FACULTY OF MARITIME STUDIES

Bruna Bacalja Bašić

Contribution to ship energy efficiency through the application of renewable sources and advanced technologies

DOCTORAL THESIS

Split, 2024

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Supervisor: Maja Krčum, Ph.D.

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ABSTRACT

Strategically, the Republic of Croatia, with its economy focused on tourism, is closely connected to the sea and coastal areas. Integrated management of these areas is essential for the country's sustainable development strategy. Shipping greenhouse gas emissions from maritime traffic accounts for 13.5% of all greenhouse gas emissions from transportation in the EU, ranking behind road transport and air transport. Despite a decrease in maritime traffic in 2020 due to the COVID-19 pandemic, the sector is predicted to expand rapidly in the future decades. This doctoral thesis develops a model for air emission reduction, using the example of the port city of Split, which incorporates renewable energy sources and technical solutions to enhance energy efficiency.

At the beginning of the research is made emission estimation for major air pollutants and greenhouse gases, including carbon dioxide (CO_2), nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compounds (VOC), sulfur dioxide (SO_2), and particulate matter (PM) from line vessels operating in the port of Split during maneuvering and hoteling phases over the years 2017, 2018, and 2019.

The fleet, with an average age of 28 years, has a reasonable lifespan, but it requires some modifications. This research explored the application of photovoltaic (PV) systems on ship retrofits. By utilizing renewable energy resources, the study demonstrates the potential for reducing greenhouse gas (GHG) emissions and enhancing energy efficiency in maritime operations within the Split coastal area. An innovative design is presented to overcome space restrictions on ships and maximize the installation area for PV panels.

The research examined the environmental benefits of propeller optimization as a technical solution, focusing on its potential to reduce ship vibrations, fuel consumption, and CO_2 emissions. A case study on a Ro-Ro passenger ship compared data collected during sea trials before and after propeller optimization, correlating expected fuel consumption savings with CO_2 emission reductions. Additionally, the paper performed a SWOT (strengths, weaknesses, opportunities, threats) analysis, comparing propeller optimization with solar and wind power applications on ships.

The collected data on reduced emissions in maritime operations was used to create a comprehensive model aimed at reducing emissions with the integration of renewable energy sources and optimized ship propeller. The model provides valuable insights for minimizing the environmental footprint of maritime activities that can be adapted to other port-cities, contributing to global efforts in reducing maritime air pollution.

Key words: line vessel emission, solar power application, propeller optimisation, decarbonisation

CONTENTS

1. LIST OF PUBLICATIONS

This thesis is based on the works described in the following articles, each of which is referred to in the text as an "Article" followed by the corresponding Roman numeral (Article I, Article II, Article III):

I. Bacalja, B.,* Krčum, M., and Slišković, M., "A Line Ship Emissions While Manoeuvring and Hotelling—A Case Study of Port Split" Journal of Marine Science and Engineering 2020, Vol. 8, Page 953 8 (11): 953. https://doi.org/10.3390/JMSE8110953.

II. Bacalja Bašić, B.,* Krčum, M., and Gudelj, A., "Adaptation of Existing Vessels in Accordance with Decarbonization Requirements—Case Study—Mediterranean Port" Journal of Marine Science and Engineering 2023, Vol. 11, Page 1633 11 (8): 1633. https://doi.org/10.3390/JMSE11081633.

III. Bacalja Bašić, B.,* Krčum, M., and Jurić, Z., "Propeller Optimization in Marine Power Systems: Exploring Its Contribution and Correlation with Renewable Energy Solutions" Journal of Marine Science and Engineering 2024, Vol. 12, Page 843 12 (5): 843. https://doi.org/10.3390/JMSE12050843.

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2. INTRODUCTION

Maritime transport has bad effects on the environment and human health despite being considered the most energy-efficient mode of transport [1]. Different sources of pollution from ship include oil spills, ballast waters, grey waters, black waters, anti-fouling paint, noise, solid waste, and air emissions [2]. Air emissions, including pollutants and greenhouse gases, are transferred transboundary in the atmosphere and affects air quality globally [3]. The major air pollutants include nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compounds (VOC), sulphur dioxide (SO_2), particulate matter (PM) and greenhouse gas (carbon dioxide (CO_2). Shipping contribution to greenhouse gas emissions is 2.89% [4]. Transporting goods by ships is responsible for approximately 1,056 million tons of CO_2 annually.

Shipping contributes to the anthropogenic emission of nitrogen oxide emissions (NO_X) by 15% by fuel burning at high temperatures in the ship's internal combustion engine [5]. NO_X emissions affect the environment by causing acid rain, and human health when combined with VOC [6][7]. Shipping contribution to sulphur oxide emissions in overall anthropogenic emission ranges from 5 to 8%, depending on the fuel type and percentage of suplhur in it [5],[8]. Reduced lung function, increased prevalence of respiratory symptoms and disorders, irritation of the eyes, nose, and throat, and early mortality have all been linked to exposure to sulfur dioxide in the ambient air [9]. The particulate matter (PM) is the aerosols defined by size, consisting of mixtures of solid particles and liquid droplets found in the air. Shipping emissions contribute 1–7% of ambient air PM_{10} levels, 1–14% of $PM_{2.5}$, and at least 11% of PM_1 in European coastal areas. The PMs are affecting human health by restricting the passage of oxygen to the blood [6],[7]. Overall shipping emissions is 16% for NO_X 11% for SO_X and 5% for PM_{10} [10]. NO_2 and CO emissions in ports are connected to bronchitic symptoms, and exposure to SO_2 emissions is connected with respiratory issues and premature births [11].

While the International Convention for the Prevention of Pollution from Ships (MARPOL), divided into VI Annexes regarding the different pollutions from the ships, has a crucial role in governing shipping pollution, additional directives are adopted to supplement or clarify specific fields of interest [12]. Most important organizations, conventions and laws related to air pollution from ships include: International Maritime Organization (IMO), The Technical Code on the Control of Nitrogen Oxide Emissions (NOX Technical Code 2008), The Sulphur Fuel Directive for Ships (SCMF Directive), Environmental Protection Act, Air Protection Act [13], [14], [15], [16], [17].

The maritime industry goal is to enhance energy efficiency, for new and existing ships. A technical measure in this effort is the Energy Efficiency Design Index (EEDI), which sets efficiency standards for new ship equipment and engines by requiring a minimum energy efficiency level per capacity mile [18]. The Ship Energy Efficiency Management Plan (SEEMP) is operational measure designed to improve efficiency for both existing and new vessels. Various efforts are being taken to enhance both measures including technical solutions and the adoption of renewable energy sources. These solutions can be integrated into both existing fleet upgrades and new shipbuilding projects.

Renewable sources are gradually emerging in maritime transport as a promising alternative that could replace conventional marine energy systems. It is critical to make the most of existing technologies in order to utilize renewable energy sources. Wind energy, solar energy and fuel cells, among others, are all available renewables in the maritime sector. Various studies have shown that the integration of electric ships powered solely by electricity from batteries in maritime transport has the potential to reduce carbon dioxide emissions, due to the reduced fossil fuels consumption [19],[6]. A study conducted on a Ro-Ro-type marine vessel navigating between Turkey and Italy, with a novel approach to solar array layout, revealed that the vessel achieved a 7.76% energy efficiency improvement, the solar system met 7.38% of the vessel's fuel requirements, and also resulted in atmospheric pollutants reduction [20]. Furthermore, a technoeconomic analysis proposed a mathematical model for predicting solar irradiation and revealed that the hybrid power system offers promising financial benefits [21]. Study by Kurniawan provided valuable insights into the utilization of solar energy in ships, particularly emphasizing the optimization potential through quadratic Maximization Maximum Power Point Tracking (MPPT) [22]. Additionally, Kobougias' research on typical ship's electrical grid highlights key components and installation considerations and recommending best locations for implementing solar energy systems [23]. An experiment on a passenger ship showed its ability to operate independently or connected to a smart grid using hybrid photovoltaic/diesel technology [24]. In another study, ship demand was analyzed to optimize local grid operations, proposing scheduling methods for boats and battery energy storage systems [25]. The Keep It Sustainable and Smart (KISS) project demonstrated an electric small craft, matching competitors with conventional propulsion, through a holistic design approach [26]. A study on Mediterranean nautical tourism identified barriers to renewable energy adoption, emphasizing the potential of photovoltaic modules for energy savings and presented financial and knowledge limitations as main barriers [27].

