

Assessment of emissions from the Croatian nautical charter fleet using Tier 1 methodology: insights from a 2023 pilot study



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ARTICLE INFO

Keywords:

Nautical tourism
Charter fleet
Sailboat
Yacht
Catamaran
CO₂ emission
Harmful emission

ABSTRACT

This study examines emissions from the rapidly growing nautical tourism sector in Croatia, a major hub for charter and leisure boat tourism, focusing on the significant emissions caused by vessels that lack advanced emission control systems. Despite intensive petrol and diesel consumption, emissions from this sector remain under-researched; this study addresses that gap using data from the Green Sail Association's Ecological Footprint Calculation Platform, collected during a 2023-24 pilot project in selected marinas in the Šibenik-Knin and Split-Dalmatia counties. The sample includes sailboats, yachts, and catamarans 10 to 20 m in length. Operational data (engine hours, fuel consumption, technical specifications) were gathered from charter companies and skippers. Emissions of CO₂, NO_x, CO, and PM were calculated using EMEP/EEA Tier 1 methodology based on fuel consumption and emission factors. Emissions rise with vessel length and are notably higher for catamarans due to greater fuel consumption. Though only 35 % of the sample, catamarans contributed nearly 60 % of total emissions. Based on the findings on the sample of 160 vessels, extrapolated to Croatia's fleet (~4,500 vessels), seasonal emissions are estimated at 30,000 to 40,000 t CO₂, 300 to 400 t NO_x, 100 to 150 t CO, and 15 to 25 t PM. This study represents the first large-scale emissions estimate for charter vessels and recommends further research with a more representative sample, broader geographical coverage and advanced methods such as Tier 3 calculations, collection of generator fuel consumption data and real-world emissions measurements to improve emission factors.

1. Introduction

The eastern Croatian Adriatic coast is one of the most intensively used areas for nautical tourism, especially for charter (rental) and leisure boat activities [1]. This is evidenced by the growing number of tourists using these services, as reported by the Croatian authorities via the eVisitor and eCrew web platforms [2]. The charter fleet plays an important role in the country's tourism sector - the largest economic sector in Croatia. However, this strong dependence on tourism has been explicitly recognized and critiqued by institutions such as the European Commission [3] and the OECD [4].

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The fleet of leisure vessels includes various types of boats such as speedboats, sailboats, and motor yachts. However, a significant part of this fleet, including sailing yachts, is primarily powered by petrol or diesel engines, which often require a considerable amount of fuel for navigation. These engines are generally not equipped with the latest or any emission control systems, resulting in significant emissions, especially from the propulsion engines.

Despite the considerable fuel consumption of recreational craft and the resulting emissions, little research has been done in this area. Emissions from the boating and nautical tourism sector, particularly the charter fleet, have not been sufficiently analysed and there is a lack of accurate data on total emissions. Given the growth of charter tourism, the resulting air pollution can have a significant impact, particularly in terms of emissions of carbon dioxide (CO₂), particulate matter (PM) and nitrogen oxides (NO_x). A key challenge in quantifying fuel consumption and emissions from the charter fleet is that fuel is supplied to different types of vessels at the same coastal stations, including private boats, fishing vessels, speedboats and jet skis, making it impossible to accurately isolate fuel consumption for the charter fleet alone. This research aims to address this gap by analysing the emissions (CO₂, NO_x, carbon monoxide (CO) and PM) of a segment of the Croatian charter fleet of vessels for nautical tourism (sailboats and yachts, length from 10 to 20 m, including catamarans).

Emissions from the rapidly growing nautical tourism sector, particularly the charter fleet, remain significantly under-researched despite considerable fuel consumption. A key challenge in quantifying these emissions has been the absence of systematically collected data on fuel consumption and related operational aspects; recreational craft emissions are often excluded from national inventories and Eurostat databases, and fuel supplies are difficult to accurately isolate for the charter fleet. This study directly addresses this critical gap, representing the first systematic collection of such data in Croatia, thereby providing the first large-scale emissions estimate for charter vessels and enabling preliminary conclusions regarding their environmental impact. While this foundational work offers invaluable initial insights, it is important to acknowledge that the collected data, derived primarily from questionnaires, has limitations and may not perfectly reflect the entire fleet's distribution or capture all operational specifics. Furthermore, to the best of current knowledge, similar comprehensive and systematic data collection studies focusing on charter fleet emissions have not been extensively documented in other Mediterranean countries, underscoring the novelty of this research in the broader regional context. A potential reason for this pervasive research gap may stem from a reluctance among stakeholders to rigorously investigate areas that could potentially disrupt the substantial revenue generated by nautical tourism, a sector upon which countries like Croatia are highly dependent. Having identified the research gap and the challenges in obtaining accurate emissions data for the Croatian nautical tourism charter fleet, this study is based on the central hypothesis that the emissions footprint of individual nautical tourism vessels and specific vessel categories can be determined by analysing data collected as part of a pilot project. As part of this pilot project, important information such as the average fuel consumption, the operating hours of the engines and the types of vessels and their engines were collected. By combining this empirical data with available emission factors, a quantitative assessment of the environmental impact is possible. Furthermore, the study assumes that by leveraging the data from this pilot project together with more comprehensive statistical data on nautical tourism, it will be possible to estimate emissions for a representative segment of the charter fleet, with a focus on vessels in the 12 to 15 m and 15 to 20 m length categories and on catamarans, for which a limited sample was collected.

2. Literature review

Maritime traffic is a major source of air pollution in harbour and coastal cities. Various recreational vessels, including sailboats with auxiliary engines, yachts, leisure boats and those used in nautical tourism and charter fleets, contribute to air emissions, with Non Methane Volatile Organic Compounds (NMVOC) and CO emissions from recreational boats being particularly significant at the local level during the high season and the growing number of leisure boaters expected to exacerbate these impacts [5, 6]. Emissions regulations vary depending on vessel size, with larger recreational craft (>24 m) subject to International Maritime Organization (IMO) regulations, while smaller vessels follow national or EU regulations such as the

Recreational Craft Directive, meaning that large yachts used in nautical tourism are also regulated. The Plan Bleu guidelines [7] emphasize that maritime transport, including recreational boating, is a significant source of air pollution (NO_x, SO₂, CO, CO₂, PM, O₃) and recommend the strict implementation of existing and harmonized legal requirements for nautical tourism, including cruise ships, yachts and smaller boats, to limit air emissions.

Diesel exhaust is of special public health concern, and since 2002 EPA has classified it as likely to be carcinogenic to humans by inhalation at environmental exposures [8]. EPA recognizes that these emissions from marine diesel engines contribute to ozone and CO nonattainment (i.e., failure to meet air quality standards), as well as adverse health effects associated with ambient concentrations of PM and visibility, haze, acid deposition, and eutrophication and nitrification of water. Of particular importance to human health in urbanized ports is the fact that around 95 % of the ship-generated total PM is of an aerodynamic diameter of less than two and a half microns in width, namely PM 2.5 [9]. In addition, the health effects of these air pollutants to residents of local communities include asthma, other respiratory diseases, cardiovascular diseases, lung cancer, and premature mortality. In children, there are links with asthma, bronchitis, missed school days, and emergency room visits [10].

A 2014 Baltic Sea study found that leisure boats emit significantly higher levels of NMVOCs (160 %) and CO (70 %) compared to commercial shipping, with these differences most pronounced during summer, while NO_x and PM emissions were less significant [11]. A study in the Australian region estimated annual greenhouse gas (GHG) emissions from the boating sector at 70,000 t of CO₂, with average emissions per tourist of 61 kg CO₂-e for diesel and 27 kg CO₂-e for petrol engine boat trips, including vessels used in nautical tourism [12]. The Direct Pollution Cost (DPC) approach provides a practical method for quantifying these environmental impacts in monetary terms by estimating the pollution burden and multiplying it by the unit cost of commercial environmental services. For example, air pollution from cruise ships, a sector closely linked to nautical tourism, has been estimated at €0.2413 per person per kilometre, with air emissions accounting for 98 % of the total direct pollution cost [13]. The Review Study on the EU Recreational Craft Directive of 2013 [14] notes that quantifying emissions from recreational craft is a challenge as emissions are not included in Eurostat databases or in national inventory reports at Member State level. The study suggests using the Tier 3 method from the EMEP/EEA Guidebook 2019 (Part B, 1.A Combustion, 1.A.3.d Navigation (shipping)), which provides guidance for estimating emissions from recreational craft [15]. A study in Swedish coastal waters presents the development of an advanced activity model for assessing activities and emissions from leisure boats. The model can estimate atmospheric emissions of PM, NMVOC, NO_x, SO_x, and CO, as well as direct emissions of copper and zinc from antifouling paints [16].

