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Impact of New Environmental Rules on the Fuel and Emissions Costs of a Mediterranean Cruise

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Abstract. The regulations introduced by the International Maritime Organization (IMO) and, to an even greater extent, by the European Union (EU) regarding maritime emissions present increasing challenges for shipping companies. The IMO Carbon Intensity Indicator may restrict the operations of less environmentally efficient vessels, while the inclusion of ships in the EU Emissions Trading System and the limits on greenhouse gas intensity are progressively integrating the concept of a carbon tax for vessels operating within, to, or from the EU. Furthermore, starting May 1, 2025, the Mediterranean Sea will be designated as a Sulphur Emission Control Area (SECA), requiring ships without scrubbers to use the more expensive Marine Gas Oil. This study quantifies the financial impact of these regulations by analysing fuel and emissions costs associated with a typical West Mediterranean cruise across different years. Fuel consumption is estimated using a probabilistic methodology that accounts for key environmental factors, including wind, sea state, currents, and ambient air temperature. The method is applied to a large cruise ship equipped with four diesel generators, only two of which are fitted with scrubber units. The findings indicate that in 2027, compared to a baseline scenario in 2023 when no environmental regulations were in force fuel and emissions costs will increase by more than 60% for the studied cruise.

Keywords. simulation, cruise ship, ship emissions, EU ETS, SECA

1. Introduction

The maritime sector is undergoing a major transformation driven by increasingly stringent environmental regulations. As concerns about climate change and air pollution mount, international and regional authorities are introducing policies aimed at progressively reduce GreenHouse Gas (GHG) and pollutant emissions from ships. Among these, the measures adopted by the International Maritime Organization (IMO) and the European Union (EU) are of particular significance.

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On a global level, the IMO has implemented the Carbon Intensity Indicator (CII), part of its short-term GHG reduction strategy, to monitor and improve the energy efficiency of ships in operation [1]. The CII is expected to affect the operational strategies of older and less efficient vessels, potentially limiting their market access or forcing costly retrofits, althought its effectiveness for cruise ships have been questioned [2]. In parallel, the EU has launched a comprehensive regulatory package, including the extension of the Emissions Trading System (ETS) to maritime transport [3,4] and the FuelEU Maritime regulation [5], which sets progressive limits on the GHG intensity of marine fuels used within, to, and from the EU.

One of the most impactful forthcoming measures is the designation of the entire Mediterranean Sea as a Sulphur Emission Control Area (SECA), effective from May 1, 2025 [6]. This will require ships sailing in the region to either install exhaust gas cleaning systems (scrubbers) or switch from Very-Low-Sulphur-Fuel-Oil (VLSFO) to ultra-low-sulphur fuels such as Marine Gas Oil (MGO). If the ship is equipped with exhaust gases treatment systems to remove sulphur oxides (scrubbers), the ship during navigation can continue employing High-Sulphur-Fuel Oil (HSFO).

These evolving policies introduce both direct and indirect costs for ship operators, particularly for cruise lines, as new technologies and operational strategies are adopeted [7,8]. Large passenger vessels with diesel-electric powerplants often operate in or near regulated zones for extended periods, making them especially sensitive to fuel and emissions-related costs [9]. Understanding and quantifying the economic consequences of these regulatory changes is therefore essential for stakeholders including shipowners, policymakers, and environmental analysts.

Studies have so far addressed the economic impact of the EU ETS for cruise ships, with particular attention to cold ironing [10,11]. Limited work has examined the combined financial burden of the EU ETS and SECA designation on cruise ships along realistic itineraries. This paper addresses this gap by simulating the fuel and emissions costs of a representative West Mediterranean cruise in four regulatory years (2023, 2025, 2026, and 2027). The study uses a probabilistic simulation methodology tailored for diesel-electric cruise vessels [9], incorporating environmental variability and standard operational profiles. Focus has been made on Fresh Water (FW) production, which is extremely important on cruise ships. In particular, the two options of buying or producing water onboard are compared from an economic point of view. Emissions are evaluated on a tank-to-wake basis using EU guidelines and fixed fuel/allowance prices.