These studies collectively underscore the growing potential and benefits of integrating solar energy into maritime operations, not only in reducing emissions but also in improving efficiency and finances. As a popular tourist destination with higher electricity demand during summer, Croatia holds significant potential for solar energy utilization [28]. The Croatian government's adoption of a new Energy Strategy from 2030 to 2050, outlines a comprehensive set of policies. These initiatives aim to enhance efficiency, decrease dependency on fossil fuels, increase local production, and augment renewable resources. As per the strategy, renewable energy sources are projected to contribute 36.4% of total energy consumption by 2030, rising to 65.6% by 2050 [29]. Initiative FuelEU Maritime establishes annual GHG intensity limitations for ships with more than 5,000 gross tonnage in European ports, with the goal of reducing emissions by 2% by 2025 and up to 80% by 2050. The legislation also requires zero-emission solutions, such as on-shore electricity for ships at berth, in order to reduce port air pollution. It encourages innovation in sustainable fuels and technology while giving operators freedom in fuel selection and compliance procedures [30].

The relationship between ship propeller design, vibrations, and fuel consumption has a crucial role in ship performance. Optimizing ship propellers is essential for enhancing marine vessel efficiency, maneuverability, and overall performance. This involves initial design followed by improvement in order to find the best balance between objectives and constraints, evolving into an optimization task [31]. Studies have shown that optimizing propeller design, particularly with wide chord tip (WCT) propellers, can improve efficiency by over 2% [32]. Hydrodynamic optimization using gradient and non-gradient-based algorithms has demonstrated significant efficiency improvements [33]. Research indicates the feasibility of creating medium-sized flexible composite propellers capable of reducing fuel consumption, resulting in a 1.25% reduction in fuel consumption [34]. Propeller optimization methods, such as Prop Scan technology, have proven successful in achieving substantial fuel savings. Berg Propulsion, a Swedish company specializing in propellers, has achieved notable success by redesigning propulsion systems on existing ships, resulting in remarkable fuel savings of up to 22% in recent cases [35]. Another optimization method focuses on trimaran hull form to reduce resistance and improve propeller intake flow, addressing the dual objectives of resistance reduction and intake flow enhancement [36]. Adjusting the propeller's position towards the aft part and increasing its area showed significant potential for reducing power requirements, allowing for a larger propeller diameter without the risk of transmitting pressure pulses to the hull. This efficiency enhancement can lead to reduced environmental impacts and costs [37]. Efficiency gains have been achieved through integrating optimal propeller boss cap with fins (PBCFs) designs into propeller/rudder systems, resulting in notable efficiency improvements [38].

The increasing demand for sustainable and energy-efficient maritime solutions presents a shared opportunity for both solar energy implementation on ships and propeller optimization. This thesis improves energy efficiency and reduces greenhouse gas emissions of the ships through the application of renewable energy sources in the total electricity balance for certain types of vessels, and optimizing the ship propeller for the purpose of sustainable development of the port.

3. RESEARCH OBJECTIVES

Sustainable transport supports economic activity, limits the release of harmful substances to the extent that the environment can absorb, minimizes the consumption of non-renewable energy sources to the level of sustainable use, reuses, and again uses their components. Significant attention is paid to the improvement of the Energy Efficiency Design Index (EEDI), which is affected by the installed power of the ship, the speed at which the ship cruises, the characteristics of the cargo it carries, and other relevant parameters. A lower index value means a higher energy efficiency of the ship. The application of renewable energy sources on vessels and propeller optimization are the parameters that contribute to improving energy efficiency. It is critical to have adequate infrastructure for the usage of renewable energy sources in ports. This involves installing shore power connections which allow ships to use renewable energy sources while in port. It is of high importance to supply adequate power capacity and voltage levels to properly use these systems. Integrating these technologies encourages environmentally sustainable port operations and decreases their overall environmental impact. The aim of this thesis is to propose a model of a sustainable port using renewable energy sources and technical solutions.

Article I

The goals of this paper were:

- to examine correlations between emissions over the observed period, in the manoeuvring and hotelling phase
- to identify seasonal oscillations,
- and to give recommendations on reducing the gas emissions to improve the quality of living in the city port area.

Data on the number of vessels in the port of Split were collected, and emissions of harmful gases were calculated during navigation and at berth in the port. A comparison was made with some European ports, and the parameters on some of the vessels were checked using an appropriate device for measuring exhaust gases. The main variables used are the time spent in hoteling /manoeuvring and emissions. Concerning the previously mentioned research problem of emission, the following hypotheses were defined:

(1) there has been no significant increase in the emission of harmful gases in the observed period;

(2) there is no change in the trend of CO_2 emission in a period of three months for one year

Article II

The primary goal of this paper is to propose a new optimized hybrid ship power management to maximize ship energy efficiency and minimize fuel combustion and greenhouse emissions for the port of interest. In order to achieve this goal, a new configuration for the ship power plant of the existing Ro-Ro and high-speed passenger vessels is proposed, analyzed, and compared to the actual ship power configuration. Specifically, two configurations have been considered: the standard configuration consisting of the diesel generator system and the optimized hybrid solar-diesel generator configuration. For each of these configurations, realistic power calculations, emission reductions, and economic analyses were carried out. Concerning the previously mentioned research problem of solar panel applications on ships, the following hypotheses are defined:

(1) By installing effective solar panels on ships, a significant amount of electricity can be generated, thereby reducing reliance on traditional fossil fuel-powered generators;

(2) Solar applications aboard ships can considerably decrease fuel usage;

(3) Ships fitted with solar panels can reduce the carbon footprint caused by the use of fossil fuels.

Article III

This paper aims to evaluate the impact of optimized propellers on ship vibrations and fuel consumption and explores how they can reduce the environmental impact of maritime transportation.

Concerning the previously mentioned research problem of ship propeller optimization, the following hypotheses are defined:

(1) Optimized propeller design reduces vibrations;

(2) Vibration reduction enhances propeller efficiency and decreases fuel consumption;

(3) Propeller optimization reduces greenhouse gas (GHG) emissions from shipping.

To confirm these hypotheses, fuel consumption and vibrations on the Ro-Ro passenger ship during sea trials will be measured before and after ship propeller optimization on the same route. This data will be compared and expected fuel savings will be correlated to the CO_2 emission reduction.

In order to accomplish above mentioned it is of high importance to set reasoned requirements with the aim of significantly saving energy and reducing pollution of the marine environment. The contribution is manifested in raising the quality standards of the port, environmental protection, infrastructural investment of port and the city, and improving the quality of life.

4. MATHERIALS AND METHODS

To achieve the goals of this research, the following methods are used:

- Compilation method - already known data of individual authors from their previous research as well as data that can be obtained from relevant equipment manufacturers, inspection services, classification societies, etc. The compilation method was used in the introduction while collecting and studying literature related to the topic of this research.

- Method of analysis and synthesis - collecting data and information, analysing, and concluding on the considered research problem, what to reject and what to accept. Method of analysis and synthesis will be used to determine is it an acceptable solution to have a larger or smaller number of ships with renewable sources in the port of Split at one time and can ship owners follow the appropriate changes from the proposed solution. Data usage from some European ports (Barcelona, Venice, Koper) will be compared with ports in the Republic of Croatia, determining the appropriate correlation between these ports, determining what the trend is or which solution is most acceptable for the port of Split at the appropriate time.

- During data analysis and synthesis, the results are trained and validated using statistical metrics.

- Optimization method will develop an algorithm that will determine the optimal and economically acceptable number and power of renewable energy sources for certain groups of vessels with two main objectives: minimize Net Present Cost (NPC) and minimize the life cycle of CO_2 emissions (LCE).

