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Environmental Assessment of Cruise Ships and Superyachts with Multi-Criteria Evaluation of Marine Fuels

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Abstract

Cruise ships and superyachts have experienced significant global expansion throughout the 21st century. Although the growth in cruise passenger numbers was temporarily disrupted by the COVID-19 pandemic, occupancy rates have since rebounded and even exceeded pre-pandemic levels. This study highlights the significant environmental impact of cruise ships and luxury yachts, particularly in terms of air emissions and marine pollution. Emission levels associated with different fuel types and marine engines are analysed, including the average emissions generated by the Norwegian Cruise Line fleet while docked in ports, as well as the estimated emission reductions achievable through the implementation of onshore power supply systems. To identify environmentally preferable fuel options, a hybrid ANN/MCDM framework is applied. The weighting coefficients of eight evaluation criteria are determined using the Artificial Neural Network/Extreme Learning Machine (ANN/ELM) model, ensuring an objective and data-driven assessment of their relative importance. The ANN/ELM model was trained using emission and fuel-related data collected from the literature and industry reports, and its performance was validated using standard validation procedures, achieving satisfactory predictive accuracy for determining the weighting coefficients. The final ranking of eight fuel alternatives is subsequently performed using the Ranking Alternatives by Weighting of Evaluated Criteria (RAWEC) method. The considered alternatives include conventional and emerging marine fuels currently used in practice or under technological development (A_1–A_8), while the optimization criteria (C_1–C_8) encompass major air pollutants (CO_2, NOx, SOx, CO, PM, CH_4), the fuel cost-to-consumption ratio, and the potential impact on water pollution. The water pollution criterion is assessed qualitatively using the Saaty scale. The integrated ANN/ELM–RAWEC approach enables a systematic comparison of marine fuels and supports the identification of options with the lowest overall environmental impact.

Keywords: cruiser ships and superyachts carbon emission; SOx; NOx; PM; methane slip; GHG; MCDM marine fuels ranking

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1. Introduction

The cruise ship industry has experienced substantial growth in the 21st century, characterized by increasing vessel size and passenger capacity. Despite its economic significance, it remains a major source of air and marine pollution, particularly in densely populated port cities. In parallel, the number of luxury yachts has approximately doubled each decade since 2000, driven by the growing wealth of ultra-high-net-worth individuals. Although more exclusive, superyachts generate disproportionately high emissions per capita, often exceeding those of cruise ships, while receiving comparatively limited attention in both academic research and public discourse.

Recent evidence highlights the scale of environmental impacts associated with maritime passenger transport. A 2023 study by Transport & Environment [1] reported that, following the COVID-19 pandemic, pollution levels at major ports returned to pre-pandemic conditions. Increased ship traffic, longer port stays, and an approximately 24% rise in fuel consumption led to emission increases of 9% for sulphur oxides (SOx), 18% for nitrogen oxides (NOx), and 25% for particulate matter (PM2.5). In 2022 alone, 218 cruise ships near European ports emitted 509 tonnes of SOx, along with 19,125 tonnes of NOx and 448 tonnes of PM2.5 [1].

Localized studies further highlight the significant environmental impacts associated with cruise ships' hoteling operations while docked in ports [2]. Residents of Amsterdam North commissioned the research organization CE Delft to assess emissions from the cruise ship Marella Discovery while docked at Damen Shipyard in 2021. The study revealed substantial emissions of CO_2, SOx, NOx, and PM_{10}, despite the vessel operating only a single auxiliary engine to meet onboard energy demand [2]. Broader industry analyses also underline the scale and economic relevance of cruise operations. Antonellini [3] provided a statistical overview of cruise ship activities between 2016 and 2021, including key financial indicators of major operators. In addition, Oxfam [4,5] highlighted the disproportionate environmental impact of the wealthiest individuals, emphasizing the inequality in global carbon emissions and its implications for climate targets. Scientific reference values for greenhouse gas (GHG) lifetimes, radiative efficiency, and climate metrics such as Global Warming Potential (GWP) and Global Temperature-change Potential (GTP) are provided by the Intergovernmental Panel on Climate Change [6].

A growing body of literature has examined technological and operational strategies for emission reduction in maritime transport. Shore-side electricity supply has been identified as an effective measure for reducing emissions during berthing operations [7]. Experimental studies, such as those by Sagot et al. [8], have monitored atmospheric emissions—including unburned methane—from dual-fuel engines operating on liquefied natural gas (LNG) and marine gas oil (MGO). The West Norway Research Institute [9] reported CO_2 emission factors for commonly used marine fuels, including heavy fuel oil (HFO), marine diesel oil (MDO), and marine gas oil (MGO). Similarly, the European Commission [10] conducted assessments of GHG emissions from ships in EU ports and reviewed life cycle analyses (LCAs) of maritime fuels.

To comply with stricter sulphur regulations, vessels increasingly adopt low-sulphur fuels or install exhaust gas cleaning systems (scrubbers), while alternative fuels such as LNG are gaining prominence. Comparative studies have shown that LNG can significantly reduce emissions of SOx, NOx, particulate matter, and CO_2 relative to conventional fuels [11–15]. However, the environmental performance of LNG remains uncertain due to methane slips, unburned methane emissions during engine operation, which can offset its climate benefits given methane's high global warming potential. This issue has been examined in several studies, including those analysing emissions from dual-fuel marine engines under real operating conditions [14,16].

While LNG reduces CO_2 emissions and air pollutants, methane slip remains a significant concern. In their study, ref. [16] characterized emissions of methane alongside other climate-forcing agents, including CO_2 and black carbon (BC), as well as various

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additional compounds, from a four-stroke low-pressure dual-fuel engine aboard a newly constructed cruise ship operating on both LNG and marine gas oil (MGO). Marine gas turbine data and efficiency are presented in research [17]. A Swedish study [18] found that HFO use with scrubbers in the Baltic Sea generated socio-economic costs exceeding EUR 680 million between 2014 and 2022. These results indicate that the cruise industry still benefits economically from using low-cost, high-polluting HFO rather than cleaner fuels, while scrubber use may also increase particulate matter (PM) emissions when vessels do not operate on low-sulphur (0.1%) marine gas oil (MGO). Emissions from various modes of transport research [19] and emission as well as fuel consumption data for vessels and cruise companies were also utilized [20–23].

Recent research emphasizes the integration of multi-criteria decision-making (MCDM) and machine learning (ML) techniques for addressing complex sustainability problems [24,25]. Hybrid frameworks have been applied in public health [26] and urban infrastructure planning [27,28], as well as in logistics and supply chain management, including transport sustainability evaluation using ANN–MCDM-based approaches [29–31]. These approaches integrate predictive modelling with multi-criteria decision-making to support the robust evaluation of complex systems.

In the context of marine fuel selection, such frameworks provide a systematic basis for assessing alternatives characterized by trade-offs between environmental and economic criteria. In particular, the use of machine learning for weight determination, combined with MCDM techniques for ranking, enhances the reliability and objectivity of the decision-making process, thereby enabling the identification of environmentally preferable fuel options.

Given their high environmental impact, systematic evaluation of alternative fuels and mitigation strategies are required. This study analyses emissions from marine engines operating on different fuel types, focusing on greenhouse gas emissions and other pollutants. The environmental performance of selected marine fuels is assessed using an integrated framework in which ANN (ELM) is used to determine weighting coefficients, while the MCDM method (RAWEC) is applied for ranking the alternatives. This approach enables ranking of marine fuels based on GHG emissions, providing a transparent basis for sustainability evaluation.

The ANN/ELM approach enables efficient modelling of nonlinear relationships, supporting the derivation of weighting coefficients and its integration with MCDM methods such as RAWEC in hybrid decision-making frameworks.

Although ANN-based weighting and MCDM methods have been widely applied in previous studies, their integration via the ELM approach within a unified ANN–MCDM/RAWEC framework for marine fuel evaluation remains relatively limited. The main contribution of this study lies in integrating nonlinear weight derivation with a robust ranking method, enabling a more realistic representation of complex interactions among environmental and economic criteria.

2. Oxfam Study

The analysis by Oxfam [4] indicates that the world's richest 1% exhausted their share of the annual global carbon budget, consistent with the 1.5 °C warming limit, within the first 10 days of 2025, a milestone referred to as "Pollutocrat Day." This finding highlights the disproportionate contribution of the super-rich to global emissions. In contrast, an individual from the poorest half of the global population would require approximately 1022 days to reach the same carbon budget share. Although the richest 1% generates more than twice the emissions of the poorest half of humanity, the latter are expected to experience the most severe impacts of climate change. Achieving the 1.5 °C target requires a reduction of emissions from the richest 1% by approximately 97% by 2030 [4].

According to the United Nations Environment Programme's (UNEP) Emissions Gap Report 2024, the median estimate for the 2030 emissions level compatible with limiting global warming to around 1.5 °C is 24 Gt CO_2-equivalent (range: 20–26 Gt). This corresponds to approximately 17.8 Gt CO_2, based on CO_2's 74.1% share of total greenhouse gas emissions in 2019. With the global population projected to reach 8.5 billion by 2030, dividing this 1.5-compatible emissions level (17.8 Gt CO_2) equally among all people yields an estimated annual carbon budget of 2.1 tonnes of CO_2 per person (see Table 1).

Table 1. Carbon inequality data [4].

	Tonnes CO_2 per Capita per Year	Tonnes CO_2 per Capita per Day	Annual Carbon Budget, Tonnes CO_2 per Capita per Year	Days to Use Up Share of Annual Carbon Budget
Richest 1%	76	0.209	2.1	10
Poorest 50%	0.7	0.002	2.1	1022

Oxfam study "Carbon Inequality Kills" [5] examined 23 superyachts owned by billionaires and found that these floating mansions travel an average of 12,465 nautical miles per year. The study estimates the average annual carbon footprint of each superyacht at 5672 tonnes of CO_2, an amount that would take the average person 860 years to emit.

3. Recent Trends in Cruise Ship Emissions and Pollution Levels

In 2023, the cruise industry served around 31.7 million passengers and generated more than USD 140 billion in global economic activity [20]. Despite its real economic contribution, the sector represents a notable source of environmental impact, as cruise ships account for approximately 3% of total annual global greenhouse gas emissions.

The cruise industry was in a phase of gradual recovery following the disruptions caused by the COVID-19 pandemic. In the pre-pandemic year of 2019, a total of 173 cruise ships were operating in Europe; this number increased to 218 by 2022, intensifying concerns regarding associated environmental emissions [1]. According to the Cruise Lines International Association (CLIA), passenger volumes on European cruises increased from 7.7 million in 2019 to 8.2 million in 2023 [20].

Regionally, the Caribbean and Bahamas region remained the world's leading cruise destination, accounting for 44.2% of global cruise passengers in 2023. The Mediterranean ranked second with an 18.5% share, followed by other European regions at 10.5% [20].

In 2022, the most polluting cruise vessel operating in Europe, the MSC Grandiosa, emitted 133,817 tonnes of CO_2. This amount is approximately equivalent to the annual emissions generated by 67,700 passenger cars [1]. In the same year, total shipping emissions within the European Union reached 135.5 million tonnes of CO_2.