The analysis reveals how regulatory evolution affects energy costs and quantifies the gap between business-as-usual and compliance scenarios. The findings are intended to support both economic evaluations and strategic planning for cruise operators navigating a complex regulatory future.

2. Methodology

The methodology presented in this study has been developed to simulate the environmental and economic implications of new regulatory constraints on diesel-electric cruise ships. In particular, the simulation of one itinerary is carried out for four reference years: 2023 (baseline, pre-regulation), 2025 (partial ETS and SECA), 2026 (expanded ETS), and 2027 (full implementation of ETS and fuel constraints). For each year, two operational configurations are compared: With FW production on board, using a mix of electric reverse-osmosis machines and thermal evaporators driven by waste heat from generators, which increases the load on the auxiliary system; Without FW production, assuming that all the FW is bunkered in port, reducing the hotel load but increasing port-related costs. A total of eight simulation cases are thus analysed. In the following, the assumptions and simulation processes are briefly described, focusing on the solution of equilibrium equations and the assessment of the emissions during the execution of an itinerary.

2.1. Assumptions

The simulation relies on operational and technical assumptions derived from the work in [9], where a methodology was introduced for the probabilistic assessment of diesel-electric ship performance in realistic environment. Key simplifying assumptions in this study are the following.

The ship's operational profile is divided into four distinct phases: navigation at sea, transit in canals or restricted waters, manoeuvring, and hoteling during berthing. Daily ship schedules are fixed and follow a representative itinerary, with typical hotel load demands derived from design data (e.g. electric balance).

Fuel consumption is computed for conventional marine fuels only: HSFO, VLSFO and MGO, excluding any alternative fuels or hybrid propulsion systems. Generator dispatch follows a standard priority list with equal loads on each active generator, without optimization of load sharing, thus reflecting a conservative management strategy. Fuel type is selected depending on scrubber availability and SECA regulations: HSFO can be used for all engines equipped with scrubbers, for other engines outside SECA waters, VLSFO can be used; inside, it is required to switch to MGO.

Environmental conditions (wind, wave, current, ambient air temperature) are probabilistically sampled for each leg (i.e. a port-port voyage) of the itinerary from historical meteorological datasets for the Western Mediterranean Sea as in [9].

Loading condition is adjusted to account for fuel and FW consumption. The ship's floating position is assumed always to be even-keel. Initial amount of fuel, FW and bunkering/supply assumptions as in [9].

Emission factors are adopted from the EU Monitoring, Reporting and Verification (MRV) regulation [5,12]. All prices are expressed in euros per tonne unless otherwise stated.

2.2. Simulation Process

The proposed methodology is inherently probabilistic and structured as follows:

1. The itinerary is discretised into legs and sublegs. As mentioned, each leg spans from one port departure to the next, while sublegs allow environmental conditions, course and speed over the ground to be constant over shorter segments.
2. Probability distributions are defined for key stochastic inputs, including environmental variables (wind, sea state, temperature, currents) and hotel load factors (based on passenger and crew counts).
3. Monte Carlo sampling is used to generate a large set of deterministic scenarios by drawing random values from these distributions. Each scenario assumes constant values along a leg (except for currents, which vary by subleg).

4. Each deterministic scenario is simulated to compute the values of dependent variables **y**, such as propulsion power, fuel consumption, fresh water production, and emissions:
   (a) Scenarios are processed sequentially across all legs and sublegs, accounting for vessel status (at sea, at berth, in transit or manoeuvring).
   (b) For each subleg of each scenario a 3-Degrees of Freedom (DoF) system of equations is solved to find the equilibrium of longitudinal forces, transversal forces and yaw moments, determining the required effective thrust from the propellers, the ship's heading and the rudder angle to maintain course and speed with the given environmental conditions. Then, fuel consumption and emissions are assessed employing standard maps to simulate the onboard generation system. Finally, the loading condition of the ship is assessed as reference for the next subleg.
   (c) After the simulation of all sublegs composing an itinerary, overall values of **y** are assessed for each scenario.
5. In the post-processing phase, statistical indicators—such as mean, median, and third quartile—are computed for each output variable **y**. Empirical cumulative distribution functions $cdf(y_i)$ are derived and optionally fitted using kernel density estimation as in [13,14].

