by reducing the total CO_2 emissions by 3.38%. Although this improvement is not substantial enough to change the CII score of the vessel, the Internal Rate of Return of the PV investment achieved 55% for 10 years with three years as payback period. This fact along with the robustness of the results achieved suggest PV system is a promising mitigation option for SSS vessels.

Introduction

The Carbon Intensity Indicator (CII) is a Goal Based Measure (GBM) introduced by the Marine Environment Protection Committee (MEPC 76, in June 2021) from the IMO (International Maritime Organization) as one of the tools to reduce Greenhouse Gas (GHG) emissions. CII is a yearly index with compulsory application from 1st January 2023 for vessels over 5,000 Gross Tonnage (GT). This involves, aside from a regular evaluation of vessels' accomplishment according to a reduction's schedule of emissions over time (5% for 2023, 7% for 2024, 9% for 2025, etc.) from 2019 reported emissions (under IMO-DCS), a vessels categorization by considering their operational energy efficiency performance. This rating (from A to E) will be taken into account by the institutions to incentive sustainability through significant reductions in vessels' operating costs. Proof of this is the firm intention of the International Association of Harbours and Ports (IAHP) to include CII in the ESI (Environmental Ship Index) equation. Likewise, the European Commission (EC) is currently evaluating the inclusion of maritime transport in the EU-ETS (European Emission Trading System) along with a compulsory standard for CII (MAR 4 in COM (2021) 551 (EU-ETS)).

Despite CII compliance representing a challenge for most vessels, the Short Sea Shipping (SSS) vessels introduce an additional difficulty since the CII measures CO_2 emissions per per nautical miles and ship's capacity, and these vessels do not take advantage of economies of scale (as they are quick and small [1]). First evaluations about the impact of CII forecast a size increase for the new vessels and a decrease in their service speed, however this is not economically feasible for SSS where the vessels' capacity and their shipping time are often optimized to compete with other transport modes [2]. In turn, these first approaches conclude that the commercial abatement systems will barely enable the vessels to meet the CII regulation beyond 2026, and the alternative fuels are still too expensive for propulsion requirements [3]. One of the singularities

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of SSS vessels is their high electricity demand in relation to their propulsion power (reefer plugs for perishable goods, bow thrusters for the quick manoeuvring stage and long port times regarding the total trip); meaning that up to 30% of their total CO_2 emissions arise from their electric generating plant.

In this context, this paper aims to evaluate, through the Internal Rate of Return (IRR), the techno-economic feasibility of SSS vessels' retrofitting to use Photovoltaic (PV) systems, based on solar energy, as an alternative technology to comply with CII regulations over time, in several fleet patterns. Even though renewable energies are still insufficiently mature technologies for propulsion, PV systems are commercially viable to generate electricity at moderate powers. Taking advantage of this technological state and the singularities of SSS, this paper assesses, firstly, the technical feasibility and expected performance of solar PV systems, under ideal conditions, as complementary sources to supply the electric power for SSS vessels by assuming: Ro-Ro liner shipping, regular Ro-Pax vessels and feeder vessels operating in the European Union (EU). Next, a feasibility analysis of the investment in the vessels' retrofitting considers, aside from the Capital Expenditure (CAPEX) for investment, the Operating Expenditure (OPEX) through the inclusion of shipping in the EU-ETS scheduling (progressive inclusion of verified emissions reported from 2023- COM (2021) 551-), the possible penalties by non-compliance with FuelEU Maritime initiative (successive reductions of $CO_{2\ eq}$ emissions over 2020 records- COM (2021) 562 final-) and CII implications over time, but also the resulting bunkering and maintenance savings. The analysis' method is finally applied to a case study of a SSS Car-carrier vessel operating between the Canary Archipelago and the Iberian Peninsula. To meet this aim, Homer Pro microgrid software is used to calculate PV performance on that route, together with its environmental advantages, by considering expected electric demand for its navigation stages. Finally, in order to meet the robustness of the findings and to widen their scope, a sensitivity analysis is carried out (Montecarlo simulations) by identifying, additionally, the most influent variables on the results.

Photovoltaic systems in vessels

Most authors agree that solar PV systems are expensive and low cost-effective to meet CII requirements [3,4]. However, there is also a broad consensus about the high dependency of these performances on vessel technical characteristics and especially, on their operating characteristics: navigation circumstances and loading factor [5]. This reasoning led to analyse containerships' operational data [6] to provide evidence-based results about the CO_2 reduction potential for several technical and operative compliance options [7]. The authors concluded that speed reduction through Engine Power Limitation (EPL) is the easiest solution for meeting the CII regulation and in fact, this operating alternative offers the greatest cost-effectiveness since its CAPEX is negligible. However, they warn about the unfeasibility of this solution for the smallest ships (SSS), since meeting traffic requirements would require more vessels to be in operation.

Despite these recommendations from previous research about the choice of mitigation systems for CII compliance, solar, wind, and fuel cell energy have become the most attractive on-board SSS Renewable Energy Systems (RES). PV module placement in Car-carriers and Ro-Pax have been addressed on newbuild vessels through adjustment of land technologies to the maritime sector. In this context, Atkinson [8] researched the solar power trails of a high-speed ferry (Blue Star Delos) to test energy output regarding the designed one (the expected one), by evaluating PV system performance under salt and marine conditions (dirty panels) and the stability of the power supply, with positive results.

Even though some studies tackle solar energy as a possible mode of reducing the power developed by the main engine, the energy produced by RES is mainly managed to supply ships' electrical needs and therefore, its impact on vessels' overall CO_2 reduction has been hardly conducted. Authors like Peša et al. [9] argue that the cost-effectiveness of installing PV modules in existing SSS vessels, beyond emission reductions, is indisputable for regions like the Adriatic Sea, because the price of energy obtained from PV modules is more than half the price of energy produced using a diesel-electric power unit in small vessels (43.7 m length over all). Good results were also achieved by Wang et al. [10] for similar sized vessels (41.98 m length over all), who tackled the life cycle cost relative to installation, operation, and recycling of the solar panels for the propulsion power supply of an SSS ferry (on a 30 km route) by considering fuel savings and payback time. In this case, the payback time was three years, and the marginal cost of the carbon credit should be \$ 190 per tonne, or higher, to make the shipping business successful. In the same line, but for conventional Ro-Ro vessels (208 m length over all), Karatuğ and Durmuşoğlu [11] adapted solar power to the ship's main power grid in a Ro-Ro ship, which travelled between Pendik (Turkey) and Trieste (Italy), by reaching a 7.38% reduction in yearly fuel demand for electricity generation. Additionally, the authors found that the payback period (at an interest rate of 8%) for the investment was 11 years. Parallelly, Qiu et al. [12] found feasible the integration of photovoltaic (PV) systems into a ships power grid for deep sea shipping but with a high variability to the route (payback periods between 4 and 18 years).