Moreover, cruise ships operating in Europe emitted more SOx in 2022 than an estimated one billion passenger cars, equivalent to approximately 4.4 times the total number of cars on the continent [1]. Notably, the combined emissions of all passenger cars in Europe were lower than those produced by only 64 cruise ships operated by the Royal Caribbean Group, the world's second-largest cruise company.

Although cruise ship-related pollution in port areas has largely returned to pre-pandemic levels, several cities have recorded substantial reductions as a result of targeted regulatory measures. For example, air pollutant emissions from cruise ships in Venice decreased by approximately 80% following the municipal ban on large vessels entering the historic lagoon area. Similarly, Amsterdam has introduced restrictions on cruise ship operations in response to environmental concerns.

Figure 1 presents cruise ship-related pollution at major European ports [1].

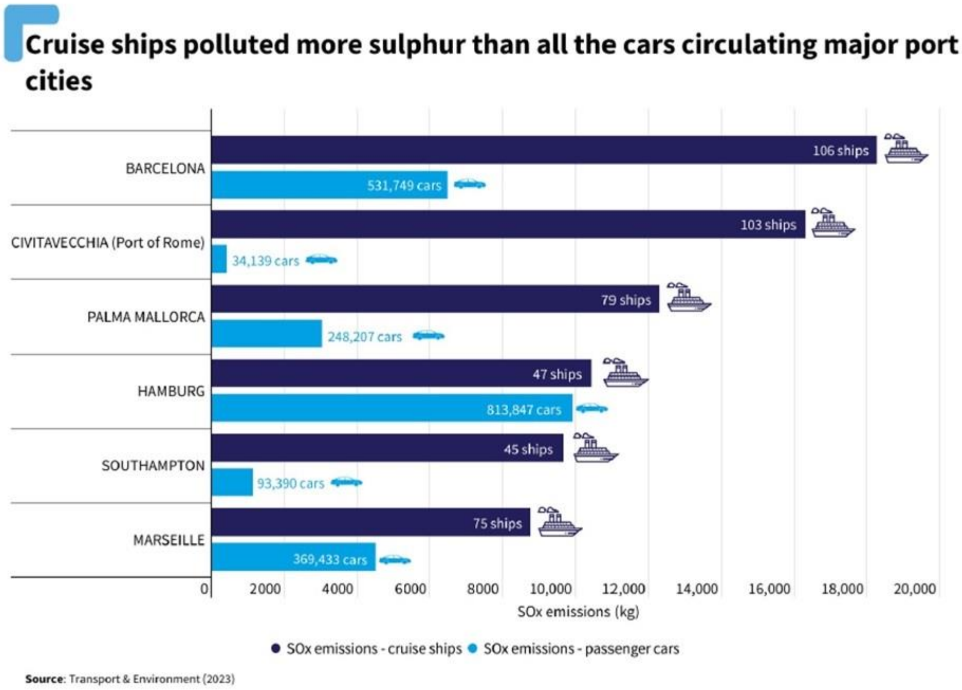

Figure 1. Cruise ship sulfur pollution in European ports compared to vehicle cars pollution [1].

According to a study by Transport & Environment [1], sulphur oxide (SOx) emissions at Europe's busiest ports reached 509 tonnes in 2022, representing a 9% increase compared to 2019 levels. Methane (CH_4) emissions also rose markedly, increasing fivefold to 7804 tonnes. This trend corresponds with the growth in the number of cruise ships operating in European waters, which expanded from 173 in 2019 to 218 in 2022. Figure 1 further compares sulphur oxide emissions from cruise ships at major European ports with those generated by residential passenger cars [1].

Barcelona recorded the highest sulphur oxide emissions among ports, followed by Civitavecchia (Rome) and Piraeus (Athens). A 2022 analysis found that the 64 ships operated by Carnival Corporation & plc produced more sulphur oxides than all passenger cars in Europe combined [1]. These pollutants contribute to acid rain and respiratory problems, intensifying the environmental and public health impacts of cruise operations.

Even the most stringent marine fuel sulphur standard (0.1% sulphur, equivalent to 1000 ppm) remains 100 times less strict than the sulphur limits applied to road diesel and petrol in Europe (0.001% sulphur, or 10 ppm), which have been in force for more than 15 years. In addition, methane (CH_4) has a global warming potential (GWP) 82.5 times greater than that of CO_2 over a 20-year time horizon and 29.8 times greater over a 100-year time.

In 2023, Carnival Corporation & plc emitted more CO_2 than the entire city of Glasgow. Similarly, the 45 cruise ships visiting Southampton in 2022 emitted nearly nine times more sulphur oxides at berth than the city's 93,000 passenger cars, according to Transport & Environment [1].

In 2024, the global cruise fleet comprised approximately 323–360 vessels, contributing significantly to atmospheric emissions. The same year, European shipping emissions reached a record level, largely driven by LNG carriers and cruise ships. Globally, the average energy-related carbon footprint was about 4.7 t CO_2 per capita, while cruise tourism generates substantially higher emissions. A cruise passenger emits around 421.43 kg CO_2 per day, over eight times more than a typical land-based vacation (≈51.88 kg/day) and significantly above high-end tourism levels (≈81.33 kg/day).

Cruise ships primarily operate on carbon-intensive fuels, producing sulphur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), greenhouse gases (GHGs), and black carbon (BC). Black carbon, generated through incomplete combustion, is a short-lived but highly potent climate pollutant often emitted together with CO_2, carbon monoxide (CO), volatile organic compounds (VOCs), and organic carbon (OC). Consequently, cruise ships represent a disproportionately large source of pollution within the maritime sector, contributing significantly to climate change and local air quality degradation. Particularly notable are black carbon emissions, for which cruise ships rank among the largest contributors in maritime transport. Figure 2 presents carbon and black carbon emissions by some ships category.

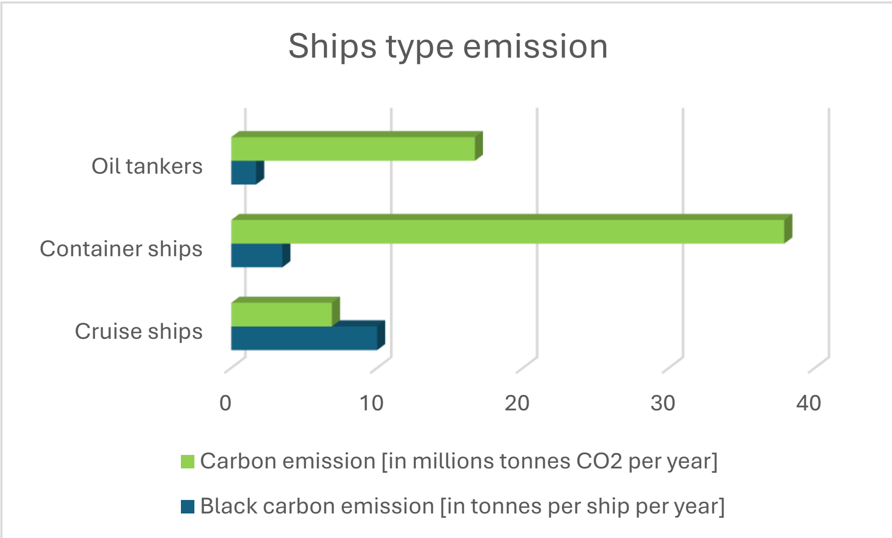

Figure 2. Annual carbon and black carbon emissions for different ship types in 2022 [1,23].

Although cruise ships represent only about 1% of the global fleet, they emit three times more black carbon than container ships and six times more than oil tankers, which account for roughly 7% and 8% of the fleet, respectively [1,23]. In terms of CO_2 emissions, cruise ships are the highest emitters on a per-vessel basis. However, their total carbon emissions are lower overall due to the relatively small size of the fleet.

There are many cruise companies, but the four largest are: Carnival Corporation, Royal Caribbean Group, MSC Cruise and Norwegian Cruise Line Holding. Table 2 shows the total cruisers fleet [20] by the four largest companies in 2023.

Table 2. Cruise companies' general data in 2023 [20].

Cruise Company	Passengers Share [in % per Year]	Total Fleet [Number of Ships]	Ships Using LNG	Ships Using Biofuel
Carnival Corporation	41.5%	93	6	1
Royal Caribbean Group	27.0%	64	1	2
Norwegian Cruise Line Hldgs	9.4%	29	0	2
MSC Cruise	10.0%	22	2	1

Carnival Corporation & plc was expected to introduce five additional LNG-powered vessels into its fleet in 2025, and Royal Caribbean Group is expected to add three additional LNG-powered vessels in 2026.

Norwegian Cruise Line Holdings in early 2025 operates a fleet of 34 cruise ships across its three brands: Norwegian Cruise Line—19 ships, Oceania Cruises and Regent Seven Seas Cruises. Norwegian Cruise Line Holdings (NCLH) is investigating using methanol instead of LNG, with no plans for LNG ships in future. NCLH also has additional cruise ships scheduled for delivery trough 2036, which will add approximately 35,500 new berths (over 70,500 in 2025).

MSC Cruises fleet of 23 ships currently has three LNG-powered ships in operation; MSC World Europa, MSC Euribia, and MSC World America joined the fleet in April 2025. Additionally, they have two more LNG-fuelled World Class ships on order, scheduled for delivery in 2026 and 2027.

4. Cruise Ships Data

4.1. Carbon Dioxide Equivalent Emission

Assuming carbon dioxide emissions equal 1, the carbon dioxide equivalent emissions (CO_2-eq) of any greenhouse gas (GHG) can be calculated as follows:

$$CO_2\text{-eq} = (\text{Mass of } GHG) \times (GWP \text{ of } GHG) \quad (1)$$

where CO_2-eq is carbon dioxide equivalent emission, and *GWP* is global warming potential from GHG compared to CO_2 emission, which is evaluated to 1. For example, the GWP for methane is 25–28, and for nitrous oxide is 273–298. This means that emissions of 1 million metric tonnes of methane and nitrous oxide, respectively, are equivalent to emissions of at least 25 and 273 million metric tonnes of carbon dioxide.

4.2. Europe's Most Polluting Cruise Lines

The Norwegian Epic was the largest carbon emitter among cruise vessels in 2023, releasing approximately 95,000 tonnes of CO_2 [32], equivalent to the annual carbon footprint of a small town of 20,000 inhabitants. With a passenger capacity of 4100, the ship emitted roughly two tonnes of CO_2 per nautical mile travelled. The vessel is powered by six main engines, totalling 79,800 kW [33], compliant with IMO Tier II standards and equipped with selective catalytic reduction (SCR) systems meeting IMO Tier III requirements. While in port, the ship generally operates a smaller engine sufficient to supply electricity for essential services such as lighting, air conditioning, kitchens, and basic passenger and crew operations. Table 3 [32] provides a ranking of the most polluting cruise lines.

Table 3. Most polluting European cruise lines based on their average CO_2 emissions per nm [32].