Limit values of harmful emissions for compression ignition engines used in vessels from nautical tourism charter fleet are set by Directive 2013/53/EU [17]. Directive 2013/53/EU of the European Parliament and of the Council of 20 November 2013 on recreational craft and personal watercraft in point 2 Exhaust emission requirements state propulsion engines shall be designed, constructed and assembled so that when correctly installed and in normal use, emissions shall not exceed the limit values. Engine power in typical vessels from nautical tourism charter fleet is several tens to a maximum of several hundred kilowatts (kW). Limit values for compression ignition engines with rated engine power $P_N < 37$ kW are for CO 5.0 g/kWh, hydrocarbons (HC) $1.5+2 \times P_N^{0.5}$ g/kWh, NO_x 9.8 g/kWh, and PM 1.0 g/kWh. This limit values for compression ignition engines with rated engine power $P_N < 37$ kW, typical engine for sailboat, have not changed since 2003. Limit values for compression ignition engines with rated engine power $37 \text{ kW} < P_N < 75$ kW are for CO 5.0 g/kWh, hydrocarbons + nitrogen oxides (HC+NO_x) 4.7 g/kWh, and PM 0.30 g/kWh and for compression ignition engines with rated engine power $P_N > 75$ kW are for CO 5.0 g/kWh, hydrocarbons + nitrogen oxides (HC+NO_x) 5.8 g/kWh, and PM 0.15 g/kWh.

Although emissions from recreational craft remain under-researched, studies from other maritime sectors, e.g. general cargo ships, show both the importance of vessel emissions and the effectiveness of operational strategies such as slow steaming to reduce them, comply with regulations such as the CII and contribute to the IMO's GHG reduction targets [18]. These developments illustrate the general evolution of regulation in the maritime industry, which could ultimately also be a model for the nautical tourism sector.

Despite its intensive petrol and diesel consumption, the nautical tourism sector, which contributes significantly to CO₂ emissions, has not yet been sufficiently researched. In contrast, the global shipping industry, including segments such as the yacht sector, is actively exploring ways to increase the use of renewable energy and optimise energy management in new energy yachts through the integration of technologies such as photovoltaics, fuel cells, and batteries [19].

3. Croatian Nautical Tourism: Fleet, Infrastructure, and Tourist Activity

The Croatian Adriatic coast, located on the eastern side of the Adriatic Sea, is saturated with intensive nautical tourism activity. In [20] authors claim that Croatia possesses one of the largest charter fleets in the world, with approximately 4,500 vessels, and that the rental of vessels, with or without a crew, is a key service within the country's nautical tourism industry. The infrastructure for nautical tourism includes a considerable number of ports for nautical tourism with a total capacity of 19,131 berths (as of 31 August 2023) published by the Croatian Bureau of Statistics and shown in Table 1 [21]. These berths or moorings are distributed across different vessel lengths, with more than half reserved for vessels between 10 and 15 metres in length. The coastline equipped for berths and moorings totals 75,118 metres, which is maintained by 2,500 employees, underlining the extensive capacity for nautical tourism. Croatia boasts a well-developed nautical infrastructure, including over 70 marinas, 167 ports for nautical tourism as of 2019 (up from 98 in 2009), and a growth in moorings from 16,848 in 2009 to 18,179 in 2019 [22].

The Croatian nautical fleet consists of a considerable number of vessels, totalling 3,906 sailboats and 42 motor yachts, which are actively in use in 2023. In terms of statistical data, nautical tourism vessels (sailboats and yachts) recorded 2,457,069 tourist overnights and 382,998 tourist arrivals for sailboats and 311,660 tourist overnights and 49,273 tourist arrivals for yachts in 2023 [23].

Based on this data, the average characteristics of Croatian nautical tourism in 2023 were calculated, resulting in an average of 6.6 overnight stays per arrival, 19.6 bookings (rentals) per vessel in the season and 129.5 rental days per vessel in the season. The average number of tourists per vessel was calculated at 5.8. These averages vary slightly depending on vessel type and length, with larger vessels tending to have slightly fewer overnight stays per arrival and bookings per vessel, but a higher number of tourists per vessel due to their larger accommodation capacity.

Table 1 Capacity of nautical ports and persons in employment, status as on 31 August 2023

| | |
|---|-----------|
| Water surface area, m ² | 4,823,256 |
| Number of moorings, total | 19,131 |
| Length of shoreline equipped for mooring, m | 75,118 |
| Number of berths for land storage | 7,102 |
| Number of employed persons, total | 2,042 |
| Of that with seasonal jobs | 467 |

Data on the total number of tourist overnight stays and arrivals on Croatian vessels for nautical tourism (sailboats and yachts) are taken from monthly and annual statistical data published by the Ministry of Sea, Transport and Infrastructure and shown in Table 2 [23].

Table 2 Total tourist overnights and arrivals on Croatian nautical tourism vessels (sailboats and yachts) in 2023

| Sailboats | | Yachts | |
|--------------------------|------------------------|--------------------------|------------------------|
| Total tourist overnights | Total tourist arrivals | Total tourist overnights | Total tourist arrivals |
| 382,998 | 2,457,069 | 49,273 | 311,660 |

Data on the total number of Croatian nautical vessels (sailboats and yachts) and the total number of vessels booked (rental) are taken from the annual statistical data published by the Ministry of Sea, Transport and Infrastructure and shown in Table 3 [23].

Table 3 Total number of Croatian nautical tourism vessels (sailboats and yachts) and total number of vessels booking in 2023

| | Active | Number of bookings* |
|-----------------------------------|--------|---------------------|
| Number of vessel rental companies | 1,003 | 83,324 |
| Number of sailboats | 3,906 | 72,847 |
| under 6 m | 7 | 23 |
| 6 - 8 m | 131 | 1,376 |
| 8 - 10 m | 395 | 6,223 |
| 10 -12 m | 3,073 | 59,824 |
| 12 - 15 m | 300 | 5,401 |
| Number of motor yachts | 42 | 489 |
| 15 - 20 m | 27 | 414 |
| over 20 m | 15 | 75 |
| Number of sailing yachts | 583 | 6,992 |
| 15 - 20 m | 305 | 4,612 |
| over 20 m | 278 | 2,380 |

* Note: Average duration of a booking = Total number of bookings per vessel / total rental days per vessel = 129.5 rental days per vessel / 19.6 bookings per vessel ≈ 6.6 days per booking

Based on the collected data, the average characteristics of Croatian nautical tourism in 2023 were calculated. For the calculation method, see Figure 1. Figure 1 presents the flowchart illustrating the calculation process. The average number of overnight stays per arrival is derived from the total number of tourist overnight stays on Croatian nautical tourism vessels (sailboats and yachts) and the total number of tourist arrivals. Additionally, by dividing the total number of tourists overnight stays by the total number of active Croatian nautical tourism vessels, the average number of overnight stays per vessel is determined. Finally, the average number of bookings (rentals) per vessel is calculated by dividing the total number of bookings (rentals) by the total number of active Croatian nautical tourism vessels. In addition, the average number of rental days per vessel can be calculated based on the average number of overnight stays per arrival and the average number of bookings (rentals) per vessel. Finally, by dividing the total number of overnight stays per vessel by the average number of rental days per vessel, the average number of tourists per vessel can be determined.

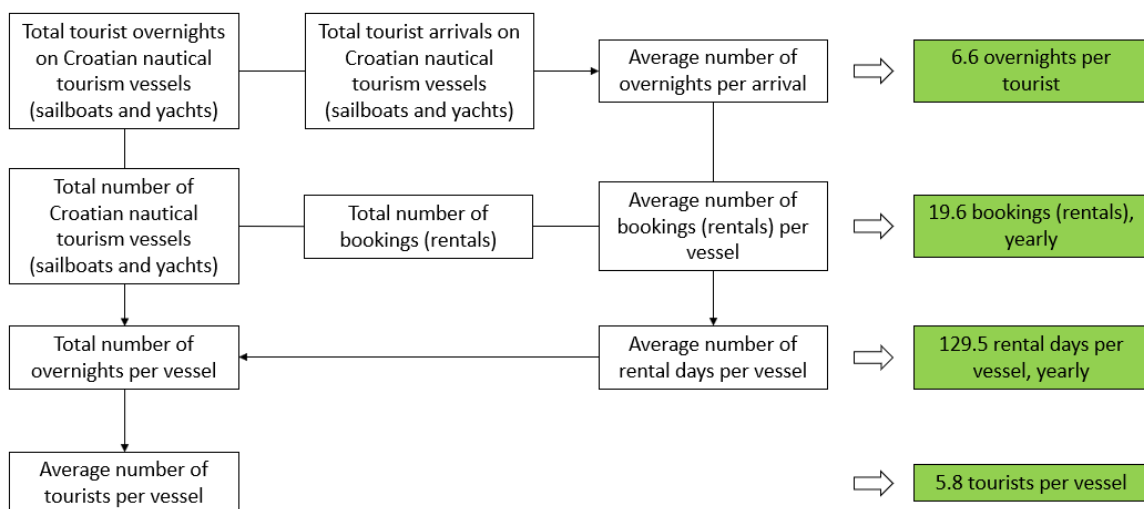


Fig. 1 The flowchart (scheme) of the calculation average number of nautical tourism in 2023

The calculated mean averages (6.6 overnight stays per arrival for tourists in nautical tourism, 19.6 bookings (rentals) per vessel per season, 129.5 rental days per vessel and season and 5.8 tourists per vessel) shown in Figure 1 are derived from overall nautical tourism statistics and enabled extrapolation of pilot project findings to the approximately 4,500 active vessels in the Croatian fleet. The number of overnight stays per arrival, bookings (rentals) per vessel and rental days per season vary slightly depending on the type and length of the vessel. Larger vessels tend to have slightly lower values, which is probably due to the higher rental costs. However, larger vessels accommodate more tourists on average, which is due to their greater capacity.