It is interesting to note that, despite the scarce existence of studies of PV performance on SSS vessels, as said, most previous insights about PV suitability on vessels (Marginal Abatement Costs-MAC- and CO_2 abatement capacity) are based on deep-sea shipping analysis where the operational measures (reduction in service speed) are feasible; even researchers focused on SSS do not consider upcoming Market Based Measures (MBM) effects, such as the extension of the EU-ETS to maritime transport (COM (2021) 551) and the penalties by non-compliance with FuelEU maritime initiative (COM (2021) 562). It is clear that a knowledge gap exists about the feasibility of PV systems for SSS under the current EU framework [7]. Thus, this paper contributes to this regard by analysing the suitability of SSS vessels' retrofitting with PV systems by considering CII compliance and the additional effects of the recent decarbonization regulation in the EU: Market and Goal Based Measures.

Method to assess the feasibility of PV systems in SSS vessels

Fig. 1 introduces an evaluation method of the convenience of the vessels' retrofitting with PV system based on two steps: Firstly (see section 4), a CII score is estimated over time for the two scenarios, an initial vessel and a retrofitted vessel, in such a way that the technical feasibility of the PV installation, along with the maximum improvement range provided by the PV systems, are estimated in a first approach. Once, the technical suitability of the vessel's retrofitting is verified, the second step involves a detailed analysis about the feasibility of the investment, through the Internal Rate of Return (-IRR- section 6). To this aim, a hybrid PV system is defined (Homer Pro software, section 5) to assess the actual improvement provided by the vessel's retrofitting. Finally, the second step tests the IRR consistency and the scope of the results through a sensitivity analysis (section 6.1). The following sections (3.1–3.5) detail the necessary equations to quantify the assessment proposed.

Carbon Intensity Indicator (CII)

The application of the CII normative involves the calculation of attained CII for the vessel (CII Guidelines from MEPC.336(76)), in grams of CO_2 per nautical miles and ship's capacity (see equation (1), and the required annual operational CII (CII Reference line guidelines from MEPC337(76) and CII reduction factors Guidelines from MEPC.338 (76)); see equation (2). The relative position between them (CII Rating Guidelines from MEPC.339(76)) determines the vessel score (A, B, C, D or E, from the most sustainable category to the least), with a C score being the acceptance boundary. Three consecutive years with a 'D class', or one with an 'E class', necessary involves providing a modification

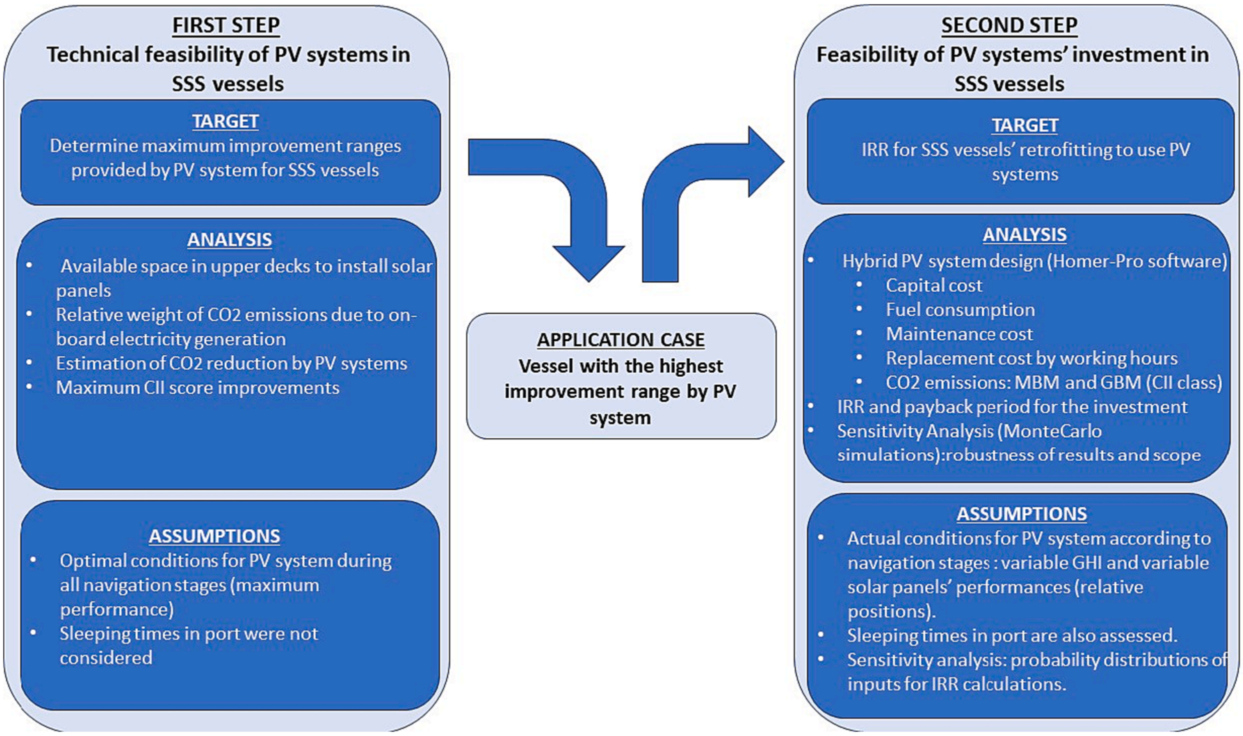


Fig. 1. Method to assess the feasibility of PV systems in SSS vessels.

plan for a vesseĺs operation or a vesseĺs retrofitting, by ensuring the return to a 'C class' (at least). Whereas the Attained CII involves estimating CO_2 emissions by taking into account the distance covered by the ship (D) and the SSS vessel's capacity (C),[1] the Required CII integrates constant factors that are dependent on the kind of vessel (a and c from MEPC337(76); see equation (1), the cargo capacity of the vessel and the annual ($K=\{1,\dots,k\}$) reduction factor (Z_k; $\forall k \in K$). The estimation of the CO_2 emissions (see equation (2) follows the approach from reports under IMO DCS by considering aside from all navigation stages: free sailing, manoeuvring, berthing and sleeping time in port ($SS=\{1,\dots,s\}$), the on-board engines ($L=\{1,\dots,l\}$) and the different fuel types ($J=\{1,\dots,j\}$), being:

TVB_s: Time invested in every navigation stage in a trip (h/trip); $\forall s \in SS$.

CFF_{jl}: Conversion factor (tonne CO_2/tonne fuel); $\forall j \in J \wedge \forall l \in L$ (resolution MEPC.308(73)).

PB_{ls}: Power for the vessel's engines (kW; $\forall l \in L \wedge \forall s \in SS$).

$SFOC_{jls}$: Specific Fuel Consumption for engines in every navigation stage (g fuel/kW.h); $\forall j \in J \wedge \forall l \in L \wedge \forall s \in SS$.

N: Number of yearly trips.

$$\text{Required}_{CII} = \left(1 - \frac{Zk}{100}\right) \times a \times C^{-c};\ \forall k \in K \tag{2}$$

The EU emission trading system

According to the European communication COM2021 (551) final, shipping will be gradually included in the EU-ETS (β_k; $\forall k \in K$; see equation (3) further considering, the port calls' jurisdiction (α_i; $\forall i \in I$; from/to Member State $I = \{1,..,i\}$; see equation (3).