Cruise Line	Average CO_2 Emissions per Ship per nm
Disney Cruise Line	1481 kg
Norwegian Cruise Line	1413 kg
Princess Cruises	1253 kg
Royal Caribbean	1248 kg
MSC Cruises	1229 kg
Virgin Voyages	1229 kg
Celebrity Cruises	1228 kg
Cunard	1207 kg
P&O Cruises	1108 kg
Costa Cruises	1051 kg

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Although cruise ships constitute less than 1% of the global ocean-going commercial fleet, their environmental impact is disproportionately large [1,23]. Mass-market vessels transporting thousands of passengers function as energy-intensive “floating resorts,” requiring power for air-conditioned cabins, restaurants, bars, theatres, shops, swimming pools, and gyms in addition to propulsion, consuming thousands of litres of fuel daily.

According to Which? [32], a seven-day cruise for two passengers sharing a cabin from London to Barcelona results in estimated emissions of approximately 2100 kg CO_2-equivalent (CO_2-eq) per person. By comparison, travelling to Barcelona by commercial aircraft combined with accommodation in a double hotel room generates around 425 kg CO_2-eq per person. Opting for rail transport with the same hotel accommodation yields a substantially lower carbon footprint, estimated at approximately 164 kg CO_2-eq per person.

4.3. Carbon Emissions of the Norwegian Epic During Cruising: A Case Study

The annual operations of the cruise ship Norwegian Epic in 2023 are analysed in this study. During this period, the vessel operated in two distinct regions: for the first four months of the year, it sailed in the Atlantic, primarily in the Caribbean, while for the remainder of the year it operated in the Mediterranean [34].

The cruise ship Norwegian Epic was launched in 2010 and underwent refurbishment in 2020. The vessel has a gross tonnage of 155,873 and is operated by Norwegian Cruise Line Holdings (NCLH). Norwegian Epic has an overall length of 329 m and a beam of 41 m, with a maximum service speed of up to 24 knots. The ship has a passenger capacity of approximately 4100 and accommodates a crew of 1724 [33].

The cruise ship Norwegian Epic is equipped with six engines, three MaK 16M43C diesel engines rated at 15.2 MW each and three MaK 12M43C engines rated at 11.4 MW each, resulting in a total installed power of 79.8 MW [33].

According to official 2023 data [20], Norwegian Cruise Line reported a combined occupancy rate of 102.9%. In all calculations below, the occupancy of Norwegian Epic is conservatively assumed to be 100%.

Fuel consumption rate FCR [t/h] during cruising (Equation (2)) is calculated as fuel for propulsion for average speed for every distance and fuel for the hoteling at the ship during cruising time.

$$FCR_{\text{cruise}} = FCR_{\text{propulsion}} + FCR_{\text{hotel}} \tag{2}$$

The engine power at reduced speeds is calculated using the standard propulsion scaling formula, which relates power to the vessel’s speed through a cubic or exponent-based relationship. When the Norwegian Epic is traveling at its cruise speed, the engines typically operate at around 80–85% of their maximum continuous rating (MCR). In this analysis, a nominal cruise speed of 22 knots at approximately 85% MCR is used, with a specific fuel oil consumption (SFOC) of 0.185 kg fuel per kWh [2,20]. First, the mean speed for the given cruising time is calculated, and we compare it with the nominal speed at 22 knots [33], for which the estimated power is 0.85 MCR:

$$P_{\text{cruise}} = 0.85MCR \cdot (v_{\text{cruise}}/22)^3 \tag{3}$$

where cruising speed v_{cruise} is in knots. After that, the cruising power P_{cruise} is multiplied by SFOC and the resulting FCR_{cruise}. Fuel consumption rate for hoteling is calculated for assumed power for hoteling of P_{hotel} = 11 kW, and calculated in the same way.

The analysis is based on the following key assumptions: constant average passenger occupancy throughout the year; uniform engine efficiency within each operational mode (cruising vs. hoteling); linear proportionality between installed power and hoteling demand; no significant variation in fuel carbon intensity across voyages; onshore power supply (OPS) availability is limited to major ports and assumed to provide up to 95% of hoteling energy demand in the mitigation scenario.

Itinerary data for Norwegian Epic in 2023 were compiled from publicly available sources. The itineraries were cross-checked against cruise offers published by multiple travel agencies, which showed consistent routes and port calls. Minor variations in arrival and departure times may occur, but they do not significantly impact the calculated results. According to the itinerary of Norwegian Epic for 2023 [34], cruise ship emissions are calculated for each voyage segment as well as for individual port calls. Distances between ports for 2023 were adopted from BednBlue Sailing Distance Calculator [35] and may be subject to minor deviations depending on the route selected by the ship's captain, prevailing weather conditions, and scheduling constraints related to arrival times at subsequent ports.

The vessel commenced the year with a New Year's cruise in the Caribbean, and beginning on 8 January, the same itinerary was operated repeatedly [34]. This seven-day, eight-night cruise was conducted a total of 13 times consecutively. The itinerary of this repeated cruise is as follows (Table 4):

Table 4. A single seven-day, eight-night cruise itinerary in the Caribbean [34].

Day	Location, Port	Arrival	Departure	Hours in Port	Cruising Hours	Distance [nm]	Speed [nm/h]
1st day	San Juan, Puerto Rico	7:00	19:00	-	5	-	-
2nd day	At Sea	-	-	-	24	-	-
3rd day	Oranjestad, Aruba	8:00	17:00	9	8	490	13.24
4th day	Willemstad, Curacao	8:00	17:00	9	15	75	5.00
5th day	Kralendijk, Bonaire	6:00	13:00	7	13	45	3.46
6th day	Castries, West Indies	13:00	20:00	7	24	460	19.17
7th day	Basseterre, St. Kitts and Nevis	9:00	18:00	9	13	240	18.46
8th day	San Juan, Puerto Rico	7:00	19:00	12	13	220	16.92
	Total:	-	-	53	115	1530	13.30

Calculated daily engine power and fuel consumption for this seven-day, eight-night cruise in the Caribbean are summarized in Table 5. The first three days of the cruise are aggregated for analysis; the initial day of operation, comprising 5 h of cruising, the second day at sea with 24 h of cruising, and the first 8 h of the third day are combined and attributed to the third day, corresponding to the vessel's arrival at the port of Oranjestad. Specific fuel consumption per passenger was calculated under the assumption of full vessel occupancy, consistent with the cruise company's reported occupancy data for 2023.

Table 5. Calculated daily engine power and fuel consumption for a single seven-day, eight-night cruise in the Caribbean.

Day of Cruise	Cruise Power		Hotel Power	Total Power	Fuel Consumption Rate	Specific Fuel Consumption	Fuel Consumption	Total Fuel Consumption
	[%]	[MW]	[MW]	[MW]	[t/h]	[t/Passenger]	[t/nm]	[t]
1st–3rd	21.81	5.24	11.4	19.96	3.69	0.0333	0.279	136.64
4th day	1.17	0.28	11.4	14.02	2.59	0.0095	0.519	38.90
5th day	0.39	0.09	11.4	13.79	2.55	0.0081	0.737	33.17
6th day	66.13	15.87	11.4	32.72	6.05	0.0354	0.316	145.30
7th day	59.09	14.18	11.4	30.70	5.68	0.0180	0.308	73.83
8th day	45.52	10.92	11.4	26.79	4.96	0.0157	0.293	64.43
		Total:			4.28	0.1200	0.322	492.26

Carbon dioxide emissions for this seven-day Caribbean cruise are presented in Table 6. The same methodology applied in Table 5 is used here: emission data corresponding to the first, second, and third days of the cruise are aggregated and reported in the third column, which represents the vessel's arrival at the port.

Table 6. Calculated cruise CO_2 emissions for a single seven-day, eight-night cruise in the Caribbean.

Day of Cruise	CO_2 Emission During Cruise	CO_2 Emission During Cruise	CO_2 Emission During Cruise	Total CO_2 Emission During Cruise
	[t CO_2/h]	[t CO_2/Passenger]	[t CO_2/Passenger/h]	[t CO_2]
1st–3rd	11.500	$103.780 \cdot 10^{-3}$	$2.805 \cdot 10^{-3}$	425.500
4th day	8.076	$29.545 \cdot 10^{-3}$	$1.970 \cdot 10^{-3}$	121.135
5th day	7.946	$25.193 \cdot 10^{-3}$	$1.938 \cdot 10^{-3}$	103.292
6th day	18.852	$110.354 \cdot 10^{-3}$	$4.598 \cdot 10^{-3}$	452.451
7th day	17.685	$56.075 \cdot 10^{-3}$	$4.313 \cdot 10^{-3}$	229.908
8th day	15.433	$48.933 \cdot 10^{-3}$	$3.764 \cdot 10^{-3}$	200.626

In this case study, all itineraries of the Norwegian Epic [34] for cruises conducted during the first four months of 2023 are analysed, and data are calculated, with the summarized results presented later, as an Atlantic cruise.

After a total of 121 days of travel, the Norwegian Epic arrived in Funchal, Portugal, on 1 May. The following day, the vessel commenced its Mediterranean cruise itinerary.

According to the 2023 itinerary of Norwegian Epic [34], the vessel operated in the Mediterranean during the second part of the year, carrying passengers for a total of 229 days. Days allocated to service and maintenance activities at the Toulon (La Seyne-sur-Mer) shipyard, as well as ship testing at sea, are excluded from this analysis.

Several distinct itineraries were followed, including a nine-day (ten-night) cruise that was repeated eight times. The detailed itinerary for this eight-time-repeated nine-day Barcelona cruise is presented in Table 7.

Table 7. A single nine-day, ten-night cruise itinerary in the Mediterranean [34].

Day	Location, Port	Arrival	Departure	Hours in Port	Cruising Hours	Distance [nm]	Speed [nm/h]
1st day	Barcelona, Spain	5:00	17:00	-	7	-	-
2nd day	Cannes, France	8:30	18:30	10	14	270	17.42
3rd day	Livorno, Italy	6:00	24:00	18	6	150	12.50
4th day	Livorno, Italy	0:00	19:00	19	5	0	-
5th day	Civitavecchia, Italy	6:30	19:00	12.5	11.5	130	11.30
6th day	Naples, Italy	6:30	17:00	10.5	13.5	165	14.35
7th day	Cagliari, Italy	10:00	17:00	7	17	275	16.18
8th day	Palma de Mallorca, Spain	13:00	23:00	10	14	350	17.50
9th day	Ibiza, Spain	7:00	18:00	11	13	80	10.00
10th day	Barcelona, Spain	5:00	17:00	12	5	160	14.55
	Total:	-	-	110	106	1580	14.836

In a few cases, arrival and departure times at individual ports differed by approximately 30–60 min; however, these minor variations do not significantly affect the results for all eight Barcelona tours. Fuel consumption calculations for the nine-day Barcelona cruise are presented in Table 8. Data for the first two days (with only 7 h of operation on day one) are aggregated, as are data for days 3 and 4, when the vessel is docked in Livorno. Fuel consumption is calculated assuming full ship occupancy.

Table 8. Calculated daily engine power and fuel consumption, and for a single nine-day, ten-night cruise in the Mediterranean.