- Propose a model of sustainable development port determination of the optimal number of vessels according to the electricity balance, seasonality, economic factors, and number of available vessels with installed renewable energy sources based on.

- Evaluation of the proposed model for the port.

5. STUDY SITE AND VESSEL QUALIFICATION

Split, the economic and cultural center of the Dalmatian region and the second-largest city in Croatia, serves as the country's preeminent passenger port, recording 2,800,502 passenger arrivals in 2019 [39]. In 2016, the port of Split led the Adriatic Sea region in ferry, hydrofoil, and fast catamaran traffic, among other Adriatic ports [40]. The Split–Supetar route is the busiest passenger transport ferry line in Croatia. Geographically, the passenger port is located on the southern side of the Split peninsula, while the northern side is the base of the Croatian Navy and the Split Cargo Port.

Historically, Split's strategic position has positioned it as a transit city for decades. However, recent increases in tourism have positioned Split as a top tourist destination, as demonstrated by numerous tourism metrics. According to the Split Tourist Board Statistics, the city registered a total of 932,722 tourist arrivals in 2019, with an 8.15% increase compared to 2018 [41].

The increasement in tourist numbers has impacted the demand for improved connectivity between the mainland and the islands. Data from the Port Authority reveal a consistent increase in ship arrivals since 2010 [42].

This study aimed to test the hypothesis that an increased number of ship arrivals correlates with higher emissions, utilizing the bottom-up method for analysis.

In *Article I*, 34 line ships were monitored in 2017, with a total of 70,699.97 hours spent in port and 12,330 calls recorded. In 2018, 33 line ships were observed, with total of 84,519.816 hours spent in port and 13,639 calls. By 2019, the number of line ships increased to 36, with a total of 65,908.61 hours spent in port and 14,522 calls. The engine power of these line ships varied significantly, ranging from 220 kW to 15,015 kW.

In *Article II* 35 ships were monitored, with over 250 port calls per day during the peak season. These line ships were categorized based on the power of their main engines as follows:

- Ships with main engine power less than 2000 kW: This category includes 8 ships, with passenger capacities ranging from 80 passengers for a ship with a 220 kW engine to 1200 passengers for a ship with a 1968 kW engine.
- Ships with main engine power between 2000 kW and 4000 kW: This category comprises 18 ships, with passenger capacities ranging from 250 passengers for a ship with a 2160 kW engine to 1080 passengers for a ship with a 3600 kW engine.

- Ships with main engine power greater than 4000 kW: This category consists of 9 ships, with passenger capacities ranging from 316 passengers for a ship with a 4000 kW engine to 1300 passengers for a ship with a 13,248 kW engine.

For this research, three vessels were selected, including two Ro-Ro passenger ships of different sizes and powers, and one high-speed passenger ship. Each vessel represents one of the categories. A detailed step-by-step analysis is presented for one Ro-Ro vessel, while the results, including CO_2 and NO_X emissions reductions and associated costs, are summarized for all three vessels.

In *Article III* propeller optimization was carried out on a Ro-Ro passenger ship. The specifications, including the year of construction, hull length, breadth, depth, gross tonnage, and propulsion characteristics, were sourced from the vessels Certificate of Registry.

6. PUBLISHED SCIENTIFIC PAPERS

6.1 Article I

The maritime traffic pollution problem is a growing concern globally, especially in coastal regions with dense populations and high maritime activity. Despite the efficiency of maritime transport, its environmental footprint is substantial. Emissions from ships are not limited to accidental spills but also occur during regular navigation and operations. These emissions impact air quality causing significant environmental and health risks such as respiratory problems, cardiovascular diseases, acid rain, and global warming.

Article I explores the emissions generated by maritime traffic in Port Split, Croatia. Split, Croatia's second-largest city, serves as a major passenger port, experiencing significant tourist traffic and ferry line operations. The study analyzes data on ship arrivals and time spent in port from year 2017 to 2019. The number of coastal ferry line arrivals in Port Split increased by 10% from 2017 to 2018 and by 6% from 2018 to 2019. The rise in number of ferry line arrivals highlights the growing significance of managing emissions in the port.

The research is focused on the emissions from line vessels during manoeuvring and hotelling phases, highlighting pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compounds (VOC), sulphur dioxide (SO_2), particulate matter (PM), and black carbon.

The methodology involves:

- Data Collection: Gathering detailed information on ship arrivals, departures, and time spent in port.
- Emission Calculations: Using emission factors to estimate emissions for different pollutants and different ship phases.
- Statistical Analysis: Applying statistical methods to analyze the data and identify trends, correlations, and patterns in emissions over time.

A bottom-up approach is used to estimate emissions, using detailed data on ship activities, as it provides more accurate data. The bottom-up method involves collecting data on ship characteristics, the ship operations phases, load factors, and the time spent in each phase.

Emissions are calculated using specific formula that considers main and auxiliary engine power, load factors, main engine time of operation, time spent in each phase and emission factors. The study uses specific emission factors for pollutants such as NOX, SO_2, CO_2, VOC, and PM. The methodology involves multiplying the time spent in each phase by the sum of installed engine power, load factors, and emission factors.

Emissions data revealed seasonal trends, with higher emissions during the summer months due to increased ferry operations. In 2018, the highest emissions were recorded in the months of July and August, corresponding to peak of tourism season. Emissions during the hotelling phase contribute significantly to the overall emissions due to the continuous operation of auxiliary engines.

This case study serves as a valuable reference for other ports facing similar challenges in managing ship emissions. The study results show the need for port cities to consider adoption of new technologies for reducing emissions and lowering their impact on human health and the environment. To reduce harmful emissions, the study suggests better voyage planning to optimize ship schedules and reduce time spent in port, encouraging the use of low sulphur fuels, adopting renewable energy technologies, such as solar panels and wind turbines, to power systems on ships, promoting integrated management involving various stakeholders, including port authorities, shipping companies, and environmental agencies, to enhance efficiency and reduce emissions.

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Article

A Line Ship Emissions while Manoeuvring and Hotelling—A Case Study of Port Split

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Abstract: Strategically, the Republic of Croatia, with its economy focused on tourism, is directly connected to the sea and coastal area, and integrated management of this area contributes to the sustainable development strategy. Worldwide, the problem of atmospheric pollution from maritime traffic is a poorly researched area, especially when this type of traffic is continuously growing. On the example of Port Split, the paper aims to present the following emission, carbon dioxide (CO_2), nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compounds (VOC), sulphur dioxide (SO_2), particulate matter (PM) and black carbon, of line vessels during manoeuvring and hotelling phase for 2017, 2018 and 2019. Furthermore, the statistical analysis and appropriate conclusions have been performed on CO_2 since all other emissions are linearly dependent. From the analyses in the hotelling and manoeuvring phase of line ships, it can be concluded that during 2019 there was a slight increase in emissions, but overall there was no significant increase in the number of line vessels and increased traffic. The obtained results of case study of port Split provide recommendations leading to further reduction of harmful gas emission, monitoring them, and integrating it into management of urban ports.

Keywords: line vessels emissions; bottom-up method; hoteling; manoeuvring; city port

1. Introduction

Maritime transport is considered to be the most energy-efficient mode of transport since it can carry the largest amount of cargo with the least energy consumed. Unfortunately, it has bad effects on the environment and human health [1]. Pollution from ships is not limited only to maritime accidents but also to the regular navigation and ship operations. The main ship impacts on the environment are sea discharges, gas emissions, and noise [2].

Sea pollution from ships has a visible impact on the surrounding area and countries since is transferred transboundary in the atmosphere and globally affects the air quality [3]. Air emissions include pollutants and greenhouse gases. The main focus of this paper are major pollutants (nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compounds (VOC), sulphur dioxide (SO_2), particulate matter (PM) and greenhouse gas (carbon dioxide (CO_2) [4]. Furthermore, there are a lot of sources of pollution that can come from the ship, such as oil spills, ballast waters, grey waters, black waters, anti-fouling paint, noise, solid waste, as shown in Figure 1 [5].