This section offers a quantification of the impact of this MBM on the vessel's operation costs: ETS (€/year). Equation (3) collects, aside from the Carbon Allowance Price (CAP in €/CO_2 tonne), the amount of CO_2 emissions per year. For this latter element, the THETIS-MRV reports will be considered according to COM2021 (551) final, which involves a CO_2 emission estimation by applying conversion factors (Annex VI of the EU Commission Regulation No 601/2012 and resolution MEPC.308(73); CFF_{jl}; $\forall j \in J \wedge \forall l \in L$ in t CO_2/t fuel) along with the specific consumptions ($SFOC_{jls}$; $\forall j \in J \wedge \forall l \in L \wedge \forall s \in SS$) for the on-board engines by operating at several powers (PB_{ls}; $\forall l \in L \wedge s \in SS$) at every moment of the navigation stages (TVB_s; $\forall s \in SS$).

$$\text{Attained}_{CII} = N \times \sum_{s=1}^{n} \left(TVB_s \times \sum\nolimits_{l=1}^{n} (SFOC_{jls} \times PB_{ls} \times CFF_{jl})\right) / (C \times D);\ \forall j \in J \wedge \forall l \in L \wedge \forall s \in SS \tag{1}$$

[1] SSS Ship's capacity (C) should be assumed as the Gross Tonnage (GT) for cruise passenger ships, car-carrier ships (vehicle carriers) and ro-ro passenger ships Moreover, Deadweight tonnage (DWT) should be used as SSS ship's capacity (C) for container ships, ro-ro cargo ships, general cargo ships, refrigerated cargo carrier and combination carriers.

$$ETS = N \times CAP \times \alpha_i \times \beta_k \times \sum_{s=1}^{s}\left(TVB_s \times \sum_{l=1}^{l}\left(SFOC_{jls} \times PB_{ls} \times CFF_{jl}\right)\right);\ \forall j \in J \wedge \forall k \in K \wedge \forall l \in L \wedge \forall s \in SS \quad (3)$$

α_i: Percentage of the overall CO_2 emissions that are included in the ETS: Null percentage when no port belongs to an EU Member State ($\alpha_i = \alpha_3 = 0\%$), the middle of the total emissions when only one port belongs to an EU Member State ($\alpha_i = \alpha_2 = 50\%$) and all emissions if both ports belong to an EU Member State ($\alpha_i = \alpha_1 = 100\%$);

β_k: Percentage of the overall CO_2 emissions that are included in the ETS according to the activity year-implementation schedule: 2023 ($\beta_k = \beta_1 = 20\%$); 2024 ($\beta_k = \beta_2 = 45\%$); 2025 ($\beta_k = \beta_3 = 70\%$); 2026 and each year thereafter ($\beta_k = \beta_4 = 100\%$);

FuelEU maritime initiative

Fuel EU Maritime initiative (COM (2021) 562 amended by European Parliament legislative resolution of 11 July 2023–2021/0210(COD)-) is an additional GBM to CII imposed by EU but which limits $CO_{2\ eq}$ instead CO_2 emissions. Thus, a progressive reduction of the greenhouse gas intensity (gr CO_2 eq/MJ) over a reference value (average greenhouse gas intensity of the vessels in 2020 determined by THETIS-MRV data, -Regulation (EU) 2015/757-) is required with the following schedule: −2% from 1 January 2025; −6% from 1 January 2030; −14.5 from 1 January 2035; −31% from 1 January 2040; −62% from 1 January 2045; −80% from 1 January 2050. This calendar motives the target greenhouse gas intensity of a vessel in a particular year ($(GHGIE_{target})_k$, $\forall k \in K$, in g $CO_{2\ eq}$/MJ); the difference between this value and the actual ($GHGIE_{actual}$) along with $Vessel_{\_Energy}$ (MJ, see equation (5)) for the reported period determines the non-compliance penalty ($Fuel\_EU_k$, $\forall k \in K$ in euros, see equation (4) and (5)), being LCV_j ($\forall j \in J$ in MJ/gFuel) the lower calorific Value of the fuel and E_p($\forall p \in P$ in MJ) the electricity delivered to the ship per connection point. Thereby, the FuelEU penalty considers as vessel energy (MJ) not only those produced by on-board engines (L= {1,…,*l*}) but also the energy from the electricity delivered to the vessel at berth through an On Shore Power Supply (OPS). Finally, the GHGIE estimation (g $CO_{2\ eq}$/MJ) for actual and target values (annex 1 and 2 COM (2021) 562 final), considers, aside from GHG emission factors, the CO_2 equivalent emissions of combusted fuel ($j \in J$).

Internal Rate of Return

This section introduces the IRR as an evaluation tool to assess the investment in PV retrofitting of the vessel. Equation (6) shows the IRR expression where CAPEX (capital costs) involves the investment for the PV system in 2022 by being operative from 2023.Therefore, the feasibility analysis considers a time range from 2022 to 2032 (K= {1,…,*k*}).

$$CAPEX = \sum_{k=1}^{k}\left(\frac{\Delta\left(CF_q\right)_k}{(1+IRR)^k}\right);\ \forall q \in Q \quad (6)$$

The second element of equation (7) shows, aside from the IRR, the difference between the Net Cash Flow($\Delta(CF_q)_k$; $\forall k \in K \wedge \forall q \in Q$), both with and without PV system installation ($Q = \{1,2\}$).

$$\Delta\left(CF_q\right)_k = \Delta\left(MC_q\right)_k + \Delta\left(RC_q\right)_k + \Delta\left(BC_q\right)_k + \Delta\left(ETS_q\right)_k + \Delta\left(Fuel\_EU_q\right)_k;\ \forall q \in Q \wedge \forall k \in K \quad (7)$$

The cash flow considers maintenance costs[2] (MC_q; $\forall q \in Q$), replacement costs[3] of the generating sets and PV systems (RC_q; $\forall q \in Q$), bunkering costs (BC_q; $\forall q \in Q$), emission trading system costs (ETS_q; $\forall q \in Q$, see equation (3) and Fuel-EU costs ($Fuel\_EU_q$; $\forall q \in Q$, see equation (4) for every year calculated. It is worth bearing in mind that the maintenance and replacement costs are dependent on accumulated working hours ($\forall k \in K$). In fact, the Cash Flow difference will be positive when the retrofitting case ($q = 2$) provides savings related to the initial case ($q = 1$). In order to offer a realistic approach to the feasibility of the vessel's retrofitting, on the one hand, the financing costs from a possible loan should be included in the total Cash Flow estimation (repayment of capital and interest). On the other hand, since the life cycle of the vessel and its activity predictively overcome the assessment period of the investment project (20 years versus 10 years), no sale on the second-hand market or scrapping is foreseeable during the evaluation time, consequently, no residual value (income) is expected for the Cash Flow.

$$Fuel\_EU_k = N.\ 2.4/41MJ/kg \times Vessel_{\_Energy} \times \left(\left(GHGIE_{target}\right)_k - GHGIE_{actual}\right)\Big/ GHGIE_{actual};\quad \forall k \in K \quad (4)$$

$$Vessel_{\_Energy} = \sum_{(s=1)}^{s}\left(TVBs \times \sum_{l=1}^{l}\left(SFOC_{jls} \times PB_{ls} \times LCV_j\right)\right) + \sum_{p=1}^{1} E_p;\ \forall j \in J \wedge \forall l \in L \wedge \forall p \in P \wedge \forall s \in SS; \quad (5)$$

[2] Maintenance costs involve labour costs and part replacement costs to maintain generating sets and PV systems.