Day of Cruise	Cruise Power		Hotel Power	Total Power	Fuel Consumption Rate	Specific Fuel Consumption	Fuel Consumption	Total Fuel Consumption
	[%]	[MW]	[MW]	[MW]	[t/h]	[t/Passenger]	[t/nm]	[t]
1st–2rd	49.64	11.91	11.4	27.98	5.18	0.0196	0.297	80.22
3th day	18.34	4.40	11.4	18.96	3.51	0.0103	0.281	42.10
4th–5th	13.57	3.26	11.4	17.59	3.25	0.0091	0.288	37.42
6th day	27.74	6.66	11.4	21.67	4.01	0.0112	0.279	46.10
7th day	39.75	9.54	11.4	25.13	4.65	0.0193	0.287	79.03
8th day	50.33	12.08	11.4	28.18	5.21	0.0254	0.298	104.25
9th day	9.39	2.25	11.4	16.38	3.03	0.0059	0.303	24.25
10th day	28.90	6.94	11.4	22.00	4.07	0.0109	0.280	44.78
Total:					4.302	0.112	0.290	458.14

Carbon dioxide emissions for this single nine-day, ten-night cruise departing from Barcelona are presented in Table 9, with the same methodology and assumptions as before.

Table 9. Calculated cruise CO_2 emissions for a single nine-day, ten-night cruise in the Mediterranean.

Day	CO_2 Emission	CO_2 Emission	CO_2 Emission	Total CO_2 Emission
	[t CO_2/h]	[t CO_2/Passenger]	[t CO_2/Passenger/h]	[t CO_2]
1st–2rd	16.117	$60.929 \cdot 10^{-3}$	$3.931 \cdot 10^{-3}$	249.811
3th day	10.924	$31.973 \cdot 10^{-3}$	$2.664 \cdot 10^{-3}$	131.091
4th–5th	10.132	$28.418 \cdot 10^{-3}$	$2.471 \cdot 10^{-3}$	116.516
6th day	12.483	$35.014 \cdot 10^{-3}$	$3.045 \cdot 10^{-3}$	143.557
7th day	14.477	$60.025 \cdot 10^{-3}$	$3.531 \cdot 10^{-3}$	246.104
8th day	16.232	$79.179 \cdot 10^{-3}$	$3.959 \cdot 10^{-3}$	324.635
9th day	9.439	$18.418 \cdot 10^{-3}$	$2.302 \cdot 10^{-3}$	75.513
10th day	12.676	$34.009 \cdot 10^{-3}$	$3.092 \cdot 10^{-3}$	139.436

CO_2 emissions in a single Mediterranean cruise range from 2.3 to 4 kg per passenger per hour, which is very similar to the values observed for the single Caribbean cruise, where emissions ranged from 2 to 4.6 kg CO_2 per passenger per hour.

In addition to the shown most frequently operated Barcelona-based itinerary in the Mediterranean, Norwegian Epic also conducted many other cruises during the second part of 2023. Norwegian Epic also operated two itineraries departing from Barcelona that lasted ten days and nine nights, with Marseille included as one of the destinations. Another comparable itinerary included a call at Messina. Following maintenance and servicing in September 2023, Norwegian Epic further expanded its cruise program beyond the itineraries listed in Table 7 to include ports in Greece, Cyprus, Turkey, Israel and Malta, as well as several destinations in the Adriatic Sea. The voyage concluded at the port of Barcelona on 31 December 2023. Based on the ship's 2023 itinerary [34], fuel consumption and emissions were calculated for all voyages, and the aggregated results are presented below.

All Norwegian Epic Mediterranean cruises and itineraries were analysed, with fuel consumption and emissions calculated, alongside the Atlantic cruise data, and shown in Table 10.

Table 10. Calculated operational parameters of the Norwegian Epic for its Atlantic and Mediterranean cruises in 2023.

	Atlantic	Mediterranean	Total
Total Days of Operations for Norwegian Epic in 2023	121	229	350
Total Time docked in Ports [h]	885	2609	3494
Total Cruising Time at Sea [h]	2007	2890	4897
Total Distance Travelled [nm]	27,555	43,057	70,612
Average Fuel Consumption Rate [t/h]	3.870	4.821	4.431
Average Fuel Consumption [t/nm]	0.282	0.324	0.307
Total Fuel Consumption [t]	7767.0	13,931.4	21,698.4
Average CO_2 Emissions During Cruise [t CO_2/h]	12.05	15.01	13.80
Average CO_2 Emissions During Cruise [t CO_2/passenger]	$5899.1 \cdot 10^{-3}$	$7784.5 \cdot 10^{-3}$	$13{,}683.6 \cdot 10^{-3}$
Average CO_2 Emissions During Cruise [t CO_2/passenger/h]	$2.939 \cdot 10^{-3}$	$2.694 \cdot 10^{-3}$	$2.794 \cdot 10^{-3}$
Average CO_2 Emissions During Cruise [t CO_2/nm]	0.878	1.008	0.957
Average CO_2 Emissions During Cruise [t CO_2/passenger/nm]	$214.1 \cdot 10^{-3}$	$180.8 \cdot 10^{-3}$	$193.8 \cdot 10^{-3}$
Total CO_2 Emissions During Cruise [t CO_2]	24,186.3	43,382.5	67,568.8

A medium-to-large-sized cruise ship typically consumes approximately 150–250 kg of fuel per nautical mile, whereas Norwegian Epic, according to these calculations (Table 10), exceeds this range with an average fuel consumption of 307 kg per nautical mile. On the other hand, because the vessel rarely operates at full speed, CO_2 emissions average approximately 0.957 t per nautical mile, and 0.181 kg CO_2 per passenger per nm.

4.4. Carbon Emissions of the Norwegian Epic in Ports: A Case Study

The calculation of fuel consumption and CO_2 emissions for the Norwegian Epic during port stays in 2023 was based on the proportion of installed engine power required for hoteling operations. Three scenarios were analysed, corresponding to 10%, 15%, and 20% of the total installed power being used to supply heating and electrical energy for onboard services while the vessel was docked and some passengers were ashore.

Under the 10% scenario, approximately 8 MW of power is allocated to hoteling, corresponding to roughly 52.5% of the rated capacity of a single generator unit. For the 15% scenario (approximately 12 MW), one generator must operate at about 78.8% of its rated load to meet hoteling demands. In the case of 20% of total installed power, at least two generators are required to operate simultaneously to provide sufficient energy for onboard services. These scenarios allow for a realistic assessment of fuel use and emissions under varying hoteling power requirements.

Table 11 presents the 2023 fuel consumption and CO_2 emission calculations for the three hoteling scenarios described above.

Table 11. Calculated fuel consumption and CO_2 emission for Norwegian Epic in 2023 for the three hoteling scenarios.

Hoteling Capacity of Norwegian Epic in 2023 [%]	10%	15%	20%
Total Fuel Consumption in Ports [t]	5450.6	7756.7	10,342.2
Total Specific Fuel Consumption in Ports [t/passenger/h]	$0.380 \cdot 10^{-3}$	$0.541 \cdot 10^{-3}$	$0.722 \cdot 10^{-3}$
Total CO_2 Emissions in Ports [t CO_2]	16,973.3	24,154.3	32,205.7
Total CO_2 Emissions in Ports [t CO_2/passenger/h]	$1.185 \cdot 10^{-3}$	$1.686 \cdot 10^{-3}$	$2.248 \cdot 10^{-3}$

Table 12 presents the summarized results of fuel consumption and CO_2 emissions of the Norwegian Epic in 2023, for the three hoteling scenarios, including both cruising and port hoteling operations (while docked), with the same assumptions that were previously adopted. The analysis relies on representative literature-based data, where key parameters are defined using commonly adopted assumptions to maintain methodological consistency across all alternatives.

Table 12. Aggregate fuel consumption and CO_2 emissions for Norwegian Epic in 2023 (both cruising and docking in ports).

Hoteling Capacity of Norwegian Epic in 2023 [%]	10%	15%	20%
Aggregate Fuel Consumption in 2023 [t]	27,149.0	29,455.1	32,040.6
Aggregate Fuel Consumption in 2023 [t/day]	77.6	84.2	91.5
Aggregate Fuel Consumption Rate in 2023 [t/h]	7.77	8.43	9.17
Aggregate Specific Fuel Consumption in 2023 [t/passenger/h]	$1.90{\cdot}10^{-3}$	$2.06{\cdot}10^{-3}$	$2.24{\cdot}10^{-3}$
Aggregate Fuel Consumption in 2023 [t/nm]	0.384	0.417	0.454
Aggregate Specific Fuel Consumption in 2023 [t/passenger/nm]	$0.094{\cdot}10^{-3}$	$0.102{\cdot}10^{-3}$	$0.111{\cdot}10^{-3}$
Aggregate Specific Fuel Consumption in 2023 [t/passenger/km]	$0.051{\cdot}10^{-3}$	$0.055{\cdot}10^{-3}$	$0.060{\cdot}10^{-3}$
Aggregate CO_2 Emissions in 2023 [t CO_2]	84,542.1	91,723.1	99,774.6
Aggregate CO_2 Emissions in 2023 [t CO_2/day]	241.5	262.1	285.1
Aggregate CO_2 Emissions in 2023 [t CO_2/h]	24.20	26.25	28.56
Aggregate CO_2 Emissions in 2023 [t CO_2/passenger/h]	$5.90{\cdot}10^{-3}$	$6.40{\cdot}10^{-3}$	$6.96{\cdot}10^{-3}$
Aggregate CO_2 Emissions in 2023 [t CO_2/nm]	1.197	1.299	1.413
Aggregate CO_2 Emissions in 2023 [t CO_2/passenger/nm]	$0.292{\cdot}10^{-3}$	$0.317{\cdot}10^{-3}$	$0.345{\cdot}10^{-3}$
Aggregate CO_2 Emissions in 2023 [t CO_2/passenger/km]	$0.158{\cdot}10^{-3}$	$0.171{\cdot}10^{-3}$	$0.186{\cdot}10^{-3}$

Norwegian Epic was reported as the largest polluter among cruise ships in 2023, with total CO_2 emissions of 95,000 t that year [32]. The calculated values obtained in this case study are consistent with publicly available data on the ship's CO_2 emissions for that year. Based on these results, it is possible to estimate the average share of installed power utilized for hoteling while the vessel was docked in ports (see Table 13).

Table 13. Calculated real fuel consumption and CO_2 emissions for Norwegian Epic in 2023 (both cruising and docking in ports).