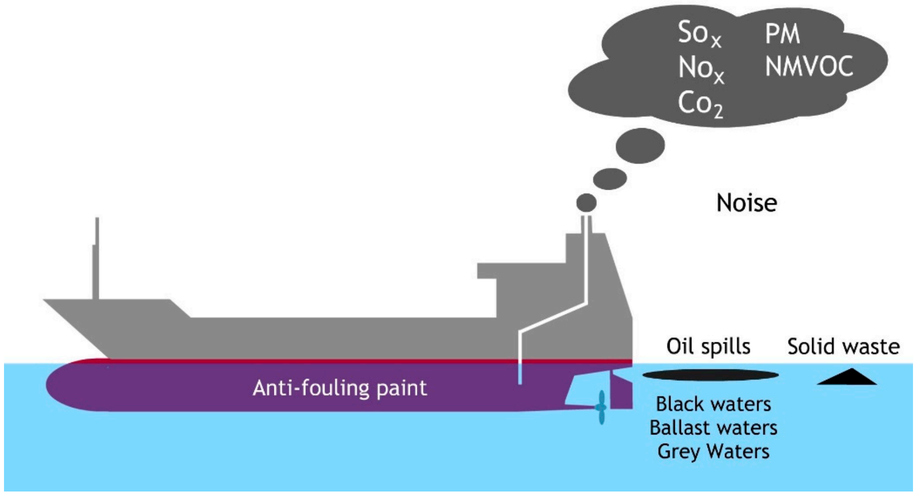

Figure 1. Environmental impact of shipping.

According to the World Health Organization (WHO), 4.2 million people died in 2016 due to air pollution [6]. Comparing the emission values of five commonly used inventories (EMEP; TNO-MACC_III; E-PRTR; EDGAR and STEAM), the contribution of shipping to overall emissions is 16% for NO_X 11% for SO_X and 5% for PM_{10} [7]. Shipping emissions contribute 1–7% of ambient air PM_{10} levels, 1–14% of $PM_{2.5}$, and at least 11% of PM_1 in European coastal areas. Shipping emissions contribute with 7–24% of ambient air NO_2. The highest values of NO_2 have been recorded in the Netherlands and Denmark [8]. In the Mediterranean area locally released NO_X is mainly responsible for the production of ozone. Excluding NO_X emissions NO_X emissions from ships in model would reduce the surface ozone concentration by 15% [8]. Ship emissions are affecting air quality and human health in the coastal communities. NO_2 and CO-emissions in ports are connected to bronchitic symptoms, and exposure to SO_2 emissions is connected with respiratory issues and premature births [9]. If the legislation and regulations on land result in a reduction of emissions from sources on land, the impact of maritime transport at the global level will increase, especially taking into account its continued growth. Therefore, by placing limits on harmful gases from maritime transport, this impact will be minimized.

Although the International Convention for the Prevention of Pollution from Ships (MARPOL) has a major role in regulating shipping pollution, several directives are adopted to supplement or clarify specific fields of interest. Table 1 shows the organizations, conventions, and laws related to ship emissions.

Table 1. The list of organizations conventions and laws regarding air pollution from ships.

Name	Abbreviation	Founded/Entered into Force	Role/Aim
International Maritime Organization	IMO	1948	Organization with the role of standardizing procedures and rules for safety at sea
International Convention for the Prevention of Pollution from Ships	MARPOL	1973	International Convention developed my IMO divided into VI Annexes regarding the different pollutions from the ships
Technical code on control of emissions of Nitrogen Oxides	NO_X Technical Code	2008	Document adopted by IMO and in accordance with MARPOL Convention for control of NO_X emissions

Table 1. *Cont.*

Name	Abbreviation	Founded/Entered into Force	Role/Aim
Sulphur Content of Marine fuels directive	SCMF directive	2005	EU directive regarding fuel regulation used by passenger vessels on regular services between EU ports. According to the directive while at berths in ports, all ships must use fuel with sulphur content less than 0.1 by weight. The same strict limit of 0.10% m/m. has already been applied in the emission control areas (ECAS), set by the International Maritime Organization.
Environmental Protection Act		2013	Croatian act which regulates environmental protection principles
Air Protection Act		2011	Croatian act which regulates air protection

The first column shows the organizations, conventions, and laws. The second column contains abbreviations. Further, the third column contains years when they are founded/entered into force, and the fourth column briefly indicates their role. For example, IMO is an organization with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.

Carbon dioxide in shipping occurs during the combustion of fossil fuels. According to the fourth IMO study (2020) on greenhouse gases emissions, maritime contribution to greenhouse gas emissions is 2.89% [10]. The same study shows that transporting goods by ships is responsible for approximately 1,056 million tons of CO_2 annually. The projections show that shipping emissions could increase between 90% and 130% of 2008 emissions by 2050 [10].

The combustion of fossil fuels emits various sulphur oxides (SO_X). As reported by several authors, shipping contributes to SO_X's overall anthropogenic emission from 5 to 8% [11,12]. The percentage of sulphur in fossil fuels can vary, depending on the fuel type. Sulphur oxides have a negative impact both on human health and on the environment [13,14]. The IMO is reducing the percentage of sulphur used in marine fossil fuels from year to year. The sulphur content of any fuel used on board shall not exceed the following limits: 4.50% by weight before 1 January 2012; 3.50% by weight from 1 January 2012 onwards; 0.50% by weight from 1 January 2020 onwards. According to the EU Directive 2005/33/EC, while at berths in ports, all ships must use fuel with sulphur content less than 0.1 by weight [15]. The same strict limit of 0.10% m/m. has already been applied in the emission control areas (ECAS), set by the International Maritime Organization [16]. Another way of air pollutants limitation is by installing exhaust gas cleaning systems ("scrubbers"). Ships with installed scrubbers can continue use heavy fuel oil of 3.5% sulphur content [17]. Nitrogen oxide emissions (NO_X) from ships are forming when fuel burns at high temperatures in the ship's internal combustion engine. The overall ship sector contributes to the anthropogenic emission of NO_X by 15% [11]. NO_X emissions affect the environment by causing acid rain. When combined with VOC, ground-level ozone is formed, and impacts human health [13,14]. NO_X emissions are regulated by the MARPOL Annex VI. The Different levels (Tiers) of control apply based on the ship construction date. The Tier I regulation refers to ships built after 1 January 2000, the Tier II regulation refers to ships built after 2011, and Tier III refers to ships built after 2016. The NO_X emission limits vary for the slow-speed engines (<130 rpm) the high-speed engines (>2000 rpm) and the intermediate speed engines ($130 < n < 2000$ rpm) [18].

The particulate matter (PM) is the aerosols, consisting of mixtures of solid particles and liquid droplets found in the air, and they are defined by size. PM_{10} are defined by size. PM_{10} are inhalable particles with a diameter larger than 2.5 micrometres and smaller than 10 micrometres and $PM_{2.5}$ are fine particles that are 2.5 micrometres and smaller. The PMs are affecting human health by the lungs, causing inflammation, and restricting the passage of oxygen to the blood [13,14]. According to the European Environment Agency (EEA) $PM_{2.5}$ concentrations in 2016 were responsible for more than 412,000 premature deaths due to long-term exposure in Europe [19].

The non-methane volatile organic compounds (NMVOCs) are a collection of organic compounds that differ widely in chemical composition when emitted into the atmosphere from a large number of sources, including combustion. NMVOCs have a negative impact on the environment and human health [13,19].

Air pollution from ships can be estimated on a global and/or local scale. The global scale impact implies emissions during the ship navigation, while the local implies emissions in the ports or nearby ports [13]. Approximately 70% of the ship emissions are estimated to occur within 400 km of land and can significantly influence the air quality of a coastal area [5].