[3] Replacement cost involves replacing a group of components of an item whenever their lifetimes have been surpassed.

Table 1
Technical Features of the SSS vessels.

	Reefer	Feeder	Ro-Pax (catamaran)	Ro-Ro	Car-carrier
Lt(m)	148	148	112.60	209.43	139,98
Lpp(m)	137.82	137.82	101.3	190.0	131
B(m)	20.50	20.50	37.6	20.00	22.40
D(main)	11.17	11.17	8.5	9.6	7.95
D(upper_deck)	—	—	15	23.55	24.45
T(m)	8.20	8.20	4.8	7.00	6.50
Service speed (kn)	18.5	18.5	37.6	19.8	16.5
BHP	8,300 kW	8,300 kW	(4x9MW)	(4x10,8MW)	6,965 kW
Main engine fuel	MDO (0.5%S)	HFO (3.5%S)	MDO (0.1%S)	HFO (3.5%S)	HFO (3.5%S)
Scrubber	no	yes (open-loop)	No	yes (open-loop)	yes (open-loop)
Waterjets	—	—	4	—	—
Cars	—	—	357	100	2057
Trucks	—	—	—	210	—
Container sockets	234	170	—	210	—
PAX	—	—	1400	—	—
TEUS	869	869	—	—	—
Auxiliary engines	3X550Kw	2x675Kw	4X490kW	3X1635kw + 1X597kW	3X860kw
GT	9,900	9,900	10,369	30,998	21,143
Deadweight (t)	10,650	10,650	1,141	10,140	4,713
Bow thrusters	1x880kW	1x880kW	2X300 kW	2X1295 kW	1X1300 kW
PTO	1x1800Kw	1x1500Kw	—	2X1800 kw	—

Table 2
Relative weight of electricity generation on total CO_2 emissions per trip.

		Reefer	Feeder	Ro-Pax (catamaran)	Ro-Ro	Car-carrier
Manoeuvring	Propulsion	26.38	26.35	19.46	91.97	44
(CO_2kg/trip)	Electricity generation	1,507.76	1,309.38	164.47	3,753.01	1,196.32
Free sailing	Propulsion	96,730.70	105,569.87	33,096.00	312,034.92	108,711.81
(CO_2kg/trip)	Electricity generation	33,971.72	26,349.68	389.33	82,977.09	22,111.12
Berthing	Propulsion	0,00	0,00	0,00	0,00	0,00
(CO_2kg/trip)	Electricity generation	5,372.64	4,203.06	243.66	9,283.29	2,657.07
(CO_2 by Electricity generation/total CO_2)$_{trip}$		**29.69%**	**23.18%**	**2.34%**	**23.52%**	**19.27%**
		SOLAR PHOTOVOLTAIC SYSTEM				
Available Surface (m^2)		2,000	2,000	1,900	3,433	2,200
Maximum Solar Power (kW)		422	422	400	724	464
Maximum CO_2 reduction with PV		**−2.96%**	**−3.60%**	**−1.37%**	**−3.13%**	**−4.90%**

First step: technical feasibility of PV systems on the Short Sea Shipping fleet

This section offers a first approach to the potential effectiveness of solar energy in terms of CO_2 savings. To meet this aim, the relative weight of electricity generation on vessels' total emissions is estimated along with the consequent evolution of CII class over time, when the PV systems are set up in order to identify any possible advantages obtained by retrofitting the vessels.

A number of vessels are able to operate under SSS conditions, however only a few currently have a general arrangement with upper decks that are sufficiently opened to instal solar panels. According to this criterium, the following types of vessels were selected for a first feasibility analysis of PV systems on SSS vessels (see Table 1): reefer container vessels, feeder vessel, Ro-Pax vessel (fast catamaran), Ro-Ro vessel (cargo ship) and a Car-carrier vessel (vehicle carrier).

Table 2 shows the CO_2 emissions in kg/trip for each kind of vessel by considering the different navigation stages. A route between Las Palmas (Canary Islands, Spain) and Cadiz port (Spain) is assumed (687 nautical miles) for all estimations as a base-case, with the exception of the catamaran case. For this latter vessel, an inter-island route is considered (55 nautical miles): Las Palmas (Gran Canaria Island) and Morrojable (Fuerteventura Island). The emission savings estimated for PV systems, collected in Table 2, assume ideal conditions that involve: continuous maximum efficiency for the working of the solar panels (211 W/m^2) in all navigation stages and 4,382 solar hours per year (NASA Resources from Homer software). However, in the container vessels' application (feeder and reefer vessels), PV systems' operation is only possible during free sailing since the solar panels must be retractable in port to enable loading/unloading operations.

Likewise, the CO_2 estimations have assumed: MDO 0.1%S as the fuel for berthing and manoeuvring operations in all vessels to meet the EU regulation (Directive 2005/33/EC; amending Directive 1999/32/EC); on-board electricity demand equal to the electricity generating plan for every navigation stage, and; an available surface to install solar panels that is equivalent to the size of an open upper deck, according to the general arrangement of the vessels. Finally, to adjust scheduling, sleeping times at berth were not considered in this first approach. Ship Design Programs for Emission Calculations, (developed in the Danish RoRoSECA project; [13,14]) have been used to calculate emissions; moreover, these estimations were tested by considering the reports published by THETIS-MRV[4] (see Table 2) about vessels with similar technical features.

Table 2 shows that these vessels' CO_2 emissions, due to electricity generation, surpassed 19%, and were significant in all vessels, with the exception of the high-speed catamaran. In this case, the high propulsion power required (BHP = 33,795 KW) to provide 37.5 kn of service speed (see Table 1) makes the CO_2 emissions from the generating sets negligible (2.34%, see Table 2), into whole vessel's emissions. Paying

[4] https://mrv.emsa.europa.eu/#public/emission-report.

Table 3
CII scores for SSS vessels, by considering their current operation and expected performance with PV systems.

	Reefer vessel (MDO 0.5%S)		Feeder vessel (Open Scrubber HFO 3.5%S)		Ro-Pax catamaran (MDO 0.1%S)		Ro-Ro (Open Scrubber HFO 3.5%S)		Car-carrier (Open Scrubber HFO 3.5%S)	
Year	*Base Case*	*PV system*	*Base Case*	*PV system*	*Base Case*	*PV system*	*Base Case*	*PV system*	*Base Case*	*PV system*
2023	B	B	B	B	E	E	E	E	B	B
2024	C	B	C	B	E	E	E	E	B	B
2025	C	C	C	B	E	E	E	E	C	B
2026	C	C	C	C	E	E	E	E	C	B
2027	C	C	C	C	E	E	E	E	C	C
2028	C	C	C	C	E	E	E	E	C	C
2029	D	C	C	C	E	E	E	E	C	C
2030	D	C	D	C	E	E	E	E	D	C
2031	D	D	D	D	E	E	E	E	D	C
2032	D	D	D	D	E	E	E	E	D	D
2033	D	D	D	D	E	E	E	E	D	D
2034	E	D	E	D	E	E	E	E	E	D

attention to the expected improvement range provided by PV systems, the Car-carrier achieved the maximum percentage of expected CO_2 reduction (4.9%).