2.3. Balance of Forces and Moments

As mentioned, the balance of forces on the ship is expressed in a 3-DOF system considering surge (X), sway (Y), and yaw (M_Z) components. The reference system is fixed at the ship's midship perpendicular, with X pointing forward, Y to starboard, and Z downward, as shown in Figure 1.

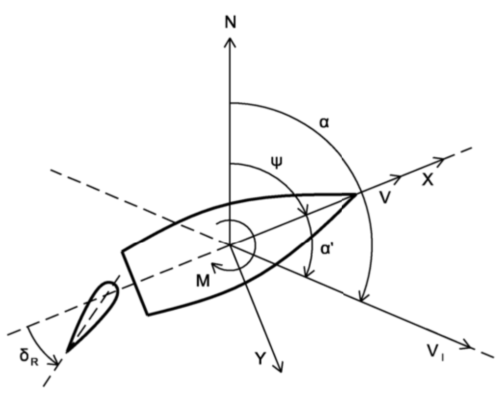

Figure 1. Ship reference system used in the balance of forces [9]

The overall balance of forces is written as:

$$\mathbf{F} = \mathbf{F}_{prop} + \mathbf{F}_{rudder} + \mathbf{F}_{wind} + \mathbf{F}_{wave} + \mathbf{F}_{hydro} = 0, \tag{1}$$

The components are described as follows: Propeller force $\mathbf{F}_{prop}$ is the thrust vector generated by the propellers, assumed to act along the longitudinal axis X. The thrust magnitude T is one of the primary unknowns in the system and is linked to the effective power through propulsion efficiency; Rudder force $\mathbf{F}_{rudder}$ includes rudder resistance, lateral force and yawing moment, depending on the rudder angle δ_r, flow velocity, and empirical coefficients. The rudder contribution is modelled according to standard maneuvering formulations as in [15]; Wind force $\mathbf{F}_{wind}$ is calculated using empirical coefficients as a function of the apparent wind velocity $\mathbf{V}_{aw}$ and direction β_{aw} using Blendermann method [16]; Wave-induced force $\mathbf{F}_{wave}$ accounts for wave-induced added resistance and drift forces. These are calculated for irregular seas using semi-empirical expressions provided in [17], considering significant wave height H_s, zero-crossing period T_z, and encounter angle; Hull hydrodynamic force $\mathbf{F}_{hydro}$ includes the bare hull resistance R_0 (from calm water trials) corrected to account for fouling, shallow water and loading condition. Hydrodynamic drift force and yawing moment are modelled according to [18]. All the components are evaluated considering the relative speed through the water which takes into account the current speed.

The unknowns of the system include the actual ship heading ψ (which may differ from ship course over the ground due to drift), the required thrust T for steady navigation and the rudder angle δ_r. The system in Eq. (1) is solved iteratively for force and moment equilibrium in steady conditions using a thrust region algorithm [19].

2.4. Tank-to-Wake CO_2 Emissions Assessment

Starting from the required thrust T (evaluated through the force balance in Section 2.3), the brake power is computed as:

$$P_B = \frac{T \cdot V_A}{n_S \cdot \eta_0 \cdot \eta_H \cdot \eta_R \cdot \eta_S} \tag{2}$$

where V_A is the ship advance speed, n_S is the number of propellers and shafts, η_0 is the propeller efficiency and η_H is the hull efficiency, η_R is the relative rotative efficiency and η_S is the shaft line efficiency. η_H and eta_R are assessed as a function of the longitudinal component of the ship speed, whereas η_0 is evaluated according to the actual functioning point of the propeller considering fouling. The electric power demand for propulsion is then assessed as:

$$P_{prop} = \frac{n_S P_B}{\eta_{PEM} \cdot \eta_{tc}} \tag{3}$$

where eta_{PEM} is the Propulsion Electric Motor (PEM) efficiency computed as a function of load and η_{tc} is the is the efficiency of electric transformers and converters.