Calculated data on tourist preferences for different types of vessels are shown in Figure 2.

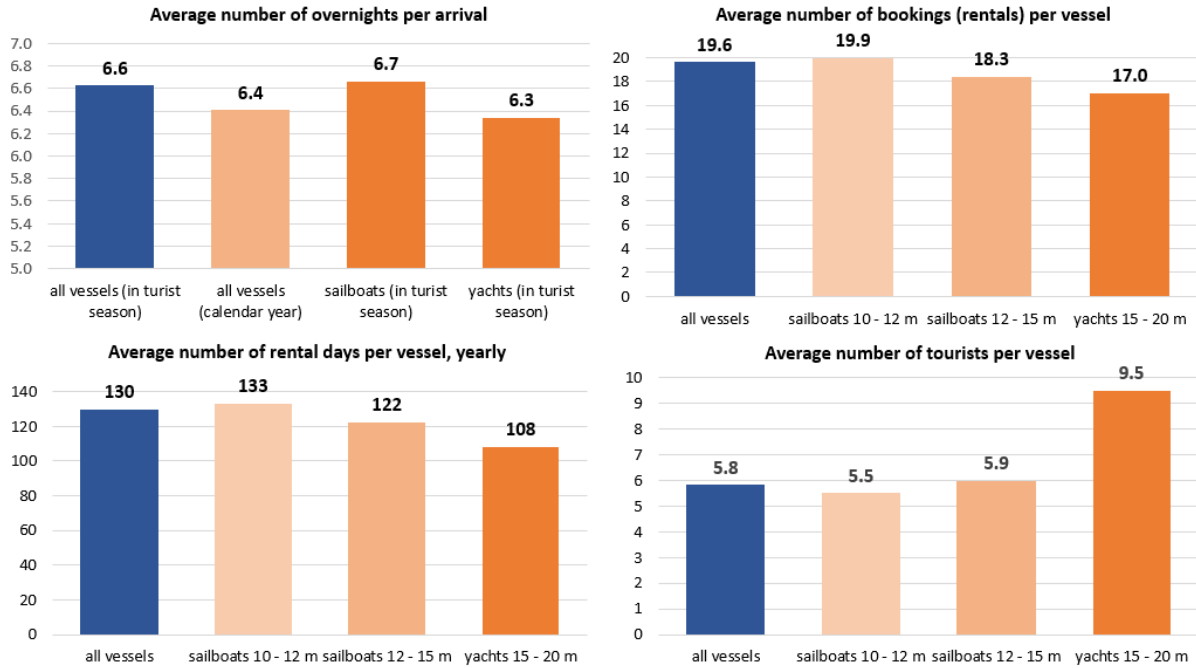


Fig. 2 Characteristic statistical average numbers of nautical tourism by type of nautical tourism vessels (sailboats and yachts)

4. Methodology, research description and data input

The methodology and input data for this study are primarily based on a pilot project conducted by the Green Sail Association in 2023-24 using their Ecological Footprint Calculation Platform. This research initiative focused on collecting detailed operational data from nautical tourism vessels (sailboats and yachts) using forms prepared by the authors and the Green Sail Association and completed by skippers and the responsible staff of partner charter companies (rental companies).

The geographical coverage of this pilot project encompassed selected nautical ports (marinas) within the Šibenik-Knin and Split-Dalmatia counties on the Croatian Adriatic coast (Figure 3). These two counties were selected as they account for a significant share of nautical tourism activity and revenue in Croatia, generating 48.7 % of the total income from nautical ports (Status as on 31 August 2023) [24].

The vessel groups included in the survey were sailboats and yachts (both motor and sailing), ranging in length from 10 to 20 meters, including catamarans. This segment accounts for 74.1 % of the total berth/mooring capacity (Status as on 31 August 2023) [24], representing the majority of the nautical charter tourism sector.



Fig. 3 Nautical ports of Croatian Adriatic counties (Šibenik-Knin and Split-Dalmatia) included in the Green Sail Association pilot project: Ecological Footprint Calculation Platform

The data analysed in this paper originates directly from this pilot project conducted by the Green Sail Association.

The Green Sail Association conducted the data collection efforts throughout 2023 and 2024 through a collaborative effort with their partner charter companies. The sample selection for the 2023 survey, which included a total of 160 nautical tourism vessels (146 with complete data), was based on random selection. The representativeness of the sample was considered in relation to the share of moorings for corresponding vessel lengths, with sailboats 12–15 m, yachts 12–15 m, and catamarans being well represented.

The classification of vessels in the survey also allowed for an analysis based on home port, vessel type, length and age, i.e. the average characteristics for different segments. The collected data was subjected to a systematic analysis categorised by vessel length, vessel type and marina location.

For each vessel that participated in the survey, the following key information was collected:

- Model, length and vessel type, including vessel manufacturer and model number.
- Year of manufacture and number of previous seasons as a charter vessel.
- Bed capacity (excluding saloon).
- Engine details, including type, number of engines, manufacturer, model, total operating hours, normal operating speed and average fuel consumption per hour (litres).
- Engine operating hours were recorded.
- The average fuel consumption was calculated.

Based on the recorded engine types, the corresponding emission factors were determined for the subsequent calculations.

The research was divided into several phases, which are listed below.

- Data Collection Forms: predefined forms were used to record engine operation, fuel consumption, vessel specifications, and propulsion system details.
- Data Entry: Data entry was carried out by the skippers and responsible personnel from the partner charter companies involved in the project.
- Geographical Coverage: The study focused on selected marinas located in the Šibenik-Knin and Split-Dalmatia counties on the Croatian Adriatic coast.
- Vessel Categories Covered: The pilot project included the following vessel categories:
 - Sailboats and yachts ranging from 10 to 12 m, 12 to 15 m, and 15 to 20 m in length.
 - Catamarans.

After analysis and evaluation of vessel segments activity and fuel consumption, using Tier 1 method and emission factors (EFs) from the EMEP/EEA Air Pollutant Emission Inventory Guidebook [25] CO₂, NO_x, CO and PM emissions are calculated. According to the Tier 1 method, total emissions are calculated based on total fuel consumption and corresponding EFs. Additionally, a brief demonstration of the Tier 3 method is also made. For this more complex method there is currently not enough collected data. Both, Tier 1 and Tier 3 methods are explained in more detail later along with the presented results.

5. Data analysis and statistical evaluation of vessel segments, fuel consumption, and operational trends

5.1 Sample size and representativeness

The survey provides valuable data for certain vessel segments, especially those in the 12-15 m and 15-20 m categories. However, smaller segments, and those with fewer vessels in the survey, are underrepresented, which may impact the robustness of the conclusions drawn for these groups. The 2023 survey consists of 160 vessels, representing just 3.5 % of the total vessels in the Croatian charter tourism market (4,531 vessels) as illustrated in Table 4. While the survey offers useful insights into the operational characteristics of vessels, the small sample size for certain segments, especially the larger ones, limits its statistical significance and generalizability.

Table 4 Comparison of vessels in charter tourism and vessels included in the 2023 survey by length segment

| Segment | Vessels in charter tourism | Vessels in 2023 survey |
|--------------|----------------------------|------------------------|
| under 6 m | 7 0.15 % | - |
| 6 - 8 m | 1312.89 % | - |
| 8 - 10 m | 3958.72 % | 1 0.63 % |
| 10 - 12 m | 307367.82 % | 19 11.86 % |
| 12 - 15 m | 3006.62 % | 95 59.38 % |
| 15 - 20 m | 3327.33 % | 44 27.50 % |
| over 20 m | 2936.47 % | 1 0.63 % |
| Total | 4531100.00 % | 160 100.00 % |

Comment on sample size, quality, and statistical representativeness per segment:

- Under 6 m: This segment is underrepresented in the survey, with only seven vessels in the charter market and none included in the survey. This limits the statistical significance for this group. At first glance, it is evident that this category is not important for the overall result.
- 6 to 8 m: Although there are 131 vessels in charter tourism, none were surveyed, making this segment poorly represented. The lack of data makes it difficult to draw reliable conclusions about this vessel category.
- 8 to 10 m: With 395 vessels in the charter market and only one included in the survey, this sample size is too small to yield statistically significant insights about the operational or environmental characteristics of this segment.
- 10 to 12 m: This segment has a larger sample size with 19 vessels surveyed out of 3,073 in the market, but the small proportion (0.6 %) limits statistical relevance.
- 12 to 15 m: The charter tourism segment comprises 300 vessels, of which 95 vessels were surveyed. This is an impressive 31.7 % of the segment, making it one of the better represented groups. This sample size provides a relatively high degree of reliability and ensures strong statistical representation.
- 15 to 20 m: With 332 vessels in the charter tourism market and 44 vessels in the survey, this segment is well represented at 13.3 % of the total segment. The survey data for this group can provide a reasonably reliable overview of the operational characteristics of larger vessels.

- Over 20 m: There are 293 vessels in the charter tourism market in this segment, with only 1 vessel participating in the survey. This minimal representation significantly limits the ability to draw reliable conclusions about this segment in the context of this study.

5.2 Organisation and classification of data

Vessels in the survey were grouped based on their home port (as defined by the maritime code), vessel type, length, and age (number of previous seasons in charter or production year). For each group, key metrics such as the number of vessels, average fuel consumption, average engine hours, average length, and average age were calculated. The results are generally presented by vessel length, as defined by the maritime code, and vessel type. Figure 4 illustrates the classification of vessels from the 2023 pilot survey.