Several studies on port emissions are related to shipping, but it is difficult to compare their results since they use different methodologies [9]. Several methodologies are used for estimating emissions, which can be summed into a bottom-up approach and a fully top-down approach [20]. Reviewing the literature [21–34], comparing the methodologies used in bottom-up and top-down methods, and taking into account that our research problem was based on ship activity data, the bottom-up method has been used. The bottom-up method uses more data from the Automatic Identification System (AIS) such as ship characteristics, ship phase, loading factors, and the time spent in each stage [13]. In contrast, the top-down method uses sold fuel and the fuel emission factor [35]. The uncertainties of top down methodology are based on question are bunker fuel sale statistics representative [5]. According to the 4th IMO GHG study sources of uncertainties can be fuels reported under different categories or placed in both categories (national and international navigation) [10].

Furthermore, the bottom-up method is used for estimating gas emissions in the following ports: Zadar port in Croatia, Busan port in Korea, Izmir port in Turkey, Barcelona port in Spain, Yangshan port in China, Portugal ports Leixões, Setúbal, Sines, and Viana do Castelo [25,30,32,35–37].

The goals of this paper are: to examine correlations between emissions over the observed period, in manoeuvring and hotelling phase, to identify seasonal oscillations, and to give recommendations on how to reduce the gas emissions to improve the quality of living in city port area.

2. Materials and Methods

The main variables used are the time spent in hotelling/manoeuvring and emissions. Concerning the previously mentioned research problem of emission, the following hypotheses can be defined: (1) there has been no significant increase in the emission of harmful gases in the observed period; (2) there is no change in the trend of CO_2 emission in a period of three months for one year.

The city of Split is the economic and cultural centre of the Croatian region Dalmatia and the second-largest city in Croatia. It is also the greatest passenger port in Croatia, with 2,800,502 passenger arrivals in 2019 [38]. In 2016 the port of Split was the leading port in the ferry, hydrofoil, and fast catamaran traffic on the Adriatic Sea, compared to other Adriatic ports from other countries. The Split–Supetar route is the main passenger transport route in Croatia [39]. The passenger port is located on the south side of the Split peninsula, while on the north side of the Split peninsula is the base of the Croatian Navy and Split Cargo Port.

As a consequence of its position, Split has been a transit city for decades. Recent tourism growth profiled Split as a top destination and tourist record holder by numerous indicators. According to the Split Tourist Board Statistics page, in 2019, Split city had a total of 932,722 tourist arrivals [40]. In comparison to 2018, an 8.15% increase in tourist arrivals has been noted. With its rich historical heritage and favourable climate, it has become a trending location for tourists, whether they are arriving to Split, or just passing by on their way to the Central Dalmatian.

With the increase on tourists, the need for a better connection between the mainland and islands also increases. According to the Port Authority data, the number of ship arrivals is recording growth from 2010 onwards. This growth is graphically presented in Figure 2.

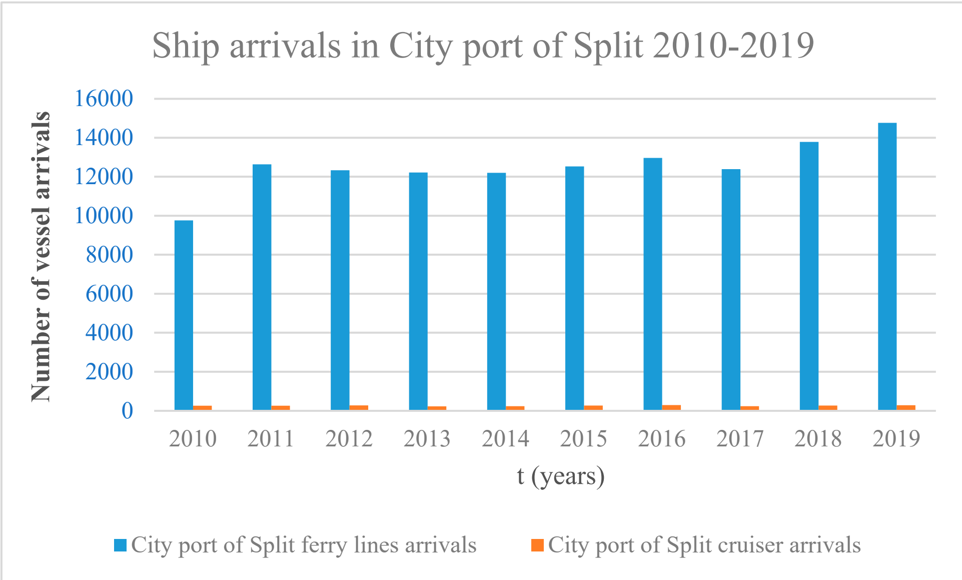

Figure 2. Ship arrivals in the City port of Split from 2010 to 2019.

In this paper, the port gas emission estimation is calculated for the line ships since these ships make the majority in the number of arrivals and, therefore, impact air pollution. In 2017, there were 12,389 ship arrivals, of which 59 excursion boats and 12,330 coastal ferry line arrivals. In 2018, there were 13,785 ship arrivals of which 146 excursion boats and 13,639 coastal ferry line arrivals. In 2019, there were 14,759 of which 237 excursion boat and 14,522 ship arrivals coastal ferry line arrivals. The number of coastal ferry line arrivals was increased from 2017 to 2018 by 10% and from 2018 to 2019 by 6%.

3. Emission Estimation for City Port of Split

The approach used in estimating the emissions is consistent with the methodology for quantifying ship emissions in the EMEP/EEA air pollutant emission inventory guidebook. As mentioned in the introduction, the bottom-up approach uses more detailed information than top-down in estimating the emissions.

Although there are several methods for emission calculation, the Tier 3 method was used since it provides insight into the emission of different ships activity like manoeuvring, hotelling and cruising [41].

By comparing several references for estimating emission (ENTEC 2002, ENTEC 2007, and EMEP/EEA 2019 Shipping Tier 3–Ship movement calculation), older emission factors are used due to the fact that in newer literature are only given emission factors for NO_X, NMVOC and PM. By comparing newer and older literature, NMVOC factors were the same, and PM and NO_X emission factors had slight differences. NO_X factors are the same for the ships older than year 2000, making the majority of observed vessels in this paper.

When estimating ship emissions, it is necessary to determine the ship activity. The ship activities are divided into three phases: at the sea, the manoeuvring and the hotelling. The hotelling is the phase when the ships are berthed, while they await their next voyage or cargo load/discharge. The total ship emissions are the sum of the emissions in the abovementioned activities. In this paper, due to the field of interest (the City port of Split), and the data availability, only the manoeuvring and the hotelling phase emissions are calculated. The so-called "At sea" phase is not taken into account in this paper since the area of interest is the City port of Split and emissions in the harbour. Split Port Authority provided the number of ship arrivals and the time spent hotelling as daily based. It must be pointed out that data have been converted into hours for the estimation formula's purpose.

Although ENTEC gives a value of 0.8 h for passenger ships spent in the manoeuvring phase, passenger ships in the port of Split on average of 20 min (0.33 h) spent in manoeuvring phase were provided by Jadrolinija officeholder [42].

The emissions are related to the engine and the fuel type. For each ship installed main or auxiliary engine power data is provided form CRS (Croatian Registry of Shipping) or E-vessel portal, which gives access to electronic services of the Ministry of the Sea, Transport and Infrastructure [43,44]. Hence, in 2017, 35 ships were observed, 2018, 32 ships were observed, and in 2019, 36 ships were observed. The auxiliary engine power is unknown for ten ships, which affects the amount of emissions.

It has to be noted that the main and the auxiliary engines installed in the passenger ships are assumed to be using MDO (marine diesel oil) to comply with the sulphur limits of the Sulphur Content of Marine fuels (SCMF) directive for fuels used by the passenger vessels on the regular services between EU ports.

The engine load factor is defined as the engine's actual power output relative to its Maximum Continuous Rating (MCR).