The total electrical power demand is the sum of the propulsion and hotel loads:

$$P_{el} = \frac{P_{prop} + P_{ch} + P_{fw} + P_{scrub} + P_{const} + P_{aux}}{\eta_{sw}}. \tag{4}$$

where P_{ch} is the power required for cooling or heating, as a function of the ambient air temperature; P_{fw} is the power needed for fresh water production (e.g., via desalination or reverse osmosis systems) if in use; P_{scrub} is the power required to operate scrubbers, if in use; P_{const} is the constant hotel load for basic onboard services (e.g., lighting, electronics, safety systems) function of the phase of the voyage; P_{aux} includes auxiliaries loads evaluated as a function of the sum of all the other terms; η_{sw} is the switchboard efficiency, accounting for electrical distribution losses within the ship.

Under the standard power management system (PMS), the total electrical load is shared uniformly among the minimum number of generators required to meet demand, each operating at a load factor l, obtaining the following fuel consumption $\dot{m}_{f_{ij}}$ for the i-th generator burning the j-th fuel type:

$$l = \frac{P_{el}}{\eta_G \cdot \sum_{i=1}^{n} MCR_i}, \quad \dot{m}_{f_{ij}} = d \cdot SFOC_j(l) \cdot l \cdot MCR_i \cdot 10^{-6}. \tag{5}$$

where η_G is the generator efficiency, MCR_i is the maximum continuous rating of the generators engines, n is the number of active generators, d is a factor to account for fuel filtering and $SFOC_j(l)$ is the specific fuel oil consumption.

Total Tank-to-Wake CO_2 emissions' mass is calculated as:

$$CO_2 = \frac{D_l}{V_l} \cdot \sum_{j=1}^{m} \sum_{i=1}^{n} EF_{f_j} \cdot \dot{m}_{f_{ij}} \tag{6}$$

where D_l is the length of the subleg in nm, V_l is the speed over the ground of the subleg in kn, m is the number of fuel types emplyed in the subleg and EF_j is the emission factor of the j-th fuel defined according the IMO or EU rules.

3. Application

The proposed methodology is applied to a modern diesel-electric cruise ship with a gross tonnage of 150,000 GT. The ship is equipped with four medium-speed diesel generators, two of which are fitted with open-loop scrubbers, and operates under a standard power management strategy. More details about the ship model can be found in [9].

The analyzed itinerary spans one week in the Western Mediterranean, with port calls at Genoa, Civitavecchia, Palermo, Ibiza, Valencia, and Marseille. The route covers a realistic profile for a typical summer cruise in the Western Mediterranean Sea. Furthermore, all the calls relates to EU ports, hence, all the produced emissions are subject to EU ETS. More details about the legs, speed and course can be found in [9].

Two operational variants of the itinerary are simulated:

- **IT1:** FW is produced on board throughout the voyage. Port FW resupply is used only when the FW tank level drops below a safety threshold of 30% of total capacity. Additional electric power is accounted to operate reverse osmosis machines during navigation.
- **IT2:** No FW is produced on board. The ship relies entirely on port-side FW resupply, reducing energy demand but increasing logistical dependency and introducing higher costs for resupply, which is carried out whenever the FW tanks level is blow 35% of total capacity.

Each itinerary is simulated for 3,000 Monte Carlo scenarios per year to account for environmental and operational variability. Four regulatory years are considered in the analysis. In 2023, the baseline scenario assumes no application of the EU Emissions Trading System (ETS) and no Sulphur Emission Control Area (SECA) designation for the Mediterranean Sea. In 2024, the ETS is partially enforced, with 40% of the ship's CO_2 emissions subject to carbon pricing, while the Mediterranean is still outside SECA. From May 2025, the Mediterranean becomes a SECA, requiring ships without scrubbers to switch to low-sulphur fuels, and the ETS coverage increases to 70% of total CO_2 emissions. From this date, test ship engines not equipped with scrubbers are compelled to emply MGO instead VLSFO in navigation, whereas engines with scrubbers can keep using HSFO. Finally, in 2026, both regulations are fully enforced: the Mediterranean remains a SECA and 100% of CO_2 emissions are included under the ETS.