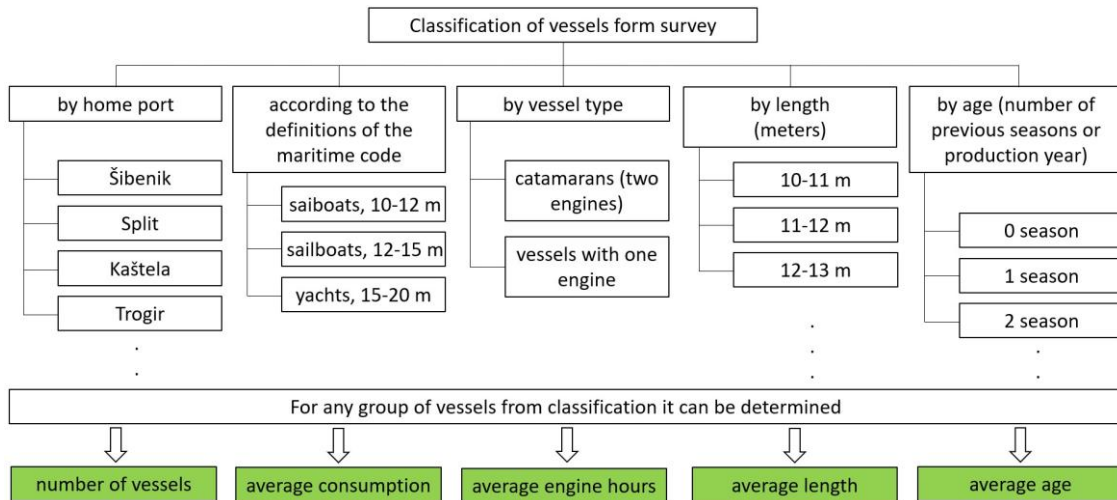


Fig. 4 The scheme of classification of nautical tourism vessels from 2023 pilot survey

Most vessels analysed were sailboats in the 12-15 m category as defined by the Maritime Navigation Act as seen from Figure 5. The average length of the surveyed vessels was 13.9 metres. Of the surveyed vessels, 95 had one engine, while 51 were catamarans, i.e. 35 % of the surveyed vessels were catamarans (vessels with two hauls and two engines). The mean average vessel had been in service for 5.2 seasons.

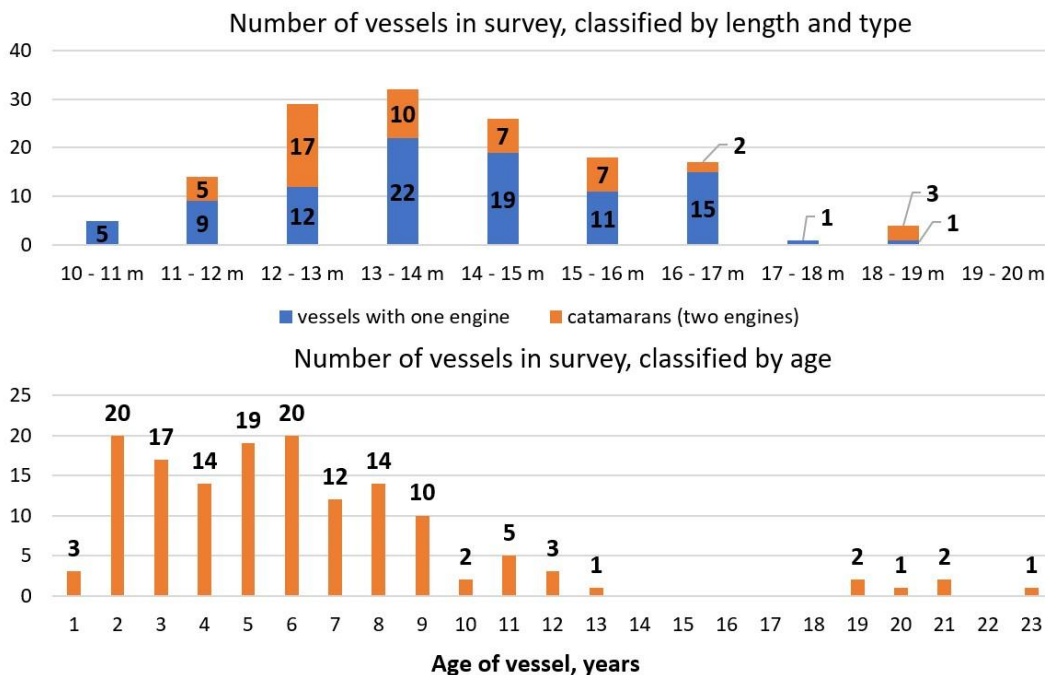


Fig. 5 Number of vessels in survey by size, type and age

5.3 The fuel consumption

The average fuel consumption of all vessels analysed was 9.4 l/h, with single-engine vessels consuming 6.8 l/h and catamarans (with two engines) 12.8 l/h. A Catamarans generally have a significantly larger surface area compared to monohull vessels, both in terms of deck space and overall dimensions. This allows them to be equipped with more luxurious features and amenities, such as larger cabins, additional living areas, and expanded recreational equipment. However, the increased size and weight, together with the higher wind and water resistance caused by their wider beam, typically result in higher fuel consumption compared to standard monohull boats of similar length. As expected, the average fuel consumption increases with the length of the vessel, with the increase in fuel consumption being more pronounced for catamarans, Figure 6.

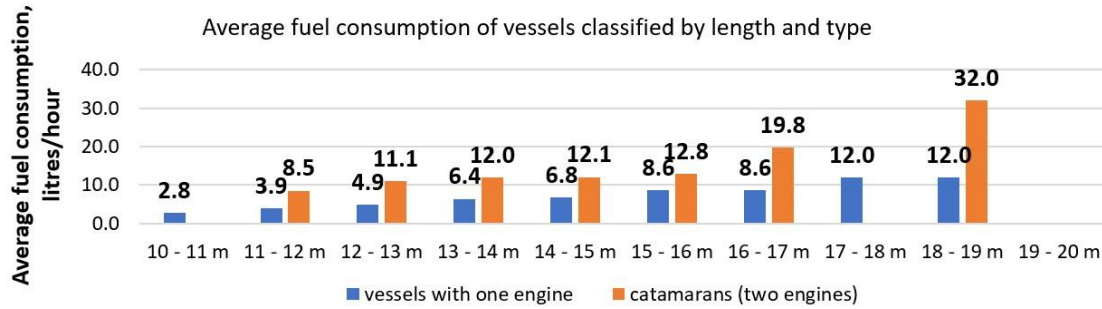


Fig. 6 Average fuel consumption of vessels in the survey by size and type

The average fuel consumption, average engine hours, and total annual fuel consumption for the analysed nautical tourism vessels are presented in Figure 7. The data is presented for vessels by length (top row), the average vessel (first column, bottom row) and vessels by number of engines (last two columns, bottom row). Again, the fuel consumption increases the vessel size, and there is a significant difference between single-engine vessels and those with two engines (catamarans) who also have a slightly higher number of engine operating hours.

6. Results - the emission calculations

The results of this study provide a first comprehensive insight into the emissions of the Croatian nautical tourism charter fleet. Based on the data collected during the 2023-2024 Green Sail survey on fuel consumption and engine operating hours for a representative sample of nautical tourism vessels (sailboats and yachts), the average emissions per vessel were calculated using the Tier 1 method and emission factors from the EMEP/EEA air pollutant emission inventory guidebook [25].

Figure 8 shows flowchart (scheme) of the total emissions calculation. Emissions can be calculated for any vessel from survey, any group of vessels from survey (divided by length, number of engines, etc.) or for all vessels from the survey.

To estimate the total emissions of the entire Croatian charter fleet, the calculated average emissions were scaled up using characteristics statistical average numbers of nautical tourism vessels, including the average number of bookings per vessel (19.6), average number of tourists per vessel (5.8), and average number of overnights per arrival (6.6), as depicted in Figures 1 and 2. These average values, derived from overall nautical tourism statistics, allowed for the extrapolation of the pilot project findings to the approximately 4,500 active vessels in the Croatian nautical tourism fleet. The calculated emissions are expressed through CO₂ emissions per rental (x guests, y days), guest (1 guest, y days) and overnight stay (1 guest, 1 day).