The Emission Factors are taken from the ENTEC study for estimated pollutants. LF_{ME} is the main engine load factor, LF_{AE} is auxiliary engine load factor, and TO_{ME} is the main engine time of operation during the phase of manoeuvring and hoteling. Their values are shown in Table 2 [44]. The emission factors depend on several factors, such as the main engine type, the auxiliary engine type, and fuel type. Furthermore, ships are divided by the engine speed (slow speed diesel (SSD), medium-speed diesel (MSD), high-speed diesel (HSD), gas turbine, and steam turbine) and the fuel types (RO "Residual Oil" (heavy fuel oil), MDO "Marine Diesel Oil" and MGO "Marine Gas Oil"). There are different NO_X emission factors for the main engine depending if the ships are built before or after 2000. The newer engines, which comply with the NO_X Technical Code requirements, have roughly 17% lower NO_X emissions than the pre-2000 engines [42]. The requirements of the NO_X Technical Code have roughly 17% lower NO_X emissions than the pre-2000 engines [42]. The emission factors used in this paper are shown in Table 3 [42].

Table 2. The main and the auxiliary engine load factors. and the main engine time of operation.

Phase	LF_{ME} (%)	TO_{ME} (%)	LF_{AE} (%)
Manoeuvring	20	100	50
Hotelling (except tankers)	20	5	40

Table 3. Main and auxiliary engine emission factors for manoeuvring and at berth [45].

Engine Type	Fuel Type	NO_X Pre 2000 Engine	NO_X Post 2000 Engine	SO_2 (g/kWh)	CO_2 (g/kWh)	VOC (g/kWh)	PM (g/kWh)
Main engine emission factors for manoeuvring and at berth 2007							
MSD	MDO	10.6	8.8	6.8	710	1.5	1.2
Auxiliary engine emission factors for manoeuvring and at berth 2007							
M/H SD	MDO	13.9	11.5	6.5	690	0.4	0.4

In order to use the bottom up methodology, detailed data is required, including the engine type, the installed power, the hours spent in different phases and the fuel type [42]. The main engine load factors, the auxiliary engine load factors and the main engine time of operation are taken from ENTEC 2002 [45].

Mathematical Backgrounds

The emissions are calculated by multiplying manoeuvring and hotelling time with the sum of the installed main and auxiliary engine power, the load factors for the main and auxiliary engine, the load factors for the main engine, and the operation's main engine time and emission factors. The time spent hotelling was provided in days and converted into hours for the estimation formula's purposes. The same formula is used for estimating air pollution in Ancona harbor [41].

The Emissions for the phase are calculated as follows:

$$\mathbf{E} = [(\mathbf{ME} \times \mathbf{LF_{ME}} \times \mathbf{EF_{ME}} \times \mathbf{TO_{ME}}) + (\mathbf{AE} \times \mathbf{LF_{AE}} \times \mathbf{EF_{AE}})] \times \mathbf{T} \quad (1)$$

where

ME is the main engine power (kW);
$\mathbf{LF_{ME}}$ is the main engine load factor (%);
$\mathbf{EF_{ME}}$ is the main engine emission factor (g/kWh);
$\mathbf{TO_{ME}}$ is the main engine time of operation (%);
AE is the auxiliary engine (kW);
$\mathbf{LF_{AE}}$ is the auxiliary engine load factor (%);
$\mathbf{EF_{AE}}$ is the auxiliary engine emission factor (%);
T is the time spent in port (h) or manoeuvring (h);
E is emissions (g).

Presented statistical measures would give an insight into relationships between CO_2 emission variables of the Split port. The correlation between the variables is shown with the matrix C_A correlation. To get correlations between months a trend or moving average operation needs to be performed on raw data.

The mathematical foundations that are further used in the paper are based on the application from the literature, with the following variables $\boldsymbol{X_{2017}}, \boldsymbol{X_{2018}}, \boldsymbol{X_{2019}}$ being added to the vectors:

$$\begin{aligned} X_{2017} &= [x_{20171}.x_{20172}.\cdots.x_{2017i}] \\ X_{2018} &= [x_{20181}.x_{20182}.\cdots.x_{2018i}] \\ X_{2019} &= [x_{20191}.x_{20192}.\cdots.x_{2019i}] \end{aligned} \quad (2)$$

where $\boldsymbol{X_{2017}}, \boldsymbol{X_{2018}}, \boldsymbol{X_{2019}}$ represents random emission variables of ships date samples obtained from 2017 to 2019.

Standard statistical metrics such as expectation or the average value, standard deviation, and correlation coefficient are used to study random variables. The average value of the random variable $\boldsymbol{x}$ [46].

$$E[x] = \bar{x} = \frac{1}{N} \times \sum_{i=1}^{11} x_i = \frac{1}{N}\left(X \times X^T\right) \quad (3)$$

where $E[x]$ represents the expectation of a random variable $\boldsymbol{x}$, and N is the number of measurement samples. The following equation can represent the standard deviation of the random variable $\boldsymbol{x}$:

$$\sigma_{\overline{X}} = \sqrt{\frac{1}{N-1} \times \sum_{i=1}^{11} (x_i - \bar{x})^2} = \sqrt{E[x^2] - E[x]^2} \quad (4)$$

where σ_x represents the standard deviation of the random variable $\boldsymbol{x}$.

The statistical metric used to quantify the similarity and/or dependence among variables, x_p, and x_v, is the correlation coefficient between random variables. The correlation coefficient can be calculated from the following equation [28]:

$$r = \frac{1}{N-1} \times \frac{\sum_{i=1}^{11}\left(x_{ip} - \overline{x_p}\right) \times \left(x_{iv} - \overline{x_v}\right)}{\sigma_{xp} \times \sigma_{xv}} \tag{5}$$

where r represents the correlation coefficient, N- is the number of measurements while σ_{xp} and σ_{xv} represent the standard deviations of the random variables x_p and x_v. Furthermore, a model matrix A can be created using the following equation:

$$A = \begin{bmatrix} X_{2017} \\ X_{2018} \\ X_{2019} \end{bmatrix} = \begin{bmatrix} x_{20171} & \cdots & x_{201712} \\ x_{20181} & \cdots & x_{201812} \\ x_{20191} & \cdots & x_{201912} \end{bmatrix}_{(3\times 12)} \tag{6}$$

where $X_{2017}, X_{2018}, X_{2019}$ are vectors of random variables. The correlation matrix C_A is defined by the following equation:

$$C_A = \frac{1}{N-1} \times \left(A \times A^T\right) \tag{7}$$

Using (2) and (6) the correlation matrix C_A is defined as follows:

$$C_A = \begin{bmatrix} c_{2017.2017} & c_{2017.2018} & c_{2017.2019} \\ c_{2018.2017} & c_{2018.2018} & c_{2018.2019} \\ c_{2019.2017} & c_{2019.2018} & c_{2019.2019} \end{bmatrix}_{(3\times 3)} \tag{8}$$

In order to perform the smoothing. different moving average algorithms can be used: simple moving average (SMA). a weighted moving average (WMA). an exponential moving average (EMA), and an exponential weighted moving average (EWMA). To perform a simple moving average (SMA) filtering on data following equitation is used [47]:

$$SMA(n) = \frac{1}{WL}\left(x_n + x_{n-1} + \cdots + x_{n-(WL-1)}\right) \tag{9}$$

where $SMA(n)$ denotes the moving-average filtering of a vector x. A moving-average filter slides a window of length (WL) along the data and computes averages of the data contained in the (WL) window size.

4. Case Study

The port of Split is the largest passenger port in the Republic of Croatia, where the arrivals of ship depend on seasonality. The assumption that the larger number of arrivals will produce more emissions, will be tested using the bottom-up method. Because the number of all ship types arrivals is increasing, the paper's main objective is to establish the relationships between the number of arrivals and gas emissions.

In this paper, 34 line ships are observed during 2017, the total number of hours spent in the port is 70,699.97, and the number of calls is 12,330.

In 2018, the number of line ships was 33, the total number of hours spent in the port was 84,519.816, and the number of calls is 13,639.

The total number of line ships was 36 in 2019, the total number of hours spent in the port was 65,908.61, and the number of calls is 14,522.

The engine powers of line ships are different and range from 220 kW–15,015 kW.

The calculation for the ship Biokovo is performed by Equation (1), as it shown in Table 4.

Table 4. The example of the excel table for the ship Biokovo—hoteling phases on 19 January 2017.