The assumptions on fuel and freshwater prices at each port are summarised in Table 1, reflecting typical market conditions as of early 2024.

Table 1. Fuel and freshwater prices at ports (€/ton or €/m^3)

Port	MGO (€/t)	HSFO (€/t)	VLSFO (€/t)	FW (€/t)	FW Fee (€)
Genoa	1011	478	603	2.06	116
Civitavecchia	1017	478	603	3.12	120
Palermo	1011	478	603	3.90	0
Ibiza	1011	478	603	8.92	168
Valencia	952	572	653	3.12	120
Marsille	1011	478	603	3.40	143

The simulation includes updated assumptions on emissions pricing: the EU ETS carbon allowance price is set at 80.2 €/tCO_2.

The analysis compares the total environmental cost (fuel + CO_2 + FW) across years and configurations (IT1 and IT2), with particular attention to whether the higher onboard energy demand associated with freshwater production (IT1) remains economically viable in the Western Mediterranean even after the enforcement of SECA and full ETS coverage. This allows assessment of how operational strategies influence compliance costs in an increasingly regulated context.

4. Results and Discussion

The simulation results are presented in terms of total environmental costs—comprising fuel, CO_2, and freshwater—for each year and operational variant (IT1 with freshwater production on board, IT2 without). Figure 2 shows the median and third quartile values of total costs for each configuration.

Results indicate a significant cost increase over time due to the progressive implementation of SECA and ETS regulations. In 2023, the baseline cost is lower for both variants. As regulations take effect, costs rise sharply: by 2026, the total cost increases by approximately 66% for IT1 and 60% for IT2 compared to 2023. This confirms the heavy economic impact of ETS and fuel switching under SECA.

Figure 3 presents the full distributions of total cost for both itineraries across years, illustrating the spread of outcomes generated through Monte Carlo simulations. The cost

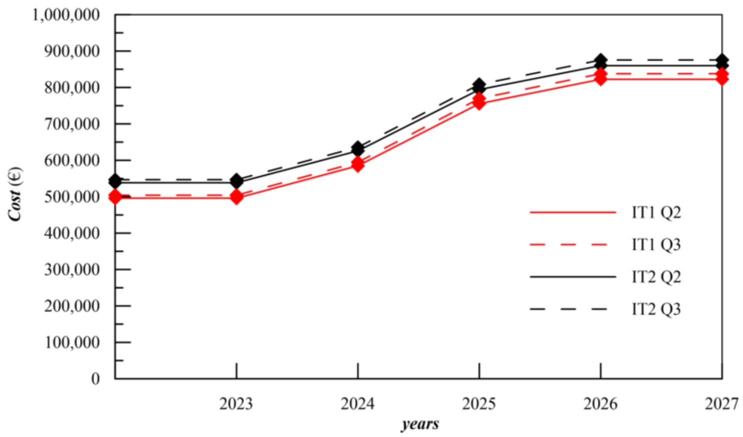

Figure 2. Median and third quartile of total cost by year and itinerary variant.

distributions become broader and more right-skewed over time, indicating increasing variability and financial risk under future regulatory scenarios.

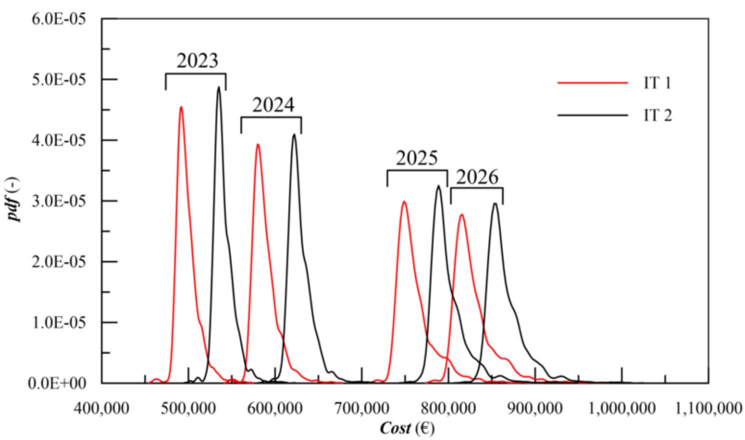

Figure 3. Probability distributions of total cost for IT1 and IT2 across the years.