Applied Norwegian Epic Hoteling Capacity [%/MW]	17.08%/13.63 MW
Estimated Total Distance Travelled in 2023 [nm/km]	70,612/130,632
Calculated Total Fuel Consumption in 2023 [t]	30,507.4
Calculated Daily Fuel Consumption in 2023 [t/day]	87.164
Calculated Fuel Consumption Rate in 2023 [t/h]	8.731
Calculated Specific Fuel Consumption in 2023 [t/passenger/h]	$2.130{\cdot}10^{-3}$
Calculated Fuel Consumption in 2023 [t/nm]	0.432
Calculated Specific Fuel Consumption in 2023 [t/passenger/nm]	$0.1054{\cdot}10^{-3}$
Calculated Specific Fuel Consumption in 2023 [t/passenger/km]	$0.0570{\cdot}10^{-3}$
Calculated CO_2 Emissions in 2023 [t CO_2]	95,000
Calculated CO_2 Emissions in 2023 [t CO_2/day]	271.429
Calculated CO_2 Emissions in 2023 [t CO_2/h]	27.189
Calculated CO_2 Emissions in 2023 [t CO_2/passenger/h]	$6.632{\cdot}10^{-3}$
Calculated CO_2 Emissions in 2023 [t CO_2/nm]	1.345
Calculated CO_2 Emissions in 2023 [t CO_2/passenger/nm]	$0.3281{\cdot}10^{-3}$
Calculated CO_2 Emissions in 2023 [t CO_2/passenger/km]	$0.1774{\cdot}10^{-3}$

To provide context for comparison with other modes of transport, a passenger on a domestic flight produces approximately 255 g CO_2 per kilometre, while travel by car generates 180 g CO_2 per kilometre, and travel by bus results in 28 g CO_2 per kilometre per passenger. Emissions from rail travel are considerably lower, ranging below 10 g CO_2 per kilometre per passenger for electric trains, and 30–45 g CO_2 per kilometre per passenger for diesel-powered trains [19,32].

This case study indicates that cruising on large luxury cruise ships results in a carbon footprint per passenger per kilometre comparable to that of private car travel, substantially higher than that of diesel trains or buses, and somewhat lower than that of air travel. From an environmental perspective, this comparison is particularly relevant because rail and bus transport primarily serve essential mobility needs, whereas cruise travel represents a discretionary, leisure-oriented activity.

In addition, other forms of pollution associated with cruise ship operations, particularly emissions of sulphur oxides (SOx), particulate matter (PM), and other air pollutants, should be considered. These emissions are significantly more pronounced for cruise ships than for most other modes of transport and were discussed in detail in this paper.

4.5. Norwegian Cruise Line Carbon Emission Reduction in Ports—Case Study

The Cruise Lines International Association (CLIA) has emphasized the critical role of onshore power supply (OPS) in mitigating the environmental impacts of cruise ship operations [20]. OPS allows vessels to connect to the local electrical grid while berthed, enabling auxiliary diesel engines to be shut down. This results in substantial reductions in greenhouse gas emissions, particularly carbon dioxide (CO_2), as well as in air pollutants such as nitrogen oxides (NOx), sulphur oxides (SOx), and particulate matter (PM). According to studies [7,19], cruise ships utilizing OPS can achieve emission reductions of up to 95–98% during berthing periods. These findings are supported by multiple case studies conducted in major port cities.

Operational data indicate that a cruise vessel's average hourly electricity demand while docked is approximately 10 MWh [7], resulting in a total energy consumption of about 90–100 MWh during a typical 9–10 h port stay. Even while berthed, a cruise ship consumes electricity equivalent to that of approximately 3000–3500 average households. The adoption of OPS therefore represents a crucial measure for reducing port-side emissions and improving local air quality.

On Norwegian Cruise Line (NCL) itineraries, the average time spent in port per vessel varies but typically ranges from 5 to 10 h, with arrivals occurring in the morning and departures in the late afternoon or early evening. In the Mediterranean region, cruise ships generally make 4–5 port calls during a 7-day itinerary [20]. The average number of passengers per cruise call at Mediterranean ports is approximately 2263, with total passenger movements reaching 33.2 million across 14,670 port calls in a recent year.

Figures 3 and 4 illustrate the medium time spent in different ports by cruise ships, as well as CO_2 emissions expressed in kilograms per passenger per hour while the vessel is berthed at the port. These data are derived from the research presented in [7].

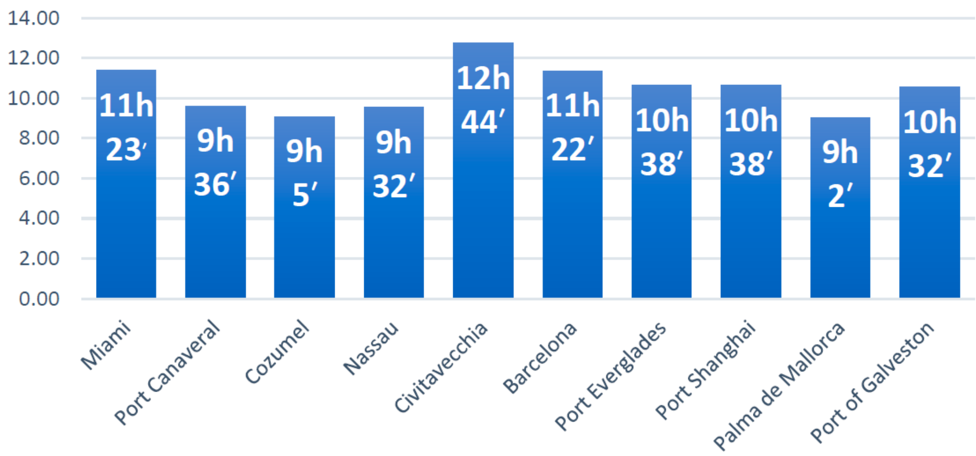

Figure 3. Medium time spent in port by cruise ships in 2024 [7].

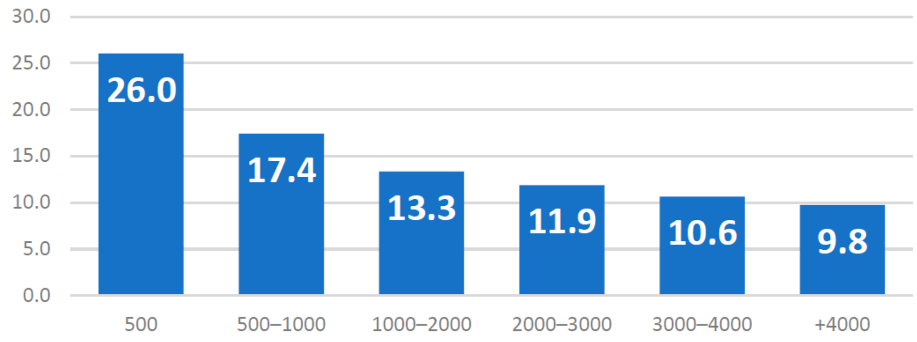

Figure 4. Average CO_2 emissions in kg per passenger per hour at berth for cruise ships of varying capacities [7].

A comparison between Figure 4 and the results of this case study indicates a substantial difference in CO_2 emissions per passenger per hour while the vessel is in port. The value reported in [7] is 9.8 kg CO_2 per passenger per hour (presented in Figure 4), whereas the present analysis for Norwegian Epic, a cruise ship with a passenger capacity exceeding 4000, yields 1.92 kg CO_2 per passenger per hour alongside. The difference may occur due to different occupancy of ships while they are anchored in ports. And combined CO_2 emissions per passenger per hour for Norwegian Epic in 2023, including both cruising and time spent in ports, are 6.632 kg CO_2 per passenger per hour (Table 13).

The CO_2 emission reduction in Table 14 is based on the assumption that 95% of the cruise ship's hoteling power demand is supplied by connection to the port electrical grid.

Table 14. Estimated CO_2 emission reductions for the entire NCL fleet, assuming 95% of hoteling power is supplied via shore grid.

NCL Cruise Ship	Year	Capacity [Passengers]	Engine Power [MW]	Hotel Power [MW]	Min. CO_2 Emission [t/Year]	Max. CO_2 Emission [t/Year]	Min. CO_2 Reduction [t/Year]	Max. CO_2 Reduction [t/Year]
Norwegian Sky	1999	1928	72.0	12.6	5444	19,599	5172	18,619
Norwegian Sun	2001	1976	44.8	7.8	3387	12,195	3218	11,585
Norwegian Star	2001	2348	58.8	10.3	4446	16,006	4224	15,205
Norwegian Dawn	2002	2340	58.8	10.3	4446	16,006	4224	15,205
Norwegian Spirit	1998	2018	58.8	10.3	4446	16,006	4224	15,205
Norwegian Jewel	2005	2376	72.0	12.6	5444	19,599	5172	18,619
Norwegian Jade	2006	2402	72.0	12.6	5444	19,599	5172	18,619
Norwegian Pearl	2006	2394	72.0	12.6	5444	19,599	5172	18,619
Norwegian Gem	2007	2394	72.0	12.6	5444	19,599	5172	18,619
Norwegian Epic	2010	4100	79.8	14.0	6034	21,722	5732	20,636
Norwegian Breakaway	2013	3963	62.4	10.9	4718	16,985	4482	16,136
Norwegian Getaway	2014	3963	62.4	10.9	4718	16,985	4482	16,136
Norwegian Escape	2015	4266	76.8	13.4	5807	20,905	5517	19,860
Norwegian Joy	2017	3833	76.8	13.4	5807	20,905	5517	19,860
Norwegian Bliss	2018	4002	76.8	13.4	5807	20,905	5517	19,860
Norwegian Encore	2019	3998	76.8	13.4	5807	20,905	5517	19,860
Norwegian Prima	2022	3099	50.4	8.8	3811	13,719	3620	13,033
Norwegian Viva	2023	3215	50.4	8.8	3811	13,719	3620	13,033
Norwegian Aqua	2025	3571	50.4	8.8	3811	13,719	3620	13,033
Pride of America	2005	2186	50.4	8.8	3811	13,719	3620	13,033
Total:		60,372	1294.6	226.5	94,076	338,674	89,372	321,741

Based on the Norwegian Cruise Line (NCL), if it is assumed that their cruise ships make an average of six port calls per week, with port stays ranging from 5 to 10 h, and operate for 25 to 45 weeks per year, and if 17.5% of the installed power is applied for hoteling on each vessel, it is possible to estimate CO_2 emissions in ports for the entire NCL fleet and the potential reduction in CO_2 emissions if cruise ships were to connect to the electrical power grid while in port instead of relying on burning diesel fuel.

Given that Norwegian Cruise Line (NCL) represents approximately 8.3% of the total passenger capacity of the global cruise fleet [20], the potential reduction in global CO_2 emissions attributable to a 95% adoption of onshore power supply (OPS) by NCL can be:

$$\text{Max. potential global } CO_2 \text{ emission reduction} = 321{,}741/0.083 = 3{,}876{,}393 \ [\text{t } CO_2/\text{year}] \quad (4)$$

$$\text{Mi. Potential global } CO_2 \text{ emission reduction} = 89{,}372/0.083 = 1{,}076{,}771 \ [\text{t } CO_2/\text{year}] \quad (5)$$

5. Luxury Yachts

The problem of pollution from billionaire superyachts is even more pronounced. Large yachts consume substantial amounts of marine diesel, releasing carbon dioxide (CO_2), nitrogen oxides (NOx), and sulphur oxides (SOx), which contribute to climate change, air pollution, and acid rain. The recreational boating sector, including yachts, produces around 16 million tonnes of CO_2 annually, representing about 0.05% of global emissions [36].

The luxury superyacht industry is also experiencing rapid growth. According to Boat International data cited by Francesca Marchese [37], 1024 superyachts were built or on order in 2022, a 25% increase from 2021. The number rose to 1203 in 2023 and is projected to reach 1138 in 2024, with a growing trend toward larger vessels. As of early 2024, the global fleet included about 5787 active superyachts (over 30 m), while the number of luxury yachts over 24 m exceeds 40,000 [37].