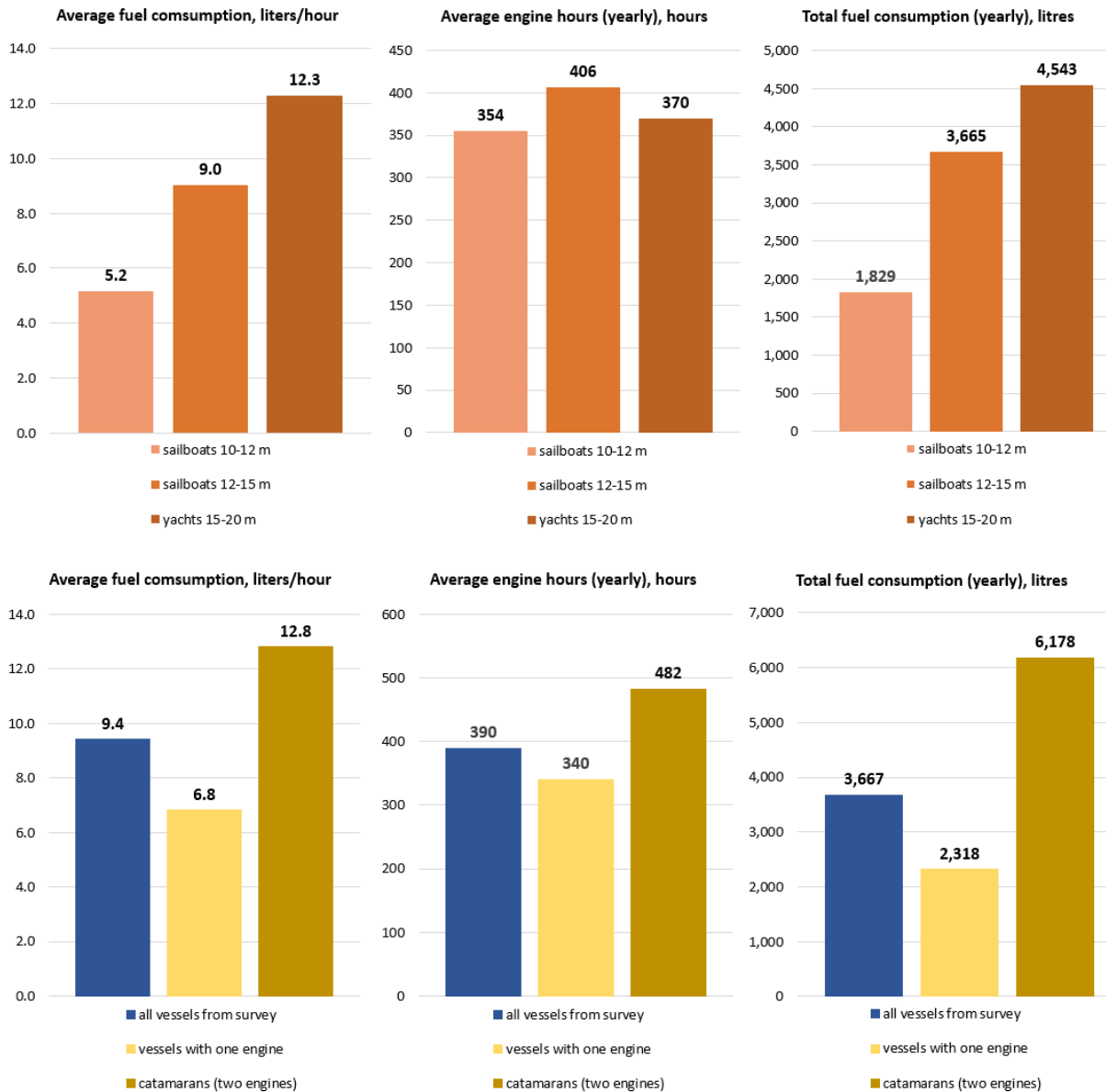


Fig. 7 Average fuel consumption and engine hour for nautical tourism vessels from survey, vessels classified according to the definitions of the maritime code (top row), average vessel from survey and vessels classified by type of vessels or number of engines (bottom row)

6.1 Emission Calculation Method

In this research, emission factors (EFs) from the EMEP/EEA Air Pollutant Emission Inventory Guidebook [25] were used. This guidebook is continuously updated to reflect new technologies implemented in modern engines. It describes three methodological approaches, ranging from Tier 1 to Tier 3, with the simplest Tier 1 method applied in this study. According to the Tier 1 method, total emissions are calculated based on total fuel consumption and corresponding EFs. In this approach, accurate data on fuel consumption and engine-specific EFs for nautical tourism vessels are essential for emission calculations.

For the Tier 1 approach, emissions are estimated using the total fuel consumed in each of the source categories covered in this chapter. For each source category, the algorithm is:

$$E_{pollutant} = \sum_{fuel\ type} FC_{fuel\ type} \times EF_{pollutant, fuel\ type} \tag{1}$$

where:

$E_{pollutant}$ = the emission of the specific pollutant,

$FC_{\text{fuel type}}$ = the fuel consumption for each fuel (diesel, LPG, four-stroke gasoline and two-stroke gasoline) for the source category,

$EF_{\text{pollutant}}$ = the emission factor for this pollutant for each fuel type.

The calculation used emission factors ($EF_{\text{pollutant}}$) from the sector Agriculture / forestry / fishing: Off-road vehicles and other machinery from *Table 3-1 Tier 1 emission factors for off-road machinery* of EMEP/EEA Air Pollutant Emission Inventory Guidebook (2023) Tier 1 emission factors for Diesel fuel are: $EF_{\text{CO}_2} = 3160$ kg/t, $EF_{\text{NO}_x} = 34.457$ kg/t, $EF_{\text{CO}} = 11.469$ kg/t and $EF_{\text{PN}} = 1.913$ kg/t.

All vessels in the survey, and the assumption is that also all vessels in the fleet are equipped with a diesel fuel engine, so in calculation only emission factors for Diesel fuel are used.

The fuel consumption is calculated as follows:

$$FC_{\text{fuel type}} = \sum_1^N FC_{\text{average}} \times T \quad (2)$$

where:

$FC_{\text{fuel type}}$ = the fuel consumption for each fuel (diesel, LPG, four-stroke gasoline and two-stroke gasoline) for the source category,

N = number of vessels, can be one vessel from survey, group of vessels from survey (divided by length, number of engines, etc.) or all vessels from the survey

FC_{average} = average fuel consumption of vessel

T = engine hours (yearly or in season)

Calculated emissions are expressed through the following key indicators:

- emissions per rental (x guests, y days).
- emissions per guest (1 guest, y days).
- emissions per overnight stay (1 guest, 1 day).

Emissions per one booking (rental) are calculated as follows:

$$E_{\text{pollutant, rental}} = \frac{E_{\text{pollutant}}}{N_{\text{rental}}} \quad (3)$$

where:

$E_{\text{pollutant, rental}}$ = the emission of the specific pollutant per one booking (rental) of vessel,

$E_{\text{pollutant}}$ = the emission of the specific pollutant,

N_{rental} = the number of bookings (rental) per vessel in season (yearly).

Emissions per one tourist are calculated as follows:

$$E_{\text{pollutant, tourist}} = \frac{E_{\text{pollutant, rental}}}{N_{\text{tourist}}} \quad (4)$$

where:

$E_{\text{pollutant, tourist}}$ = the emission of the specific pollutant per one tourist on vessel,

$E_{\text{pollutant, rental}}$ = the emission of the specific pollutant per one booking (rental) of vessel,

N_{tourist} = the number of tourists per vessel.

Emissions per one overnight (day) are calculated as follows:

$$E_{\text{pollutant, overnight}} = \frac{E_{\text{pollutant, tourist}}}{N_{\text{overnight}}} \quad (5)$$

where:

$E_{\text{pollutant, overnight}}$ = the emission of the specific pollutant per one overnight of tourist on vessel,

$E_{\text{pollutant, tourist}}$ = the emission of the specific pollutant per one tourist on vessel,

N_{tourist} = the number of overnights per tourist.

If all the performed calculations of emissions and key indicators are considered, the performed calculations can be shown in the corresponding scheme (flow chart) shown in Figure 8. The results of the calculations according to the scheme given in Figure 8 are shown by diagrams in Figures 9 and 10.