Although IT1 requires more energy due to onboard freshwater production, it consistently results in lower total cost compared to IT2. This is mainly due to the high port water prices and associated supply fees in many of the visited ports, which outweigh the additional fuel and CO_2 costs. Figures 4 and 5 highlight the relative cost increase from 2023 to 2026 for both configurations.

These results demonstrate that onboard freshwater production remains economically viable (even preferable) despite higher energy consumption. Furthermore, the probabilistic analysis highlights how regulatory changes introduce not only higher costs but also greater uncertainty, reinforcing the need for robust operational planning.

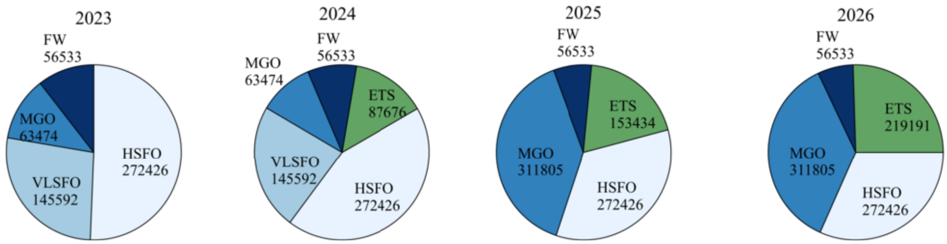

Figure 4. Percentage increase in total cost from 2023 to 2026 for IT1.

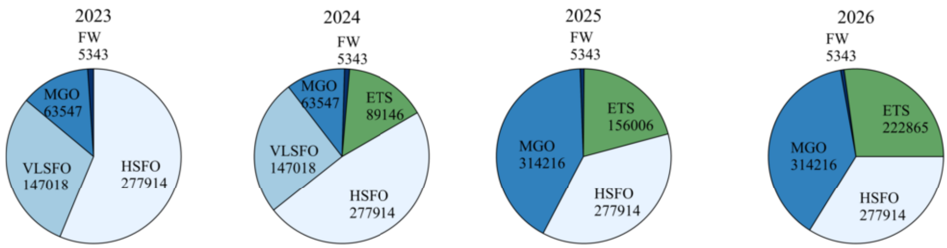

Figure 5. Percentage increase in total cost from 2023 to 2026 for IT2.

5. Conclusions

This study quantifies the financial impact of recent and upcoming environmental regulations, namely the EU ETS and the designation of the Mediterranean as a SECA, on fuel, emissions, and FW-related costs for a typical Western Mediterranean cruise. A probabilistic simulation framework was applied to two operational variants: with and wihout FW production. Results show that total environmental costs increase by over 60% between 2023 and 2026 due to ETS enforcement and fuel switching required under SECA. Despite its higher energy demand, the FW production strategy remains more cost-effective in all years considered. However, the profitability gap between the two strategies narrows over time: IT1 shows a 9% cost advantage over IT2 in 2023, but only 5% by 2026. This reduction reflects the growing cost burden of energy-intensive operations under a full ETS framework and highlights that the two options are becoming more comparable in terms of economic performance.

These findings underline the importance of integrated cost modeling under uncertainty and provide actionable insights for cruise operators facing a tightening regulatory environment. Still, several limitations of the present work must be acknowledged. The present analysis is valid primarily in the short-term and does not account for the forthcoming FuelEU Maritime regulation and GHG intensity limits, which will impose additional compliance costs beyond 2026. Moreover, CII compliance may progressively require speed reductions or retrofitting of existing ships as performance thresholds are lowered over time. To account for these issues, a long-term scenario analysis is advisable. Future studies should incorporate fuel lifecycle emissions, GHG intensity penalties, vessel retrofitting costs, and the operational constraints associated with CII ratings, to offer a comprehensive picture of compliance strategies and their financial implications.

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