Superyachts are extremely fuel-intensive, with some mega-yachts consuming up to 500 L of marine diesel per hour, resulting in a disproportionately large carbon footprint. Their environmental impact is further intensified because they often operate as floating hotels powered by onboard generators, which may emit even more CO_2 than propulsion engines [37–39]. The annual emissions of the world's 300 largest superyachts alone are estimated at nearly 285,000 tonnes of CO_2. Meanwhile, the global fleet has expanded from fewer than 2000 vessels around 2000 to nearly 6000 today, and the market is expected to roughly double in the coming decade.

Super Yacht Azzam—Case Study

The largest private superyacht in the world is Azzam, with an overall length of 180 m. The vessel is equipped with four propulsion units: two diesel engines (2 × MTU diesel engines rated at 17,524 kW each) and two gas turbines (2 × GE gas turbines rated at 17,524 kW each), resulting in a total installed power of approximately 70 MW [40]. The annual operating costs of Azzam are estimated at USD 60–65 million, corresponding to roughly 10% of the yacht's construction cost, with a crew of approximately 80 personnel. The weekly charter cost alone is reported to be in the range of USD 6–7 million. Given these characteristics, an important question arises: what is the annual carbon dioxide (CO_2) emission associated with the operation of the world's largest private superyacht?

Marine gas turbines provide a high power-to-weight ratio, making them well suited for high-speed vessels; however, they generally exhibit higher fuel consumption than diesel engines, particularly under part-load conditions. According to [17], the specific fuel consumption (SFC) of modern marine gas turbines typically ranges from 0.20 to 0.27 kg/kWh, with higher-power units achieving improved efficiency and thus lower SFC values. In this case study, an SFC of 0.215 kg/kWh is adopted to represent the performance of advanced gas turbines installed on high-end yachts.

Assuming a specific fuel oil consumption (SFOC) for marine diesel oil of 0.185 kg MDO per kWh [2,9], the carbon dioxide emissions can be estimated as follows:

For top speed (≈32 kn), Azzam yacht uses all four engines, with total power

$$4 \times 17{,}524 \text{ kW} = 70{,}096 \text{ kW};$$

The top speed fuel consumption rate is

$$35{,}048 \text{ kW} \times 0.185 \text{ kg/kWh} + 35{,}048 \text{ kW} \times 0.215 \text{ kg/kWh} = 14{,}019.2 \text{ kg fuel/h};$$

For cruise speed (≈18 kn), Azzam yacht uses two diesel engines with power

$$2 \times 17{,}524 \text{ kW} = 35{,}048 \text{ kW};$$

Cruising fuel consumption rate is

$$35{,}048 \text{ kW} \times 0.185 \text{ kg/kWh} = 6483.9 \text{ kg MDO/h};$$

Typical average hours underway for super yachts are roughly 500 h per year (around 5–10% of the year), where the assumed split sea time is 95% cruise and 5% sprint [39].

Then, the fuel required for propulsion per year can be calculated as

$$475 \text{ h} \times 6.5 \text{ t/h} + 25 \text{ h} \times 14 \text{ t/h} \approx 3430 \text{ t fuel/year};$$

CO_2 factor for marine diesel oil (MDO) is 3.082 t of CO_2 per tonne of fuel.

Then, there is the CO_2 emission from propulsion:

$$3430 \text{ t fuel/year} \times 3.082 \text{ tCO}_2\text{/t MDO} = 10{,}572.3 \text{ t of CO}_2\text{/year};$$

Generator operation while the yacht is at anchor or berthed in port, supplying onboard hotel services, has been shown in numerous studies to account for approximately 50% or more [39] of a yacht's total greenhouse gas (GHG) footprint. Based on this assumption, the total annual carbon dioxide emissions of the Azzam superyacht are estimated to be approximately 21,145 tonnes of CO_2 per year.

A realistic engineering uncertainty range of ±10–20% may be assumed; however, a more accurate estimation is not possible due to the lack of operational data, particularly regarding the yacht's operating profile, including duration of use and speed.

According to Eurostat [41], the average greenhouse gas footprint in the European Union in 2022 amounted to 10.7 tonnes of CO_2 equivalents per capita. On this basis, the annual emissions of the superyacht Azzam alone are comparable to the total yearly greenhouse gas footprint of approximately 1710 EU residents. This comparison highlights the disproportionate environmental impact associated with the operation of a single luxury yacht.

Furthermore, according to dezeen.com [42], the yacht refitting company MB92 Group estimates that a superyacht can generate up to 7020 tonnes of CO_2 annually, corresponding to more than 1500 times the emissions of a typical family car. The same source reports that the combined emissions of the 300 largest superyachts in regular operation exceed those of Burundi's population of approximately 13 million inhabitants.

6. Cruise Ship Engines and Fuels

6.1. Modern Eco-Friendly Cruise Ship Engines

Icon of the Seas, part of Royal Caribbean Group, is a new ship in its fleet from 2024, the newest and largest cruiser in the world, which costs about USD 2 billion. This colossal cruise ship has six huge Wärtsilä 46DF dual-fuel engines (3 × 14V46DF, with a power of

16,030 kW each; and 3 × Wärtsilä 12V46DF, with a power of 13,740 kW each) with a total power of 89.31 MW and burns combined about 10 tonnes of fuel every hour [43]. It means that for a one week trip, this cruiser alone burns fuel worth one million USD. Icon of the Seas emissions amount to 180,000 tonnes CO_2 per year, equal as small town in the EU with a population of around 20,000.

MSC Euribia, from MSC Cruises, first set sail in June 2023. MSC Euribia is twice as cheap as Icon of the Seas, and has also four Wärtsilä dual-fuel engines (2 × 16V46DF, with a power of 18,320 kW each and 2 × 12V46DF, with a power of 13,740 kW each) with a total power of 64.1 MW. MSC Euribia emits 19% less greenhouse gas per passenger per day than her sister ships running on traditional fuels. It also emits 44% less greenhouse gas daily than vessels constructed a decade ago.

These Wärtsilä 46DF four-stroke dual-fuel engines [43] can be run on liquefied natural gas (LNG), heavy fuel oil (HFO), marine gas oil (MGO), or marine diesel oil (MDO). This meets the IMO Tier III standards. According to Finnish engine producer data, Wärtsilä 46DF dual-fuel engines in gas mode have 20–25% less CO_2 emissions than diesel-fuelled engines, 85% lower emissions of NOx, and an up to 99% reduction in sulphur and particulates.

Diesel cruise engine pollution is significant, but environmental experts warn that LNG can be even more harmful than diesel due to its higher methane emissions, a very potent greenhouse gas.

The main problem with LNG-fuelled ship engines is methane slip. This refers to the leakage of methane (CH_4), a primary component of LNG, during the combustion process, rather than being fully burned. Studies indicate that methane slip from cruise ship engines can be a significant portion of the total emissions, even 6.4%. Methane slip can vary depending on the engine's load, and may be higher at lower engine loads. Methane is a far more potent greenhouse gas than carbon dioxide (CO_2) over a shorter time horizon. While LNG burns more cleanly than traditional marine fuel, this methane slip can negate some of the CO_2 reduction benefits. Although the average fuel consumption of a cruise ship using LNG is lower than the consumption of standard diesel fuels, LNG requires pressurized reservoirs at very low temperatures. Additionally, many ships built with LNG capabilities continue to rely on heavy fuel oil during parts of their journeys. The environmental think tank Transport & Environment estimated that Europe's LNG-powered cruise ships emitted methane in amounts equivalent to those produced by approximately 62,000 cows in 2022, while a single cruise ship emitted methane comparable to that produced by about 10,500 cows per year.

6.2. Cruisers and Yachts Fuels

There are several marine fuels used for cruisers and yachts:

(1) Heavy Fuel Oil (HFO)—A residual fuel oil left after refining crude. Although very cheap, it is highly polluting and is still used in older ships, particularly outside Emission Control Areas (ECAs).

(2) Marine Diesel Oil (MDO)—A lighter form of fuel than HFO, distillate-based, cleaner but more expensive. Commonly used for auxiliary engines and backup generators.

(3) Marine Gas Oil (MGO)—A high-grade distillate with low sulphur content. Preferred in Emission Control Areas (ECAs).

(4) Very Low Sulphur Fuel Oil (VLSFO)—A blended fuel that meets IMO 2020 sulphur cap ($\leq$0.5%). Widely adopted post-2020 as an HFO substitute.

(5) Liquefied Natural Gas (LNG)—Methane (CH_4) stored at -162 °C, and burns much cleaner than oil-based fuels. The problem is methane leak.

(6) Methanol (MeOH)—Cleaner-burning alcohol fuel, and can be produced renewably. The technology is in the early adoption phase. Methanol is currently the most practical solution, but it only provides partial decarbonization unless produced renewably.

(7) Hydrogen (H_2)—Emission-free if produced with renewable energy ("green hydrogen"). However, this technology remains experimental and has so far been applied only to small vessels. Hydrogen offers the highest sustainability potential, but faces major feasibility and regulatory barriers.

(8) Biofuels—Renewable fuels from organic sources like algae or cooking oil. Some lines are testing blends with diesel for carbon reduction.

(9) Ammonia—Carbon-free if made from green sources. An emerging fuel for future-ready ships, still in R&D and not yet commercially used.

(10) Battery (Electric)—Stored electricity used in hybrid systems or fully electric ferries. Used for hybrid or short-distance ships (not practical for long cruises). Battery-electric propulsion for cruise ships is technically feasible only for short distances or hybrid operation due to current energy density and storage limits, but it offers high sustainability with near-zero operational emissions when powered by renewable electricity.

Policy frameworks (especially from the IMO) are decisive in shaping adoption, yet regulatory uncertainty remains a key bottleneck.

Many ships operate on heavy fuel oil (HFO) and use exhaust gas after-treatment systems such as scrubbers or selective catalytic reduction (SCR) to reduce emissions, while improvements in internal combustion engine design and performance also play a significant role in emission reduction strategies [44]. Marine scrubbers remove particulate matter and pollutants, particularly sulphur oxides (SOx) and partly nitrogen oxides (NOx), from exhaust gases. However, although widely installed to meet sulphur regulations, scrubbers often transfer pollutants from the air to the marine environment, causing ecological damage.

Selective catalytic reduction (SCR) is an advanced active emissions control technology that reduces nitrogen oxides (NOx) in exhaust gases to near-zero levels in modern diesel-powered marine engines [11,18].

A major limitation is the incomplete life-cycle assessment (LCA), especially for LNG and biofuels. Methanol and biofuels studies are limited by feedback variability and supply constraints. There are also uncertainties related to future fuel prices, availability and policy frameworks.

Ammonia and hydrogen as fuels and batteries for cruise ships were not further analysed because they are not in commercial use, i.e., they are still in the R&D phase.

7. ANN and MCDM Methodology

The application of the ELM model within an MCDM problem is particularly justified in systems with pronounced nonlinear dynamics, such as transportation, energy, and logistics systems, where criteria often interact in a complex manner. By integrating the artificial intelligence approach [45–47] into the classical multi-criteria framework [48–53], a methodological synthesis is achieved, combining the objectivity of statistical methods with the flexibility of neural networks, thereby enhancing the reliability and interpretability of the decision-making process.