SHIP	BIOKOVO
Main engine (kW)	1968
Auxiliary engine (kW)	532
Main engine EF NO_X (g/kWh)	8.8
Main engine EF NMVOC (g/kWh)	1.5
Main engine EF TSP PM10 $PM_{2.5}$ (g/kWh)	1.2
Maine engine EF SO_2	6.8
Maine engine EF CO_2	710
LF main engine (%)	0.2
Main engine time of operation (%)	0.05
LF auxiliary engine (%)	0.4
Auxiliary engine EF NO_X (g/kWh)	11.5
Auxiliary engine EF NMVOC (g/kWh)	0.4
Auxiliary engine EF TSP PM10 $PM_{2.5}$ (g/kWh)	0.4
Auxiliary engine EF SO_2	6.5
Auxiliary engine EF CO_2	690
NO_X (g)	23,394.78835
NMVOC (g)	1023.50592
PM (g)	970.795008
SO_2 (g)	13,543.9903
CO_2 (g)	1,435,665.25
Arrival	19.01. 11:35
Departure	19.01. 20:30
Hours	8.927

Biokovo ferry has the main engine power of 1968 kW and the auxiliary engine power of 532 kW. The emission factors for the main engine are taken from Table 3. The main engine emission factor for NO_X is 8.8 g/kWh due to the fact that the engine is post-2000. The Auxiliary engine emission factors are calculated from Table 4. The main and the auxiliary engine load factors and the operation's main engine are taken from Table 2. The Port Authority provided the arrival time and the departure time. as well as the days spent in the port.

5. Results and Discussion

5.1. Results

In this study, the ship emissions are calculated using the activity-based emission estimation for the City port of Split, which is the most significant passenger port in Croatia. The ship emissions are estimated for the ship manoeuvring and hotelling phase. The hotelling phase is responsible for the largest emissions in the port: NO_X 90.1%; $PM_{2.5}$ 78.0% and SO_X 88.5% [28]. These percentages can vary depending mainly on time spent hotelling and duration of manoeuvring phase [13].

Total emissions in tons of emitted parameters are shown in Table 5. for each month of the observed years. As seen in Table 5. the highest amount of emissions in 2018 was calculated during ship manoeuvring and hotelling operations for all investigated pollutants.

Table 5. Total emissions in grams of emitted parameters for each month of the observed year for the Port of Split.

Year/Months	NMVOC (t)	PM (t)	CO_2 (t)	NO_X (t)	SO_2 (t)
2017 total	12.40	10.98	12,501.68	215.84	118.30
1	0.86	0.78	942.39	16.07	8.91
2	1.39	1.22	1335.65	23.13	12.65
3	0.79	0.70	820.13	14.07	7.76
4	1.00	0.90	1062.19	18.47	10.05

Table 5. *Cont.*

Year/Months	NMVOC (t)	PM (t)	CO_2 (t)	NO_X (t)	SO_2 (t)
5	1.08	0.95	1081.02	18.60	10.23
6	1.05	0.92	1000.19	16.97	9.47
7	1.19	1.04	1091.28	18.37	10.34
8	1.07	0.93	966.85	16.14	9.16
9	1.13	1.00	1104.90	18.96	10.46
10	1.30	1.18	1480.56	26.92	13.99
11	0.70	0.63	742.39	13.09	7.02
12	0.83	0.74	874.12	15.05	8.27
2018 total	13.07	11.62	13,487.27	234.57	127.59
1	0.96	0.87	1066.49	18.52	10.08
2	1.08	0.98	1269.32	22.81	11.99
3	0.95	0.85	1021.16	17.95	9.66
4	1.08	0.97	1139.95	19.94	10.78
5	1.30	1.15	1345.52	23.36	12.73
6	1.13	0.99	1088.83	18.54	10.31
7	1.30	1.13	1192.61	20.10	11.30
8	1.13	0.98	990.79	16.47	9.39
9	1.19	1.05	1158.38	19.87	10.97
10	1.34	1.21	1484.75	26.64	14.04
11	0.74	0.66	781.49	13.75	7.39
12	0.86	0.77	947.98	16.61	8.96
2019 total	12.84	11.37	12,920.00	224.76	122.26
1	0.86	0.77	951.16	16.76	8.99
2	0.88	0.80	967.08	17.20	9.14
3	0.83	0.74	881.92	15.77	8.34
4	0.99	0.89	1065.28	18.91	10.07
5	1.40	1.24	1428.29	24.93	13.51
6	1.21	1.05	1103.50	18.58	10.45
7	1.29	1.11	1087.88	17.94	10.32
8	1.24	1.06	1043.28	17.21	9.89
9	1.27	1.11	1170.37	19.79	11.09
10	1.28	1.16	1463.33	26.58	13.83
11	0.81	0.73	915.58	16.37	8.65
12	0.79	0.70	842.32	14.70	7.97
Grand Total for 3 years	38.31	33.97	38,908.95	675.17	368.15

From recent literature, the traffic data for passenger ships other than a cruise, together with annual emissions (tons per year) of NO_X and PM_{10} for the ports Barcelona, Hong Kong, Copenhagen, Venice, Elsinore, St Petersburg, Las Palmas, Genoa, and Marseille are given [13]. These ports have no similarities in size or number of ship arrivals/departures, but the aim was to take into account emissions in urban cities that have ports within the city, such as Split. The minimum NO_X emissions are 20 tons per year in the Hong Kong and 1300 tons per year calculated in Marseille port [13]. For PM_{10} emissions in ports, the range is between 1 ton per year in the Hong Kong port and 80 tons per year in Marseille port [13]. Exhaust gas emissions from ships are calculated for Izmir Port using the ship activity-based methodology. Total emissions from ships in the port is estimated as 1923 tons per year for NO_X, 1405 tons per year for SO_2, 82,753 tons per year for CO_2, 1 ton per year for HC, and 165 tons per year for PM in the year 2007 [30].

The Emissions for each pollutant, divided into manoeuvring and hotelling phase, are shown in Figures 3–7. The emissions are divided into years and months and are represented in tons (t). Blue plots represent the hotelling phase (H) and the orange plots represent the manoeuvring phase (M). If side by side comparison is done, the emissions were higher for all pollutants during the hotelling phase than during manoeuvring phase, due to longer time spent in port.

As shown in Figure 8 the hotelling phase contributes to most SO_2 emissions with several peaks during the year. On the contrary, the emission trough the manoeuvring phase shows seasonality each year, and it is always relatively smaller than emission during the hotelling phase. The total annual SO_2 emission varies from 118 to 127 tons per year, which is way lower than 1405 tons per year in Izmir port [30].

Furthermore, NO_X emission varies between 215 tons per year and 235 tons per year (Figure 3), which is almost equal to Barcelona NO_X emissions. Ports Hong Kong. Copenhagen, Venice, and Elsinore have lower NO_X emissions in ports. Ports St Petersburg, Las Palmas, Genoa and Marseille, have higher NO_X emissions. Croatian port of Zadar has total annual cruise ships emissions 310.23 tons per year for NOx, and 9.62 tons per year for PM [35]. Port of Split has lower NO_X emissions and higher PM emissions compared to the port of Zadar.