This is because it is the least demanding vessel in propulsion power (6,965 kW without PTO, see Table 1) and electricity supply requirements (3X860kW, see Table 1); however, according to its general arrangement, this vessel offers the greatest available surface for solar panels in relative terms (2,200 m^2, see Table 2). For this reason, even though the Car-carrier and feeder vessel provide the lowest contributions from electricity generation to overall CO_2 emissions (19.27% for the former and 23.28% for the latter, see Table 2), they also offer the best improvement ranges, due to PV system installation (4.9% and 3.60%, respectively).

Table 3 shows CII class evolution by assuming current vessels' operating pattern and possible vessels' retrofitting for PV systems. It is interesting to note the non-compliance of the Ro-Ro and Ro-Pax catamaran under all circumstances (they returned an E score for all years). These vessels, with high propulsion power and low utilization ratios of cargo space, face great difficulties in complying with CII and only wider solutions, such as a drastic reduction in their operating patterns (a reduction in service speed with an increase of the number of necessary vessels) would enable their CII compliance. An alternative is to achieve fleet level compliance [3] by using low or zero-fuels for some of a shipping company's vessels, which might enable a C class for the whole fleet.

The container vessels, reefer and feeder, under current conditions, will not meet CII requirements in 2031 and 2032 (third year with a D score), respectively. According to this first approach, PV system installation would allow them to delay this non-compliance by two and one year respectively (see Table 3), and meanwhile, a better vessel classification could provide ship-owners with additional savings related to lower CO_2 emissions (higher ESI values in ports means greater rebates for port dues and lower Carbon allowance costs in EU-ETS), beyond the bunkering cost savings. Despite container vessels' good performance, Car-carriers offer the best situation in terms of CII compliance. The latter not only delays its non-compliance by two years (from 2032 to 2034) with the PV system set-up but also improves the initial CII score for four years, with the aforementioned advantages.

Moreover, conventional PV systems are suitable for installation on Car-carriers' decks. However, as said, PV systems in container vessels need to cover the containers during free sailing, with the panels then being withdrawn for port tasks, which complicates vessels' operation. Even though this technology is available, and in fact is used in other sectors, its application to the vessels would be an innovative solution (i. e., not mature), and therefore its efficiency is uncertain. In light of this, the Car-carrier is identified as those with the highest improvement capacity by solar energy and therefore, this vessel was selected as an application case for the feasibility analysis of the PV system's investment in the next sections (see Fig. 1).

Step 2: Hybrid PV system definition

Homer Pro software was used to evaluate the actual benefits of PV systems on an SSS vessel. The software simulates hybrid renewable energy systems, considering off-grid and grid-connected power system designs. It aims to minimize the Net Present Cost (NPC) while maximizing energy savings and reducing fuel consumption, emissions, and costs. This study examines the system's operational feasibility and total cost by simulating its performance for every hour of the year.

Inputs

The considered load has been obtained through the examination of a real scenario, covering a one-year time frame for conducting the simulation, acknowledging the distinct states of the ship: free sailing (905 kW, $TVB_1 = 43$ h/trip), manoeuvring (1,907 kW; $TVB_2 = 1$ h/trip), berthing (727 kW; $TVB_3 = 6$ h/trip), and sleeping (210 kW; $TVB_4 = 14$ h/trip). The grounding maintenance time has also been considered, which will be a total of 15 days per year of no load.

Conventional general arrangement of Car-carriers (see IMO: 9473468, IMO: 9473456, among others) shows that a wide-open surface is available for solar panels' installation on the upper deck. Consequently, for the application case (see Table 1) an installation area of 2200 m^2 (see Table 2) was assumed as a result of positioning panels on this deck: the area spans 100 frames aft of the bridge and 50 on the bridge (108 m in length) and being the available beam for this stage (20.4 m).

Solar radiation data were taken from the NASA Resources (see in

Supplementary Material, Fig. B.1) for Las Palmas de Gran Canaria, 28° 8.3′N, 15° 24.8′W, which are available in Homer Pro. The annual average solar Global Horizontal Irradiance (GHI) was found to be 5.40 kWh/m^2/day; with 6.98 kWh/m^2/day as a maximum value. PV panels were simulated with a 20° slope, under the Gran Canaria optimal point. However, due to the dynamic position of the vessel (routes), the results obtained from the base-assumptions (optimal angle of panels and particular solar GHI source for a static localization) involve an uncertainty level. In order to minimize this, a sensitivity analysis is subsequently carried out by considering possible variations of these inputs (20% variation see section 6.1) which determine the vessel's expected fuel reduction (see Table 6). These variation ranges enable to assess broader scenarios than the application case by including possible imponderables that might affect the system's efficiency.

Hybrid system design

A hybrid PV system with Diesel Generator and BESS is considered for the study. For designing this Hybrid system, four items must be taken into consideration.

The first one is the 855 kW MAN 9L16/24 generating set. Using the MAN Product Guide, all technical data will be included in the calculations. As far as cost values are concerned, the publications of Bui et al. [15,16] about the "Part replacement cost" which will be the assumed base value to estimate the replacement cost for the generating sets, as well as the study done by Jeong et al. [17], ending up with a replacement cost of 322.54 €/kW (277,382€/generating set). This value is confirmed by Abma et al. [18] who sets 250€/kW and 400 €/kW. The maintenance costs have been obtained considering 30€/h of labour [15]. The external costs are included in the NPC by considering the emission factors of the generating sets [19] along with their unitary costs [20] updated to 2022 according to the EU-27 countries' average CPI (13.3% from 2016 to 2022, Eurostat, 2022).

The PV array Tiger Neo N-type 72HL4 530–550 W with a 25-year estimated lifespan at 0.9 derating factor. Through an analysis of the maximum available area within Ro-Ro vessels and considering the installation requirements of the PV system, the maximum implemented power reached a value of 498.42 kWh. The photovoltaic system is connected to the vessel's electrical system through two Multi-MPPT String Inverter SUNGROW Inverter SG250HX. Costs were obtained from a manufacturer and include PV system and converter installation (see in Supplementary Material, Table B.1).

In addition to these items, the Power conversion system SUNGROW SC500TL Hybrid Inverter of 550 kVA (AC side) and an efficiency of 99% were included in the simulation. This converter is responsible for battery charge & dis-charge management, delivering a capacity of 440 kW. To identify the optimal solution, we additionally simulated the system with two converters, thereby enabling the batteries to fully supply the energy required during the port state (with a berthing power of 727 kW). The costs have also been also provided by a manufacturer (see in Supplementary Material, Table B.1).