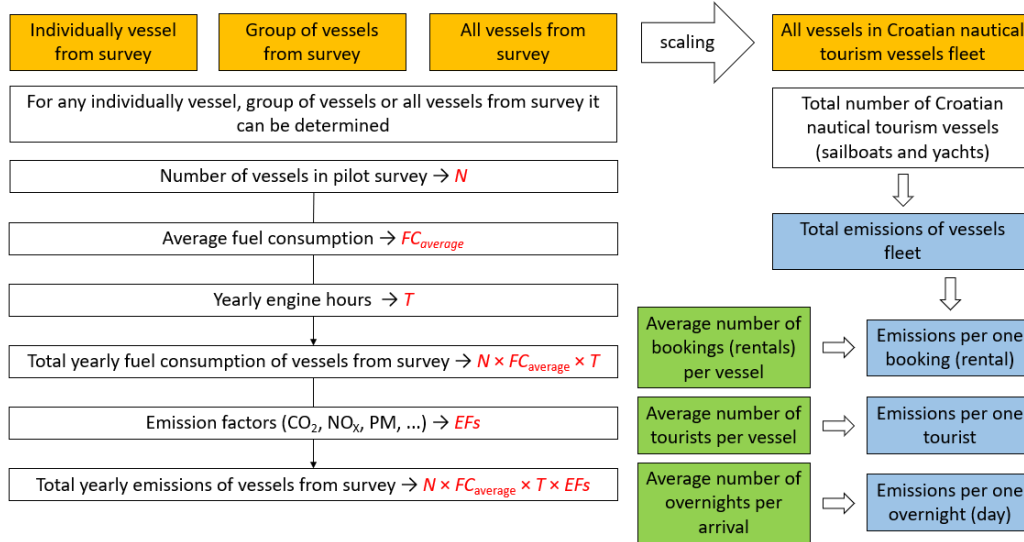


Fig. 8 The flowchart (scheme) of the total emissions calculation

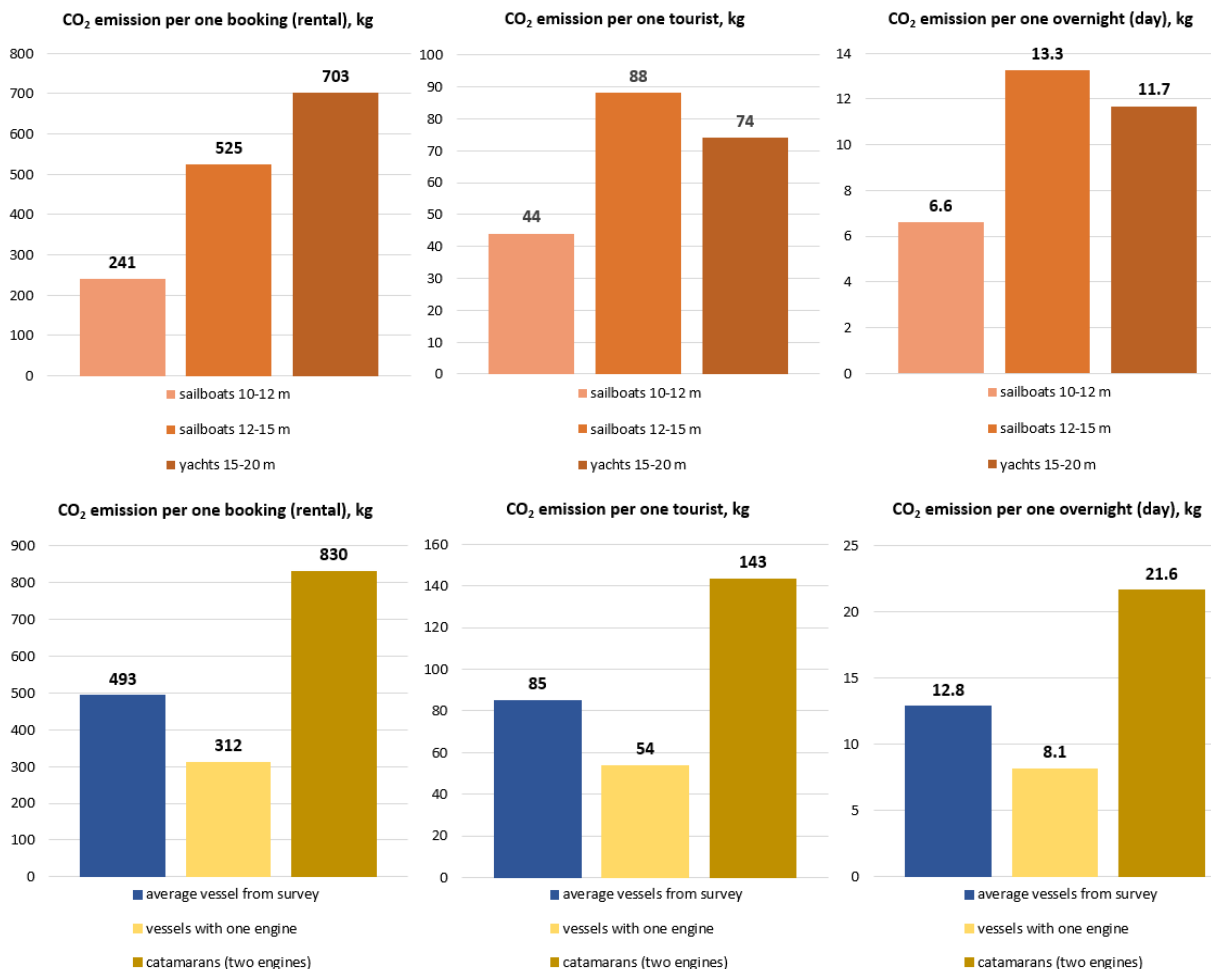


Fig. 9 CO₂ emissions of nautical tourism vessels from 2023 pilot survey, vessels classified according to the definitions of the maritime code (top row), average vessel from survey and vessels classified by type of vessels or number of engines (bottom row)

Figure 9 shows the CO₂ emissions per booking (rental), per tourist and per overnight stay (day) for the analysed nautical tourism vessels surveyed. The data is presented for vessels categorized by length, vessels classified according to the definitions of the maritime code (top row), and for the average vessel in the survey and vessels classified by number of engines (bottom row). As expected, CO₂ emissions increase with vessel length and are significantly higher for catamarans (twin-engine vessels) than for single-engine vessels.

Furthermore, emissions of harmful air pollutants, NO_x, CO, and PM were calculated. PM contains microscopic solids or liquid droplets, fine inhalable particles.

Figure 10 shows harmful emissions (NO_x, CO, PM) per one booking (rental), per one tourist and per one overnight(day) for nautical tourism vessels from the survey. The data is presented for vessels categorized by length, vessels classified according to the definitions of the maritime code (top row), and for the average vessel in the survey and vessels classified by number of engines (bottom row). As expected, harmful emissions increase with vessel length and are significantly higher for vessels with two engines (catamarans) compared to vessels with one engine.

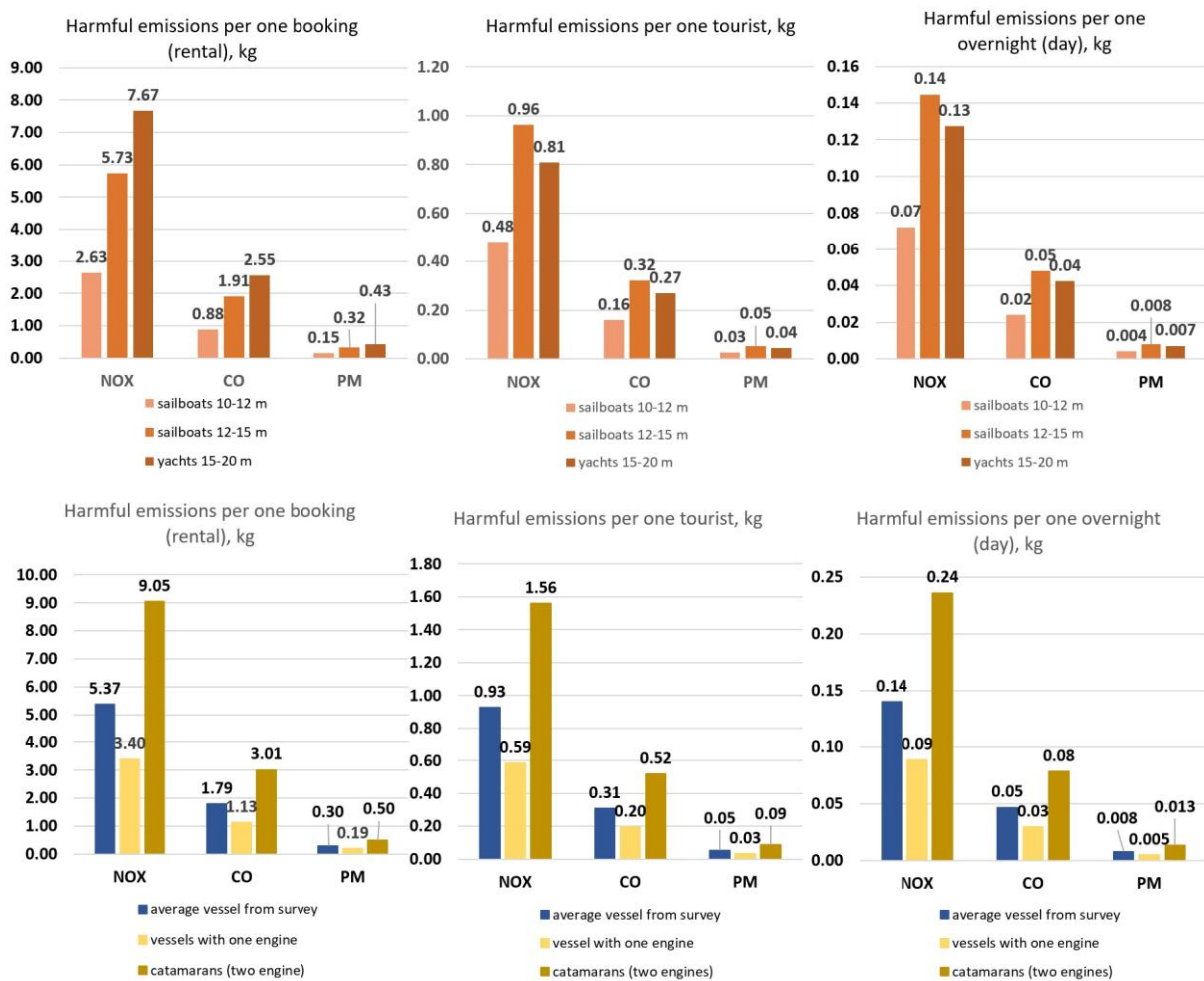


Fig. 10 Harmful emissions of nautical tourism vessels (sailboats and yachts) from 2023 pilot survey, vessels classified according to the definitions of the maritime code (top row), average vessel from survey and vessels classified by type of vessels or number of engines (bottom row)

6.2 Scaling survey data to whole fleet

The data from the survey can be scaled to estimate fuel consumption and operational trends for different vessel groups within the Croatian nautical tourism fleet or for the entire fleet of Croatian charter vessels. By using the statistical averages of nautical tourism vessel characteristics—such as average number of bookings per vessel, average number of tourists per vessel, and average number of overnight stays per booking—the

emissions per booking, per tourist, and per overnight stay can be calculated for the vessels included in the survey.