For clarity and reproducibility, the complete ANN (ELM)–MCDM (RAWEC) procedure applied in this study can be summarized as follows:

(1) Construction of the decision matrix based on defined alternatives and criteria;

(2) Normalization of the decision matrix for benefits and cost criteria;

(3) Definition of the target output vector as the aggregated performance of alternatives;

(4) Training of the ELM model and analytical determination of output weights;

(5) Nonlinear criterion contribution and weight coefficients derivation;

(6) Application of the RAWEC method, including normalization, weighting, deviation calculation, and final ranking of alternatives.

This structured procedure ensures full transparency and enables straightforward implementation and replication of the proposed methodology.

The overall research framework of the proposed ANN/ELM–MCDM/RAWEC methodology is illustrated in Figure 5. Furthermore, it provides a clear visual link between the machine learning and MCDM components of the framework.

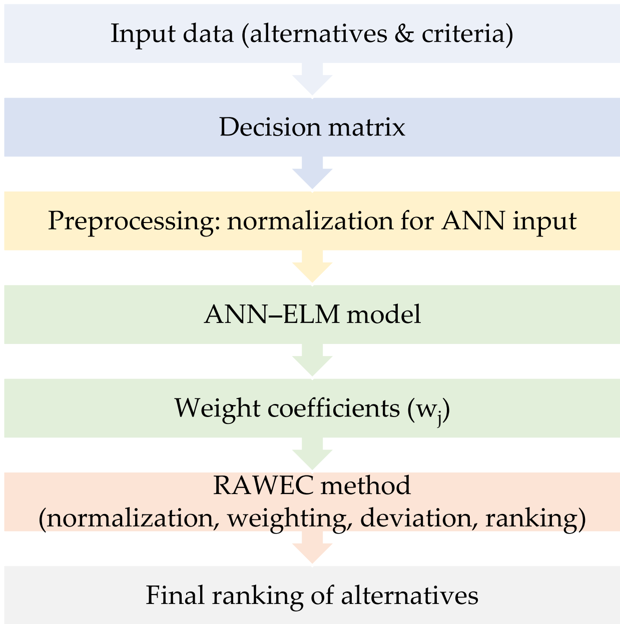

Figure 5. Framework of the proposed ANN (ELM)–MCDM (RAWEC) methodology.

All computations were performed in MATLAB 2018b, ensuring reproducibility of the obtained results.

7.1. ANN/ELM for Determining Weight Coefficients

Determining weight coefficients represents a central phase within multi-criteria decision-making, as the weights directly influence the evaluation and final ranking of alternatives [54–58]. In classical approaches, weights are assigned either subjectively, based on expert judgments, or objectively, using statistical measures of data dispersion. Although such methods are widely accepted, they implicitly assume a linear structure of relationships between criteria and do not account for possible nonlinear interactions. To overcome these limitations, this study applies an approach based on artificial neural networks, specifically the Extreme Learning Machine (ELM) model [30,31].

Let the decision matrix be given as follows:

$$X = [x_{ij}] \in R^{mxn} \tag{6}$$

where m is the number of alternatives, n is the number of criteria, and x_{ij} is the value of alternative A_i with respect to criterion C_j. The objective is to determine the weight vector [30,31],

$$w = (w_1, w_2, \ldots, w_n)^T \tag{7}$$

subject to the non-negativity and normalization conditions:

$$w \geq 0, \sum_{j=1}^{n} w_j = 1 \tag{8}$$

In the first step, the decision matrix is normalized to bring all criteria onto a comparable scale. For benefit criteria, the following expression is used:

$$x'_{ij} = \frac{x_{ij} - min_i x_{ij}}{max_i x_{ij} - min_i x_{ij}} \tag{9}$$

For cost criteria, the following transformation is applied:

$$x'_{ij} = \frac{max_i x_{ij} - x_{ij}}{max_i x_{ij} - min_i x_{ij}} \tag{10}$$

In this way, the normalized matrix $X^{\backslash} \in R^{mxn}$ is obtained, which represents the input space of the neural network.

To enable training of the ELM model, the output vector is defined:

$$Y = (y_1, y_2, \ldots, y_m)^T \tag{11}$$

where, in the neutral case, the aggregate value of an alternative is determined as the arithmetic mean of the normalized criteria:

$$y_i = \frac{1}{n}\sum_{j=1}^{n} x^{\backslash}_{ij} \tag{12}$$

In this way, the ELM model approximates the functional relationship:

$$f : R^n \to R, \tag{13}$$

that is, the mapping from the criteria space to the overall performance space of the alternatives.

The Extreme Learning Machine represents a single-layer feed-forward neural network with a hidden layer of L neurons. The input weights and bias values are generated randomly:

$$W \in R^{nxL},\ b \in R^{1xL} \tag{14}$$

The hidden layer output is formed as follows [29,30]:

$$H_{ik} = g\left(\sum_{j=1}^{n} w_{jk} x^{\backslash}_{ij} + b_k\right) \tag{15}$$

where g(z) is a nonlinear activation function (e.g., sigmoid function $g(z) = \frac{1}{1+e^{-z}}$). This yields the hidden layer matrix:

$$H \in R^{mxL} \tag{16}$$

Unlike classical neural networks, ELM determines the output weights analytically by solving a linear system [30,31]:

$$H\beta = Y \tag{17}$$

where the minimum-norm solution is given by the following expression [30,31]:

$$\beta = H^{+}Y \tag{18}$$

where H+ is the Moore–Penrose pseudo inverse of matrix H [30,31]. This approach enables a closed-form solution without iterative optimization, ensuring numerical stability and high efficiency. After training the model, the contribution of each criterion is determined by analysing the combined effect of the input and output weights. The total nonlinear contribution of criterion C_j is defined as follows:

$$I_j = \sum_{k=1}^{L} \left| \beta_k \cdot w_{jk} \right| \tag{19}$$

which represents a global measure of its influence on the decision function. These values are then normalized to obtain the final weight coefficient [30,31]:

$$w_j = \frac{I_j}{\sum_{j=1}^{n} I_j} \tag{20}$$

In this way, the weight coefficients represent the result of a global optimization of the nonlinear approximation function and reflect the true data structure and interdependencies among criteria. Unlike entropy- or correlation-based methods, the ANN–ELM approach enables modelling of complex interactions between criteria and the identification of their combined contribution to the overall performance of alternatives. This ensures greater robustness, analytical depth, and methodological consistency in the process of determining weights within multi-criteria decision-making.

To ensure methodological transparency and reproducibility of the proposed ANN–ELM approach, the training settings and validation procedure are explicitly defined as follows.

The dataset used for training the ELM model is derived from the normalized decision matrix and consists of m = 8 alternatives and n = 8 criteria, forming an input matrix of dimension 8 × 8. The corresponding output vector is defined as the arithmetic mean of normalized criteria values for each alternative, representing a neutral aggregation scenario.

The Extreme Learning Machine is implemented as a single-hidden-layer feed-forward neural network with L = 20 hidden neurons. A sigmoid activation function is employed in the hidden layer, while input weights and biases are randomly generated in accordance with the standard ELM algorithm. The output weights are computed analytically using the Moore–Penrose pseudo-inverse, ensuring a unique and stable solution without iterative optimization.

Given the relatively small dataset, model robustness was evaluated through multiple runs with different random initializations of input parameters. The obtained results showed negligible variations in the calculated output weights and derived criterion importance, confirming the stability and consistency of the model.

7.2. MCDM/RAWEC for Ranking Alternatives

The weight coefficients obtained from the ANN–ELM model (Section 9.1) are used as input parameters in the subsequent RAWEC method for ranking the alternatives.

The construction of the decision matrix constitutes the initial phase in every MCDM approach [59–62]. In this stage, the considered alternatives are evaluated according to previously defined criteria, which lead to the development of the primary decision matrix.

The second phase involves the normalization of the decision matrix, which represents an essential procedure within MCDM techniques, including the RAWEC method [63–66]. In this approach, the original matrix undergoes a double-normalization procedure through the application of Equations (21) and (22) [67,68].

For benefit-type criteria (those intended for maximization), normalized scores are determined using

$$n_{ij} = \frac{x_{ij}}{x_{j\,max}},\; n_{ij}^{*} = \frac{x_{j\,min}}{x_{ij}} \tag{21}$$

For cost-type criteria (those intended for minimization), normalized scores are obtained by applying

$$n_{ij} = \frac{x_{j\,min}}{x_{ij}},\; n^*_{ij} = \frac{x_{ij}}{x_{j\,max}} \tag{22}$$

In Equations (21) and (22), x_{jmin} indicates the lowest value among the alternatives for a given criterion, whereas x_{jmax} denotes the highest value recorded for that same criterion.

The third phase integrates the weighting procedure of the normalized matrix with the determination of deviations relative to the criterion weights [68]. This step is performed by implementing Equations (23) and (24):

$$v_{ij} = \sum_{i=1}^{n} w_j \cdot (1 - n_{ij}) \tag{23}$$

$$v^*_{ij} = \sum_{i=1}^{n} w_j \cdot \left(1 - n^*_{ij}\right) \tag{24}$$

Here, w_j represents the weighting coefficients assigned to the criteria.

For the first deviation value (v_{ij}), a lower magnitude is considered more favourable, while for the second deviation measure (v^*), a higher magnitude is preferred. These deviation measures are subsequently utilized to compute the overall performance scores of the alternatives [68].

Finally, the fourth phase consists of generating the ranking of alternatives by the RAWEC method [68], carried out through the application of Equation (25):

$$Q_i = \frac{v^*_{ij} - v_{ij}}{v^*_{ij} + v_{ij}} \tag{25}$$

The RAWEC method produces evaluation outcomes within the interval from −1 to 1 [68]. The final ranking is obtained by ordering the alternatives in descending sequence according to their calculated scores, where the alternative with the greatest value is identified as the optimal choice.

Based on the described methodology, the input data and obtained results are presented in the following section.

7.3. Input Data and Obtained Results

In order to compare and rank different fuels used in marine engines, a set of environmental pollution criteria is first defined. The assessment considers emissions of the following air pollutants: carbon dioxide (CO_2), nitrogen oxides (NOx), sulphur oxides (SOx), carbon monoxide (CO), particulate matter (PM), and methane (CH_4). In addition, the analysis includes the fuel price-to-consumption ratio as an economic indicator, as well as the potential impact of each fuel on water pollution.

The fuels considered in this MCDM analysis are those most commonly used in current marine practice, together with several alternative fuels that are either being tested in existing marine engines or for which new engine designs are under development.

These fuels (A_1–A_8) include HFO (2.6% S), HFO with a scrubber, VLSFO (0.5% S), MDO (0.5% S), MGO (0.1% S), LNG, B30, and grey methanol (MeOH).

Regarding methanol (MeOH), the price is expressed on an energy-equivalent basis relative to conventional marine fuels.

The optimization criteria (C_1–C_8, respectively) considered in this study include emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), sulphur oxides (SOx), carbon monoxide (CO), particulate matter (PM), and methane (CH_4), as well as the fuel cost-to-consumption ratio and the potential impact on water pollution. The impact of each fuel on water pollution (C8) is presented based on a quantitative assessment, using a numerical scale from 1 to 9, where 9 represents the most harmful water pollutant and 1 the least.