Finally, the selected battery for analysis is the Corvus Dolphin Energy 16 Modules, featuring a nominal capacity of 1,059.2 kWh. The battery has been chosen to fulfil the energy requirements during berthing and sleeping, aiming to identify an optimal solution for our specific case, analysing the results from installing from 1 to 7 batteries of this type in the vessel. The data from previous publications have been used to estimate the capital cost [21–26], and the maintenance cost [23,26] (see in Supplementary Material, Table B.1). The replacement cost in Supplementary Material, Table B.1 includes the acquisition and installation of equipment whenever the lifetime is over. Supplementary Material (Fig. B.2) contains the Hybrid system integration diagram in which the arrows denote the possible power flow direction.

A control algorithm or power management strategy is crucial for effectively utilizing renewable energy. It determines how energy will be distributed throughout the year, including using excess renewable energy during times of sufficient supply and meeting demand when renewable energy falls short. In this study, two different control algorithms or power management strategies were considered:

- Load Following (LF), this strategy ensures that each generator operates solely to generate enough power to meet the load requirements.
- Cycle Charging (CC), this strategy involves running the generator at its maximum power output whenever it is required to supply the primary load. Any surplus electricity production, for instance, is stored in the storage system. Consequently, the diesel generator consistently operates at its rated power output, ensuring optimal performance. This hybrid system facilitates improved energy management even without the installation of photovoltaic solar panels. The diesel generator operates at full capacity whenever necessary to meet the demand, while any excess energy is stored in the batteries. In the event of using a charge controller, it is essential to establish the setpoint of the state of charge (SOC). This value determines the maximum capacity of the Battery Energy Storage System (BESS) that is charged by the diesel generator. In this case, 80% of the total BESS capacity is considered as the setpoint.

Outputs

After comparing the initial case performance (initial Car-carrier with three generating sets) with all 208 PV solutions (combinations of different numbers of batteries -from 1 to 7-, inverters -from 1 to 2-, number of solar panels, and number of operative generating sets), obtained by Homer by minimizing the NPC, the optimal system finally includes, aside from the initial three diesel generators, a PV system made up of: 853 solar panels at 20° slope (498.42 kW installed power), one battery, and two converters (maximum power equivalent to the berthing power: 880 kW). This solution offers a fuel reduction over the initial case for on-board electricity generation of 15.5%,[5] in other words, this represents a share of solar energy on yearly electricity generation of 13.97%.

Step 2: Feasibility analysis of PV system investment

This section collects a further feasibility analysis based on the IRR calculation. All items shown in Table 4 for the cash-flow calculation were updated from 2022 to future years (K= {1,…,k}) by assuming an average CPI inflation rate of 0.83% for EU-27 countries in the next 10 years (Eurostat, 2022). The replacement (RC_q; $\forall q \in Q$) and maintenance costs (MC_q; $\forall q \in Q$) to calculate the cash flow (see equation (5) were taken from Homer's optimization for 2022 (see section 5) by considering the expected working hours for the generating sets and PV system to meet demand (electricity generating plan).

The bunkering cost (BC_q; $\forall q \in Q$) was obtained by taking into account the generating sets' consumption of the optimized working pattern by Homer for the base case and for the scenario, with the optimized PV system installed (see equation (5). Additionally, a price of 992.40€/t (MDO 0.1%S in 2022 for Rotterdam; Shipandbunker, 2022[6]) was taken for the bunker cost calculation. Finally, the ETS calculation (ETS_q; $\forall q \in Q$, see equation (3) has assumed as Carbone allowance cost CAP = 67€/t [7,27,28].

Table 4 shows the feasibility analysis based on IRR for a PV system installation in the Car-carrier for a time range of 10 years when the investment is financed through a loan (70% of CAPEX), with an interest rate of 6% and a payment period of five years. Under these conditions,

[5] Whether the solar panels are installed with angles of 10 and 0 degrees, the fuel saving achieves 14.7% and 13.3% respectively.

[6] https://shipandbunker.com/prices/av/global/av-g20-global-20-ports-average.

Table 4
IRR estimation for a Car-carrier's retrofitting with PV system and Cash flow items for a base scenario (€/year).

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Capital Cost	−754,968										
Replacement										298,893	
Loan	528,478										
Loan's Principal		−93,750	−99,375	−105,338	−111,658	−118,357					
Extra-operative cash flow	−226,490	−93,750	−99,375	−105,338	−111,658	−118,357	0	0	0	298,893	0
Maintenance		198,072	199,723	201,387	203,065	204,757	206,464	208,184	209,919	211,668	213,432
Bunkering		186,637	188,192	189,760	191,342	192,936	194,544	196,165	197,800	199,448	201,110
ETS		8,079	18,330	28,751	41,415	41,760	42,108	42,459	42,813	43,170	43,530
Fuel-EU		0	0	5,503	5,503	5,503	5,503	5,503	24,307	24,307	24,307
Loan's Interest		−31,709	−26,084	−20,121	−13,801	−7,101					
Operative cash flow		361,079	380,161	405,280	427,524	437,856	448,619	452,312	474,839	478,593	482,379
Total cash flow	−226,490	267,329	280,786	299,943	315,866	319,498	448,619	452,312	474,839	777,486	482,379
IRR	124.16%										
NPV	−226,490	29,977	288,409	553,255	820,829	1,080,483	1,430,258	1,768,584	2,109,327	2,644,580	2,963,176
Payback time	1										

Table 5
CII scores for a Car-carrier vessel by considering PV system performance (Homer's estimations).

Year	*Base case*	*PV system*
2023	B	B
2024	B	B
2025	C	B
2026	C	C
2027	C	C
2028	C	C
2029	C	C
2030	D	C
2031	D	D
2032	**D**	D
2033	D	**D**
2034	E	D

Table 6
Initial inputs for 2022 scenario of the base case.

Variables	Minimum	Base Case	Maximum
Capital cost (€)	603,976	754,968	905,961
Maintenance cost(€/h)	24	30	36
Replacement cost* (€)	332,858	277,382	221,905
MDO (€/t)	793.92	992.40	1191.50
Carbon Allowance Cost (€/t)	54	67	80
Fuel saving (%)	12.4	15.5	18.6

* Generating sets.

the IRR achieves 124.16%, with a payback time for the initial investment of just one year when the discounting rate is 10%. Evaluating the IRR for a non-financed project, the payback period is three years, and the IRR goes up to 55%.

These results are very promising, even though the expected ETS influence on the assessment has resulted to be less significant than expected. In fact, the maintenance and bunkering savings are the main drivers of these positive results. Paying attention to the real working efficiency achieved by the PV system (Homer outputs), the reduction of the total CO_2 emissions is 3.38% regarding the base case (propulsion and electricity generation). This percentage is considerably different from the first approach of 4.9% (see Table 2), where ideal conditions were assumed for all navigation stages without considering the sleeping times in port. Consequently, the PV system's impact on the CII score is also more limited, as can be seen in Table 5. Thus, unlike the initial analysis, where the vessel's retrofitting delivered non-compliance of two years with the CII regulation, the PV system only delivers this state for one year (from 2032 to 2033).