By scaling the data of vessels from the survey to the entire charter fleet, approx. 4,500 active vessels in the Croatian nautical tourism vessels fleet, a rough estimate is that this sector emits 30,000 to 40,000 t of CO₂ per year, 300 to 400 t of NO_x per year, 100 to 150 t of CO per year, 15 to 25 t of PM per year.

It is important to note that the application of these fleet-wide averages, derived from overall nautical tourism statistics and applied without detailed variation across vessel types, contributes to the characterization of these national estimates as 'rough,' as they do not fully account for potential heterogeneity and uncertainties across diverse vessel segments. While these scaled figures offer a crucial preliminary indication of the sector's total emissions, their reliability is directly influenced by the generalized nature of the average operational parameters used for extrapolation. Consequently, these national estimates should be interpreted as approximate benchmarks for the entire fleet, with a focus on trends rather than high precision.

The data collected in the pilot study can be applied to a characteristic group of vessels, such as catamarans, which are defined as vessels with two hulls and two engines. The analysis of the sample showed that catamarans, which accounted for 35 % of the total vessels analysed, generated almost 60 % of the total emissions.

This significantly higher level of emissions - which includes both CO₂ and harmful air pollutants such as NO_x, CO, and PM — is due to their higher average fuel consumption and higher engine operating hours. Catamarans consumed an average of 12.8 litres per hour, significantly more than the 6.8 litres per hour consumed by single-engine vessels. In addition, catamarans also have a slightly higher number of engine operating hours compared to single-engine vessels.

This difference in environmental impact is calculated using key indicators such as emissions per vessel in the season, per vessel booking, per tourist or per overnight stay. This larger emission footprint of the catamaran is particularly interesting because the market for catamarans is expected to grow strongly in the coming years. A compound annual growth rate (CAGR) of 6.8 % is forecast for this market segment. [26].

7. Comparison of charter fleet emissions with other sectors

The estimated NO_x and PM emissions of the Croatian charter fleet are compared with those of the national road vehicle fleet and the cruise fleet, using data from by Transport & Environment [27]. Total road vehicle fleet and cruise ships fleet emissions are scaled in order to compare with the approximately 4,500 active vessels as shown in Figure 11. The estimated NO_x and PM emissions of the Croatian charter fleet are compared with those of the national road vehicle fleet and the cruise fleet, using data from Transport & Environment [27]. For comparability with the approximately 4,500 active vessels, the total emissions from road vehicles and cruise ships were scaled proportionally.

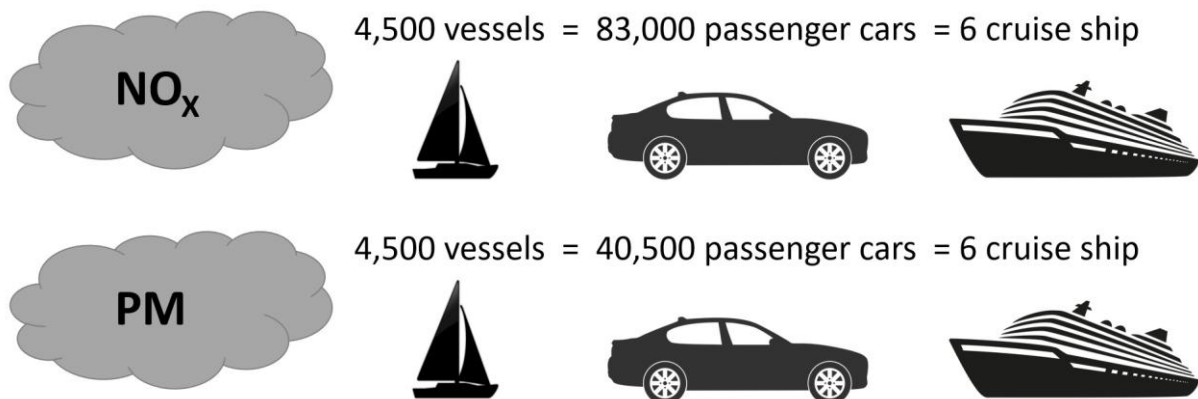


Fig. 11 Comparison of harmful emissions charter (rental) fleet of nautical tourism vessels (sailboats and yachts) with road vehicle fleet and cruise ships fleet

On the Adriatic coast, the peak tourist season typically lasts three to four months. Considering this, and the average consumption of recreation vessels, a rough analysis suggests that these vessels consume as much, or even more, fuel in this short period than the average road vehicle does over an entire year.

Figure 12 presents a rough estimate of annual emissions from the nautical tourism vessel fleet. NO_x emissions are about 5.3 % of those from the road vehicle fleet and 8.3 % of those from the cruise ship fleet. PM emissions account for around 2.6 % of emissions from road vehicles and 8 % of emissions from cruise ships. However, CO₂ emissions only account for around 0.6 % of emissions from road vehicles. This discrepancy indicates that vessel engines are equipped with significantly less advanced exhaust aftertreatment technology, which is reflected in the higher NO_x and PM shares compared to CO₂.

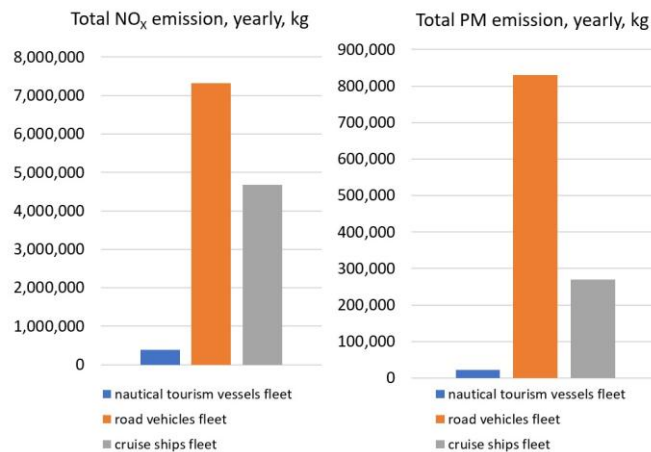


Fig. 12 Comparison of harmful emissions charter (rental) fleet of nautical tourism vessels (sailboats and yachts) with road vehicle fleet and cruise ships fleet

As these results are a first estimate or a rough estimate of emissions of the nautical tourism vessel fleet, one of the goals in improving the calculation compared to the pilot survey is to carry out own emission measurements and determine own emission factors (adjusted to the activities and specifics of the nautical tourism vessels in the Adriatic Sea).

In addition, a brief demonstration of the Tier 3 method calculation is provided here. Since national activity statistics are not separately collected for yachts, catamarans, sailboats, or smaller boats, activity data must be derived based on the vessel population categorized by boat type, fuel type, engine type, and technology level along with estimated engine load factors and annual hours of operation. Fuel consumption and emissions by fuel type are then estimated using the following approach:

$$E_{i,m} = \sum_b \sum_e \sum_z (N_{b,e,z} \times T_{b,e,z} \times P_{b,e,z} \times LF_{b,e,z} \times EF_{b,e,z}) \quad (6)$$

where:

E = emissions per year (tonnes),

N = number of vessels (vessels),

T = average duration of operation of each vessel per year (hours/vessel),

P = nominal engine power (kW),

LF = engine load factor (%),

EF = emission factor (g/kWh),

b = vessel type (yawl, cabin boat, sailing, ...),

e = engine type (inboard, onboard, 2S, 4S),

i = pollutant (CO, HC, NO_x, PM, NH₃, NMVOC, ...) or fuel consumption,

m = fuel type (gasoline, diesel),

z = technology level (conventional, 2003/44/EC).

The calculation used emission factors ($EF_{b,e,z}$) from the sector International maritime navigation, international inland navigation, national navigation (shipping), national fishing, military (shipping), and recreational boats from *Table 3-1 Tier 3 emission factors for recreational vessels* of EMEP/EEA Air Pollutant Emission Inventory Guidebook (2023).

The calculation used activity data for vessel from *Table 3-21 Activity data for recreational craft in Denmark* of EMEP/EEA Air Pollutant Emission Inventory Guidebook (2023).

Table 5 shows the results of harmful emissions (NO_x and PM) using principle calculation of emissions according to the Tier 3 method compared to the results of Tier 1 method used in this research.

There are no emission factors in EMEP/EEA Air Pollutant Emission Inventory Guidebook (2023) for all vessel categories included in pilot project survey, so calculations are only for a sailboat length of 10-12 m. Using Tier 3 emission factors and load factor (0.5) from EMEP/EEA Air Pollutant Emission Inventory Guidebook (2023), average number of engine hours (354 h) of a 10-12 m sailboat from a pilot project survey and the engine power (30 kW) typical for such vessels, harmful emissions (NO_x and PM) can be calculated.