It should be noted that the input data used in this study are primarily derived from secondary literature sources and represent typical average values for marine fuels and propulsion systems. Key parameters, including specific fuel oil consumption (SFOC), engine load factors, and hoteling energy demand, are based on standardized assumptions commonly adopted in the literature.

Although this introduces a degree of uncertainty, all assumptions are applied consistently across the considered alternatives, ensuring comparability of results. Since the objective of the study is to provide a relative evaluation and ranking of fuels, rather than an absolute quantification of emissions, the impact of input data variability on the final results is considered limited.

For illustration, the normalization procedure can be demonstrated using criterion C_1 (CO_2), which is treated as a cost criterion. Based on the data in Table 15, the minimum and maximum values are x_{min} = 1.375 and x_{max} = 3.206. For alternative A_1, where x_{11} = 3.114, the normalized value is calculated according to Equation (8):

$$r_{11} = (3.206 - 3.114)/(3.206 - 1.375) = 0.050$$

This example illustrates the transformation of the original decision matrix into the normalized matrix used as the input for the ANN–ELM model and the subsequent RAWEC analysis. The same procedure is consistently applied to all criteria and alternatives.

Table 15. Cruisers' fuel and emissions data for ANN/MCDM.

		C_1 min	C_2 min	C_3 min	C_4 min	C_5 min	C_6 min	C_7 min	C_8 min
		CO_2 [g/g fuel]	NOx [g/kWh]	SOx [g/kg fuel]	CO [g/kWh]	PM [g/kWh]	CH_4 [g/kWh]	Fuel Price [Ratio]	Water Pollution
A_1	HFO (2.6% S)	3.114	11.5	52	0.4	0.75	0	1	8
A_2	HFO (2.6% S) scrubber	3.114	11	12.5	0.4	0.1	0	1	9
A_3	VLSFO (0.5% S)	3.176	11	10	0.3	0.2	0	1.018	7
A_4	MDO (0.5% S)	3.190	10	10	0.3	0.25	0	1.274	6
A_5	MGO (0.1% S)	3.206	9	2	0.3	0.1	0	1.240	5
A_6	LNG (methane)	2.750	2.5	0.75	1.5	0.01	5.6	1.060	1
A_7	Biofuel-B30 (0.5% S)	2.4	7.5	0.007	7	0.2	0	1.524	4
A_8	Gray Methanol MeOH	1.375	4	0	3.7	0.1	0.02	1.367	2

8. Results and Discussion

The obtained weighting coefficients clearly reflect the relative importance of the considered criteria within the applied multi-criteria decision-making model. The sulphur oxide (SOx) emission criterion carries the highest weight (0.229), indicating its dominant influence in the evaluation of alternatives. This implies that fuels with higher SOx emissions are significantly penalized, while low-sulphur alternatives achieve more favourable scores. Additionally, nitrogen oxide emissions (NOx = 0.167) and fuel cost (0.146) also contribute substantially, emphasizing the balance between environmental and economic aspects. Other criteria, including CO_2, CH_4, CO, PM emissions, and water pollution, have lower weights but still affect the final ranking. Overall, the weighting distribution highlights the prioritization of environmental criteria, in line with sustainable development requirements.

Based on the values presented in Table 15, a normalized decision matrix is constructed, after which, by applying the previously defined mathematical expressions (5–18), the input dataset for the ANN–ELM model is generated. Using the aforementioned equations for forming the hidden-layer matrix H, calculating the output weights β, and determining the criterion contributions w_j, a quantified measure of the global influence of each criterion is obtained.

Normalization of these values is performed according to Equation (18), which satisfies the unit-sum condition. The resulting weight coefficients, presented in Table 16, represent the output of the ANN–ELM approximation model based on the data structure from Table 15.

Table 16. Cruisers' fuel and emissions data for MCDM.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	Q_i	Rank	
					min						
w_j	0.121	0.167	0.229	0.093	0.074	0.112	0.146	0.058			
A_1	3.114	11.5	52	0.4	0.75	0	1	8	0.01769	7	HFO (2.6% S)
A_2	3.114	11	12.5	0.4	0.1	0	1	9	0.02882	6	HFO with scrubber
A_3	3.176	11	10	0.3	0.2	0	1.018	7	0.05049	4	VLSFO (0.5% S)
A_4	3.190	10	10	0.3	0.25	0	1.274	6	0.04249	5	MDO (0.5% S)
A_5	3.206	9	2	0.3	0.1	0	1.24	5	0.06937	3	MGO (0.1% S)
A_6	2.750	2.5	0.75	1.5	0.01	5.6	1.06	1	0.28240	1	LNG (methane)
A_7	2.4	7.5	0.007	7	0.2	0	1.524	4	0.19155	2	Biofuel-B30
A_8	1.375	4	0	3.7	0.1	0.02	1.367	2	−0.73411	8	Gray Methanol

Starting from the values presented in Table 15 and applying the previously defined mathematical expressions (Equations (19)–(23)), the procedure for calculating the final values of the alternatives was conducted in accordance with the RAWEC methodology. Following normalization, weighting, and deviation determination, the aggregated values were obtained, which served as the basis for ranking the alternatives. The ranking results, presented in Table 16, constitute the final evaluation of the alternatives, where the alternative with the highest value occupies the first position and is considered the most favourable solution.

For each of the eight fuels considered (A_1–A_8) an analysis was performed according to the defined criteria (C_1–C_8) using the ANN/MCDM methodology. The weight coefficients w_j indicate the relative importance of each criterion in the overall fuel evaluation. The highest weights are assigned to SOx emissions (C_3, w_3 = 0.229) and NOx (C_2, w_2 = 0.167), highlighting the significance of air pollution reduction in assessing fuel sustainability, whereas criteria such as the impact on water pollution (C_8, w_8 = 0.058) carry lower significance in the overall weighting.

The ranking of alternatives indicates that the most favourable fuel is A_6 (LNG), which achieves the best balance between low emissions, acceptable cost, and minimal environmental impact, with a final value of Q_i = 0.28240 and rank 1. This is followed by A_7 (biofuel B30) at rank 2, while traditional heavy fuels (A_1 and A_2, HFO with and without scrubber) are ranked lower (7th and 6th), primarily due to high emissions and limited ecological suitability. The least desirable fuel is A_8 (MeOH) with Q_i = −0.73411 and rank 8, reflecting its combination of relatively high emissions of certain pollutants and economic disadvantage compared to the other alternatives.

These results indicate that the ANN/MCDM methodology enables an integrated evaluation of both environmental and economic criteria, favouring fuels with lower GHG emissions and reduced harmful pollutants, while conventional fossil fuels rank lower.

These findings provide a practical basis for decision-makers in maritime transport to support the selection of environmentally and economically sustainable fuel options.

To further examine the robustness of the obtained results, a simple sensitivity analysis was performed by varying the most influential weight coefficients (SOx and NOx) within a ±10% range, while maintaining normalization constraints. The ranking of the top alternatives remained unchanged, confirming the stability and reliability of the proposed ANN–MCDM framework. Minor variations were observed only among lower-ranked alternatives, without affecting the overall conclusions. No rank reversal was observed for the top three alternatives under the considered perturbations.

The stability of the top-ranked alternatives indicates low sensitivity of the model to moderate perturbations in key weights.

The findings confirm the capability of the proposed ANN/ELM–MCDM/RAWEC framework to capture complex nonlinear relationships among criteria and provide a consistent ranking of alternatives. This confirms the suitability of the approach for complex decision-making problems in maritime systems. The methodology enables an objective integration of environmental and economic aspects, ensuring robustness of the decision-making process. Future research should focus on incorporating real operational data and expanding the set of considered criteria to further improve model applicability. The results are based on literature-derived data, which may introduce a certain degree of uncertainty.

The following policy recommendations are proposed:

1. Invest in OPS infrastructure at major cruise ports, prioritizing high-traffic hubs.

2. New regulatory measures should mandate OPS usage where available, especially in densely populated port cities and tighten emissions for ships similar to passenger cars.

3. Establish progressive emission limits for hoteling operations, and provide subsidies or tax reductions for ships equipped with OPS compatibility and LNG systems.

4. Support R&D for low-slip or slip-free LNG engines and promote hybrid solutions, including battery storage.

5. Cruise operators should adopt dual strategies combining LNG propulsion with maximum OPS utilization.

6. Integrate OPS with renewables electricity to maximize lifecycle emission cuts.

Fuel substitution for low-carbon shipping should follow a phased approach: in the short term, it includes the adoption of onshore power supply (OPS) and methanol; in the medium term, a transition toward e-methanol combined with hybrid systems; and in the long term, the deployment of hydrogen-based zero-carbon propulsion.

9. Conclusions

This study evaluated marine fuel alternatives using an integrated ANN/ELM–MCDM/RAWEC framework under realistic operational conditions.

9.1. Technical Findings

The case study of the Norwegian Epic confirmed the applicability of the proposed methodology for estimating fuel consumption and CO_2 emissions. Total annual emissions were estimated in the range of 84,542–99,775 t CO_2, closely matching reported values (~95,000 t CO_2), while the average hoteling power demand was determined to be 17.08% of installed capacity. Scenario analysis showed that the implementation of onshore power supply (OPS), covering up to 95% of hoteling demand, can significantly reduce emissions of CO_2, NOx, SOx, and particulate matter in port areas.

The MCDM results indicate that LNG is the most favourable fuel option based on the selected criteria. However, due to operational constraints related to dual-fuel engine systems, LNG is not continuously utilized. Under such conditions, biofuel B30 represents a robust second-ranked alternative, while MGO (0.1% S) can be considered a complementary option.

Sensitivity analysis confirmed the robustness of the obtained ranking, as moderate variations in key weight coefficients did not significantly affect the relative performance of the top-ranked alternatives.

9.2. Policy and Practical Implications

The results highlight the importance of combining cleaner fuels with port electrification strategies such as OPS to achieve substantial emission reductions. The adoption of advanced engine technologies and exhaust gas cleaning systems can further enhance environmental performance and improve air quality in port communities.

9.3. Limitations and Future Research

Methane slip was not included in the present analysis, despite its significant impact on greenhouse gas emissions. Future research should explicitly incorporate methane leakage and focus on technological solutions aimed at minimizing or eliminating methane slip in LNG engines.

The proposed framework provides a structured and reliable basis for supporting sustainable fuel selection in maritime transport.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse gases
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent emission
CO	Carbon monoxide
BC	Black carbon
NOx	Nitrogen oxides
SOx	Sulphur oxides
PM	Particulate matter
CH_4	Methane
LNG	Liquefied natural gas—methane
HFO	Heavy fuel oil
MDO	Marine diesel oil
MGO	Marine gas oil
VLSFO	Very low sulphur fuel oil
MeOH	Methanol
H_2	Hydrogen
B30	Marine fuel with up to 30% of biodiesel

SFOC	Specific fuel oil consumption
GWP	Global warming potential
MCR	Maximum continuous rating
FCR	Fuel consumption rate
OPS	Onshore power supply
MCDM	Multi-criteria decision-making

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