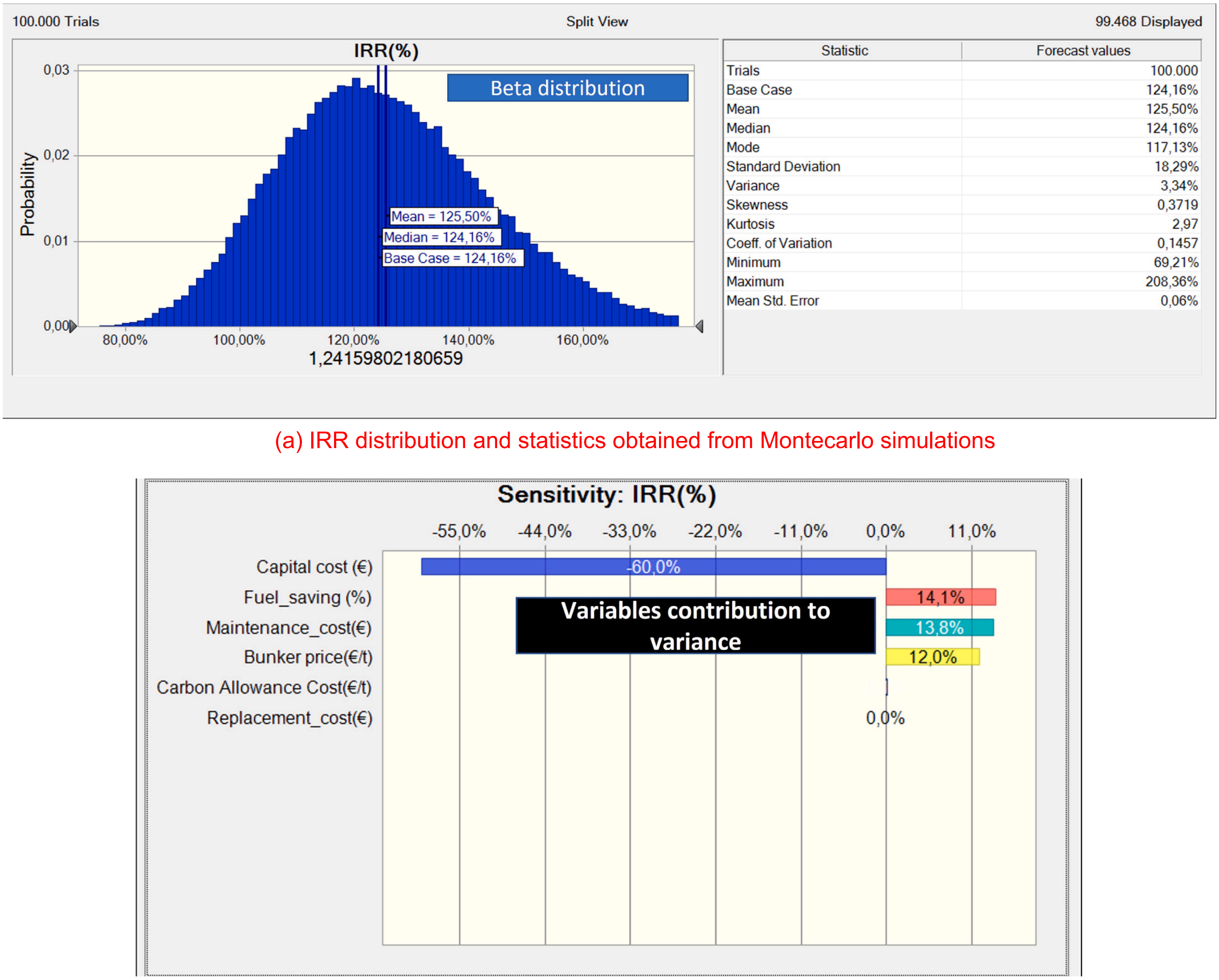
Sensitivity analysis

In order to ensure the robustness of the results achieved, a sensitivity analysis is carried out through probability functions for the following inputs related to PV system: capital cost, maintenance cost, and the efficiency of the PV system in terms of reduction of the fuel consumed. According to Homer simulations the working hours in the time range studied are not enough for incurring PV systems replacement's costs, consequently only generating sets' replacement costs are considered (see Table 6). Additionally, possible fluctuations of the Carbon Allowance Cost in the EU-ETS and the bunkering cost (0.1%S MDO price) are also evaluated.

So, a probabilistic analysis is undertaken (Montecarlo simulations) by taking triangular distributions as probability of occurrence functions for the variables, where the most and least probable values are those included in Table 6 (20% over/under base values). Fig. 2 shows the results obtained for a 100% certainty level in the simulations (100,000 trials); the IRR distribution obtained (Fig. 2(a)) shows a good fitness with beta distribution. In turn, the simulation provides a homogeneous distribution for IRR (coefficient of variation achieved 14.57%, below 25%), therefore the mean, 125.5%, can be taken as a representative value of the IRR expected under risky scenarios. Paying attention to the sensitivity chart (see Fig. 2(b)), the more influent variables on the IRR are related to the PV system: firstly, the initial capital cost (-60%) and then its operation's efficiency (14.1%). In turn, the contextual inputs (bunkering price and carbon allowance cost) are placed in the last positions, this involves that, the feasibility of the PV system's investment is largely affected by its own capacities.

Discussion

Analysis of the feasibility of investment in PV systems for a Car-carrier vessel between the Canary Islands and Iberian Peninsula suggests that retrofitting is of considerable interest to shipowners, due to the favourable payback periods of between one and three years and Internal Rate of Return (IRR) ranging from 124% to 55% for financed and non-financed projects, respectively, in a base scenario. The results are even more favourable for the former when a sensitivity analysis is carried out, meaning that the IRR could achieve 125.5%. The high consistency found for IRR results (low coefficient of variation) in the sensitivity analysis (Montecarlo simulations) suggests that these findings are applicable to all those scenarios (application cases) defined by



(a) IRR distribution and statistics obtained from Montecarlo simulations

(b) Sensitivity chart for IRR

Fig. 2. Results obtained from Montecarlo simulations (Crystal Ball software): IRR distribution and statistics (a); Sensitivity chart for IRR (b).

different combination of inputs within the assessed ranges (see Table 6).

The advantage of PV systems is mainly due to maintenance and bunkering savings. Thus, even though the feasibility analysis considered the forthcoming inclusion of shipping in EU-ETS and the possible penalty by FuelEU maritime non-compliance, these measures did not significantly influence the results. This fact was also confirmed by a further sensitivity analysis, which showed the low influence of the carbon allowance cost and the bunker price on the IRR. Therefore, although the results achieved in this application case (of 67€/t CO_2 assumed for the carbon allowance cost) are in line with previous findings [10] which not only also achieved three years for payback on solar panel investment without financing but also suggested that carbon credits need to exceed 190 $USD/t to guarantee by its own the feasibility of investing in solar panels -, the results for our study case suggest a negligible influence of the carbon allowance cost versus other contextual variables (like bunker price) on PV system feasibility.