Table 5 Comparison of harmful emissions (NO_x and PM) of sailboat length 10-12 m calculated using EMEP/EEA Tier 1 and Tier 3 methods, emissions are for one sailboat in season.

| | NO_x | PM |
|--------|--------|------|
| Tier 1 | 52.44 | 2.91 |
| Tier 3 | 52.11 | 5.32 |

As the Tier 3 methodology relies on emission factors derived two decades ago under different operating conditions of ships, future research should include direct measurements of emissions from charter vessels operating in the Adriatic Sea to determine emission factors specific to their activities and characteristics.

8. Discussion

Despite their significance, emissions from recreational craft remain difficult to quantify, as they are often excluded from national inventories and Eurostat databases. This regulatory lag underscores the need for continuous evaluation of emission standards, especially in light of rising nautical tourism activity. The pilot project conducted in 2023 provides a critical first step in understanding the air emissions from the nautical tourism charter fleet in Croatia. By collecting data on engine operation, fuel consumption, and vessel specifications from a sample of sailboats and yachts in the Šibenik-Knin and Split-Dalmatia counties, this research offers an initial quantitative assessment of the sector's environmental impact. The application of the Tier 1 emission calculation method from the EMEP/EEA guidebook allowed for the estimation of CO_2 and other harmful emissions based on fuel consumption and emission factors. The scaling of the survey data to the entire estimated active charter fleet provides a rough but valuable estimate of the total emissions generated by this significant segment of Croatian tourism. Furthermore, the comparison with emissions from the road vehicle and cruise ship sectors offers a preliminary context for the magnitude of nautical tourism emissions.

Based on the 2023 pilot survey data on fuel consumption and engine operating hours of a representative sample of nautical tourism vessels (sailboats and yachts), this study provides the first comprehensive insight into the emissions of the Croatian nautical tourism charter fleet. The average emissions per vessel were calculated using the Tier 1 method and emission factors from the EMEP/EEA air pollutant emission inventory guidebook. To estimate the total emissions of the entire Croatian charter fleet, the calculated average emissions were scaled up to the approximately 4,500 active vessels using key statistical averages of nautical tourism vessels. These averages include 19.6 bookings per vessel, 5.8 tourists per vessel, and 6.6 overnights per arrival.

The calculated emissions are expressed through the following key indicators: CO_2 emissions per rental (for x guests and y days), guest (for 1 guest and y days) and overnight stay (for 1 guest and 1 day).

As illustrated in Figure 8, CO_2 emissions increase with vessel length and are significantly higher for vessels with two engines (catamarans) compared to those with one engine. Scaling the survey data to the entire

charter fleet suggests a rough estimate of 30,000 to 40,000 t of CO₂ per year emitted by this sector. Furthermore, the study also calculated harmful air pollutants: NO_x, CO, and PM.

Similar to CO₂ emissions, the harmful emissions also increase with vessel length and are notably higher for catamarans, as shown in Figure 11. By scaling the survey data, the rough annual estimates for the entire charter fleet are 300 to 400 t of NO_x, 100 to 150 t of CO, and 15 to 25 t of PM. It's important to note that while catamarans constituted only 35 % of the sample, they accounted for almost 60 % of the total emissions due to higher average fuel consumption and engine operating hours.

However, several limitations in the current emission model warrant consideration. The study relies on data collected through questionnaires completed by skippers and charter company personnel, which may be subject to recall bias or estimation errors. The sample size of 146 vessels with complete data, while representative of the mooring share for certain vessel lengths, may not perfectly reflect the actual distribution of the entire active charter fleet in terms of size, age, and regional representation. Additionally, the use of the Tier 1 emission calculation method, while straightforward, utilizes general emission factors that may not fully capture the specific operational characteristics and engine technologies prevalent in the Croatian charter fleet. The exclusion of emissions from generators also represents a gap in the overall emission assessment. Finally, the study's geographical focus on Šibenik-Knin and Split-Dalmatia counties, while significant, might not entirely represent the emissions profile of the charter fleet across the entire Croatian Adriatic coast.

9. Conclusion

Emission assessments play an important role in estimating and evaluating the environmental impact of sectors such as nautical tourism and provide a comprehensive basis for evidence-based policy decisions. A number of valuation approaches have emerged in economic disciplines, including environmental economics, which emphasises negative environmental externalities and the “polluter pays” principle, and ecological economics, which attempts to capture the value of nature’s non-market goods and services (i.e. natural capital). To bridge the gap between conceptual frameworks and practical application, valuation models seek to make the valuation discourse more understandable and applicable in order to improve accessibility and usability [28]. Applying and combining such assessment methods to nautical tourism is essential to gain robust quantitative and qualitative insights. Emissions assessments such as this pilot study, which estimated emissions based on fuel consumption and emission factors, can support the development of targeted, evidence-based reduction strategies. Ultimately, such data will enable policymakers and stakeholders to make informed decisions that promote the sustainability of the nautical tourism sector.

This study offers the first large-scale estimate of charter vessel emissions and highlights the need for broader data collection and more advanced methods to improve accuracy. It delivers the first comprehensive insight into the emissions of charter vessels in Croatia, establishing a fundamental methodological framework for future research in this under-investigated area. Based on the findings on the sample of 160 vessels, extrapolated to Croatia’s fleet (approximately 4,500 active vessels), seasonal emissions are estimated at 30,000 to 40,000 t CO₂, 300 to 400 t NO_x, 100 150 t CO and 15 to 25 t PM. Rough estimate of annual emissions from the nautical tourism vessel fleet shows that NO_x emissions are about 5.3 % of those from the road vehicle fleet and 8.3 % of those from the cruise ship fleet. PM emissions account for around 2.6 % of emissions from road vehicles and 8 % of emissions from cruise ships. The findings provide crucial baseline data that can inform the development of improved policies aimed at mitigating emissions from the nautical tourism sector. To enhance the accuracy and comprehensiveness of future assessments, several key areas for improvement have been identified in comparison to this pilot project:

- Improved Surveying: questionnaire designed to incorporate lessons learned, sampling strategy improved to that better mirror the active charter fleet's composition regarding vessel size, age, and regional distribution.
- Sensor-based and direct emission measurements: Integrate sensor-based monitoring of vessel and engine activity with internal emissions measurements to collect objective, high-quality data. Real-world measurements could include typical sailing cycles and the use of Portable Emission

Measurement Systems (PEMS) to capture emissions under operational conditions. This enables the development of customized emission factors for charter vessels operating in the Adriatic Sea. Use of a More Complex Calculation Method: Transitioning from the Tier 1 methodology to more sophisticated approaches like Tier 3, which considers factors such as engine load and technology level. Furthermore, improving data scalability to provide a more accurate estimate of total emissions from the entire charter fleet. Future research should also focus on the definition of required data for applying Tier 2 or Tier 3 emission calculation models.

Additionally, future research should include:

- Expansion of Geographical Coverage: Extending data collection efforts to encompass a greater number of marinas across the Croatian Adriatic to achieve a more representative assessment of the entire charter fleet's emissions.
- Collection of Data on Actual Occupancy Rates: Gathering data on the actual number of guests on vessels of different categories to refine the calculation of emissions per tourist and per overnight stay.
- Analysis of Sailing Activities: Collecting data to analyse the proportion of navigation time spent under engine power versus sail power to better understand fuel consumption patterns.
- Collection of Fuel Consumption Data for Generators: Including the collection and analysis of fuel consumption data for onboard generators to provide a more complete picture of vessel emissions.

To summarise, the Plan Bleu (2022) guidelines [7] advocate a transition to more environmentally friendly fuels and energy-efficient engines in order to reduce air emissions from recreational boating. They emphasise the need for renewable and low-carbon fuels and the development of charging and refuelling infrastructure. The guidelines also call for introducing strict, harmonised legislation on air emissions from cruise ships, yachts, sailboats and smaller boats and propose the electrification of ships, ports and marinas as a viable solution. They also recommend fuel-efficient engines, optimised hull designs and tax or incentive schemes that favour electricity over fossil fuels for boats.

Future research could also explore data-driven approaches for estimating fuel consumption or emissions, drawing inspiration from studies that use nonlinear regression and other advanced techniques to predict engine power and emissions in large maritime fleets. Understanding how factors like engine load and operational profiles specific to charter vessels impact emissions, like the detailed analysis of engine power and size in bulk carrier studies, will be crucial [29]. Future research should aim for more accurate assessments by transitioning to methods beyond Tier 1 and collecting more objective data [30]. As studies on IWV suggest, due to diverse operations, only real-time measurement during navigation through different conditions would represent the actual energy efficiency of the vessel [31]. By addressing these areas, future research can build upon the foundational work of this pilot project to provide a more accurate and comprehensive understanding of the environmental impact of nautical tourism in Croatia, ultimately supporting the development and implementation of effective emission reduction strategies.

ACKNOWLEDGMENTS

The Green Sail Footprint program is a per-vessel rating system that measures emissions and sustainability actions onboard a boat. It has been developed to reduce the environmental impact of the charter industry and assist the nautical sector in its necessary transition towards a sustainable future. The rating system allows customers to make informed purchase decisions, supporting boat owners who invest in environmentally friendly solutions. The system supports yacht charter companies to measure their environmental output to develop a concrete roadmap to sustainability and it is a modern effort aimed at sustainable development within the nautical tourism sector, which will contribute to the EU's increased climate ambition.

This work was supported by the NextGenerationEU under the scientific project SURVEY+ of the Institute for Tourism, Zagreb, Croatia.

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