The research provides fuel savings of 15.5% for the electricity generation when PV is installed in SSS vessels, by reducing total CO_2 emissions by 3.38%. This abatement capacity is considerably higher than that estimated by the IMO [29] for solar panels for 2030: between 0.02 and 0.18%. Likewise, fuel savings found in this research have proved to be higher than those obtained in previous studies (15.5% versus 7.38% [11]). This improved performance is due, among other reasons, to a higher solar irradiance average level on the studied route (164.35 kWh/m^2 for Las Palmas-Cádiz versus 133.92 kWh/m^2 provided by the application case conducted by Karatuğ and Durmuşoğlu [11], and the technical features of the SSS vessels along with greater PV peak powers obtained by more efficient PV systems (17% versus 21%).

Focusing on the relative performance of solar energy versus other mitigation alternatives for decarbonization of shipping, the MAC value [30] achieved in this SSS application case is MAC = 813.61€/t CO_2 (874.75USD/t CO_2) versus the previous estimations: 1,186USD/t CO_2 [29]. The difference is due not only to a higher value for the bunkering price in this research (30%); the inclusion of FuelEU non-compliance penalties; and EU-ETS costs in the MAC calculation [30] but also to significant improvements in PV systems' efficiency achieved in recent years. Despite the fact that the MAC value for solar panels remains high in contrast to other mitigation alternatives (MAC = 17 USD/t CO_2 for speed reduction [29], for example), the performance improvements lead to a CO_2 abatement potential of 3.38% for this application case. This potential would only be enhanced by speed reduction (7.38%) and alternative fuels (5.54%) according to the IMO [29], but the former would be unfeasible to maintain SSS operation requirements.

The results achieved for PV systems also reveal that, beyond the aforementioned savings in monetary terms by MBM (EU-ETS and FuelEU penalty reductions), its impact on the improvement of the whole SSS vessel's sustainability is quite limited in terms of regulation's compliance; in the application case, the PV system is insufficient to significantly modify the CII score of the vessel. Thus, in taking into account the forthcoming inclusion of CII in the Environmental Ship Index (ESI) calculation,[7][8] the PV installation hardly affects the ESI value for the SSS vessel (ESI = 31.69 versus ESI = 31.96 in 2023 for the application case) and therefore no extra rebate on port costs is expected.

Conclusions

Marginal Abatement Cost (MAC) curves have driven the academic research towards mitigation systems with the highest abatement potential for CO_2 emissions in shipping. Consequently, PV systems were barely addressed as they were frequently defined as costly and inefficient (as they had high MAC values) However, increasing normative pressure for the decarbonization of shipping is forcing academics and shipowners to review all previous statements, especially in the EU context where additional Goal and Market Based Measures are planned. This review is especially timely in the area of SSS where the application of operative mitigation alternatives (short-term solutions) is incompatible with schedule requirements. This paper contributes to broadening knowledge about PV systems' performance in SSS vessels by providing an assessment method that considers not only its impact on the CII normative compliance but also the techno-economic feasibility of required vessel retrofitting in the EU context.

The initial analysis of the SSS fleet indicates a substantial proportion of CO_2 emissions (over 20%) stemming from electricity generation, except for high-speed catamarans. This fact confirms the favourable prospects for PV systems in SSS because, given its technological state, solar energy is predominantly used to supply vessels' electrical needs. In a first approach, promising improvements were found for the retrofitting of Container and Car-carrier vessels, with the latter being selected for further evaluation. The results show that the CO_2 abatement capacity of PV systems achieved 3.38% in this vessel, which makes solar panels the most efficient mitigation option after alternative fuels for SSS [29]. Thus, although MAC remains high, it is expected that this value will decrease over time due to rapid efficiency's improvements achieved by the solar panels in recent years (efficiency improvements: average 23% 2022, versus 18% in 2018) and the effect of the progressive inclusion of MBM in the EU.

Even though solar panels provide advantages - via MBM and savings on penalties (FuelEU maritime) imposed by the EU decarbonization normative -, these are insufficient on their own to ensure the feasibility of PV system investment. Additionally, PV systems influence on CII compliance is also limited. However, according to the results obtained, the PV system is an interesting option for SSS shipowners, since the feasibility analysis revealed high IRR values with reduced payback periods. Aside from high consistency in the results achieved, the sensitivity analysis highlighted the low dependence of IRR on contextual variables (bunker and carbon allowance costs) and therefore, the expected performance improvements for this technology in the near future will strongly determine its competitiveness versus other mitigation alternatives.

It is necessary to bear in mind that, this paper's insights are applicable to those scenarios (inputs range) assessed in the sensitivity analysis. Consequently, aside from the base route between Canary Islands and Iberian Peninsula, other EU-SSS localizations are within the scope of these findings (solar GHI resource): SSS routes in the Mediterranean Sea, Atlantic routes between the Iberian Peninsula and Madeira, Azores and France up to La Rochelle. However, northern SSS routes are not affected by the results of this paper due to the significant decrease of the solar GHI resource regarding the base scenario.

Given PV system's favourable prospects in a wide EU zone, further research should be conducted on the application of this technology in Ro-Pax vessels, since they will be obliged to use OPS or zero emission technologies in port from 2030 (COM (2021) 562 final), thereby bringing further advantages for PV systems in SSS vessels.

CRediT authorship contribution statement

Alba Martínez-López: Conceptualization, Methodology. **Paula Ballester-Falcón:** Data curation, Investigation, Writing – original draft. **Luis Mazorra-Aguiar:** Software, Formal analysis. **Africa Marrero:** Validation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A:. Nomenclature

B	Beam (m)
BESS	Battery Energy Storage System
BHP	Brake Horsepower (kW)
CAP	Carbon Allowance Price (€/CO_2 tonne)
CAPEX	Capital Expenditure (€)
CII	Carbon Intensity Indicator (g CO_2/ t nm)
CC	Cycle Charging (Control algorithm of power management strategies)
COM	Communication from the European Commission
CPI	Consumer Price Index (%)

(*continued on next page*)

[7] https://www.environmentalshipindex.org/info.
[8] https://www.iaphworldports.org/news/iaphnews/13183/.

(*continued*)

D	Depth (m)
DWT	Deadweight Tonnage (t)
EC	European Commission
ESI	Environmental Ship Index
EU	European Union
EU-ETS	European Union Emission Trading System
EPL	Engine Power Limitation
GBM	Goal Based Measure
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GT	Gross Tonnage (t)
HFO	Heavy Fuel Oil
IAHP	International Association of Harbours and Ports
IMO	International Maritime Organization
IMO-DCS	Data Collection System for International Maritime Organization
IRR	Internal Rate of Return
LF	Load following (Control algorithm of power management strategies)
Lpp	Length between perpendiculars (m)
Lt	Total Length (m)
MAC	Marginal Abatement Cost (€/t CO_2)
MBM	Market Based Measures
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
NASA	National Aeronautics and Space Administration (US)
NPC	Net Present Cost (€)
NPV	Net Present Value (€)
O&M	Operation and Maintenance Cost (€)
OPEX	Operating Expenditure (€)
PAX	Passengers
PV	Photovoltaic
PTO	Power Take Off (kW)
RES	Renewable Energy Systems
SOC	State of change (related to control algorithms of power management strategies)
SSS	Short Sea Shipping
T	Draught (m)
TEU	Twenty-foot Equivalent Unit
THETIS-MRV	Monitoring Reporting and Verification System for the European Union

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2023.103506.

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