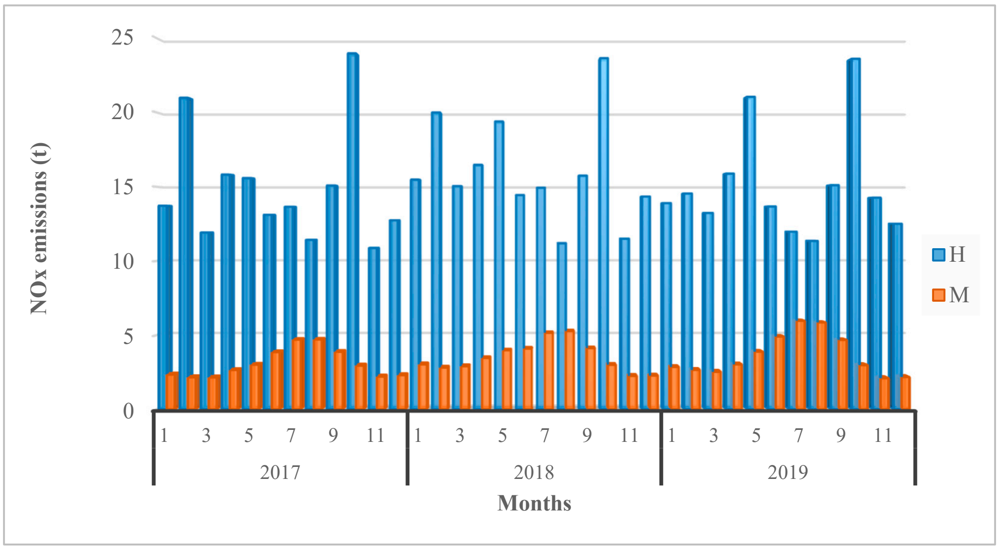

Figure 3. NO_X emissions through years for the hotelling and manoeuvring phase in Split port.

The study of PM_{10} emission in Ancona's port reveals that most emissions (70%) happen during the hotelling phase [41]. These emissions correlate with the PM_{10} emissions from the port of Split (Figure 4). During the hoteling PM emission represents 69% in 2017, 68% in 2018 and 65% in 2019 of total PM emissions in Venice port, Ports Hong Kong, Elsinore, St Petersburg, and Las Palmas have lower PM emissions. Contrary, ports with higher PM_{10} emissions are Barcelona, Genoa, Copenhagen, and Marseille [13].

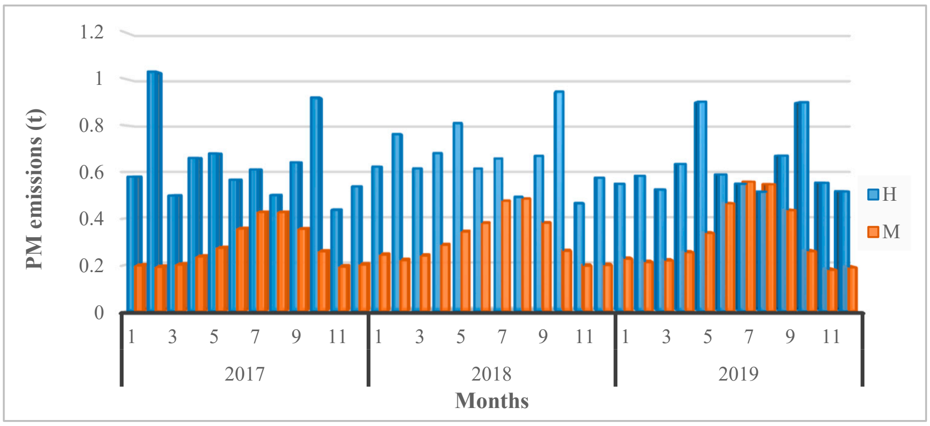

Figure 4. PM emissions through years the hotelling and the manoeuvring phase in Split port.

From Figure 5, the total annual NMVOC emission varies from 12 to 13 tons per year. In manoeuvring phase emissions are slightly higher during the tourist season period than hotelling phase emissions. This can be explained that in the tourist season period, the number of ship lines has been increased, and therefore, ships spend less time in the ports. As a consequence, the hotelling time is reduced and, therefore, emissions. Additionally, more port arrivals/departures increase manoeuvring time and thus manoeuvring phase emissions.

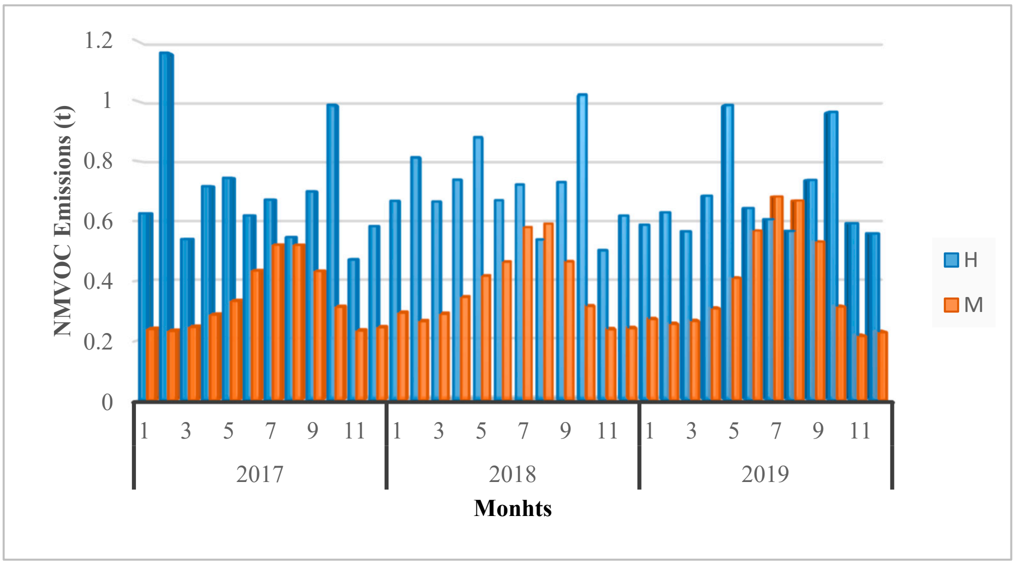

Figure 5. NMVOC emissions through years for hotelling and manoeuvring phase.

CO_2 emissions contribute majorly to total emissions. From Figure 6, the total annual CO_2 emission varies from 12.5 to 13.5 kt. From study [48] and monthly results, there is a difference between the in-season and off-season periods. All emissions slightly increase starting from May and then decrease from October towards the end of the year. The highest manoeuvring emissions are in July and August for all observed years. Such emission trend corresponds to the Croatian shipping company "Jadrolinija" which has the largest number of ship arrivals in the Split city port. The number of ferry lines increases since the end of May, with the peak arrivals in July, August, and September. From the beginning of October, the number of lines decreases.

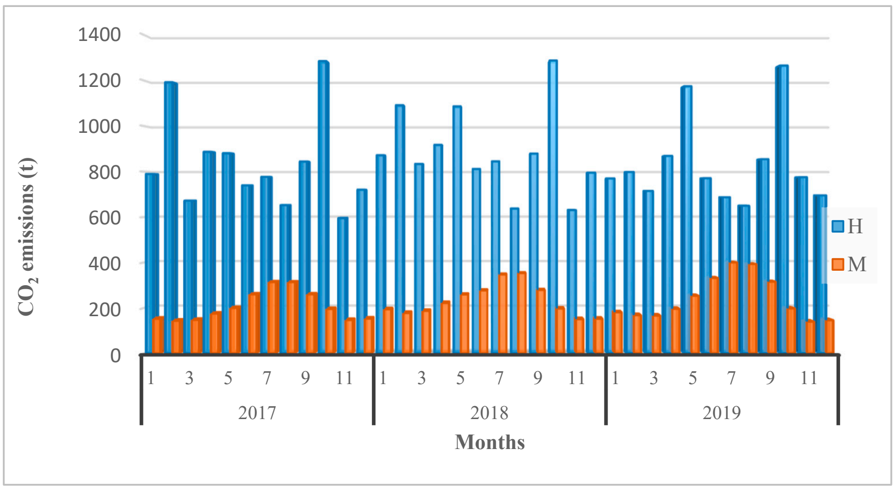

Figure 6. CO_2 emissions through years for hotelling and manoeuvring phase.

Unlike manoeuvring emissions, hotelling emissions are not showing seasonality. When hotelling emissions are estimated monthly, there are no significant differences between the in-season and off-season periods. All emissions increase between May and October and emission increase correlates with more time spent in port. The highest hotelling phase emissions in 2017 were in February. It is well known that February is a month when the ship spends almost all the time in the port. Consequently, when hotelling phase emission data are observed, it is evident that the months with a reduction in emissions are the months with a time reduction in port retention.

5.2. Analysis of Data

In the next section, a trend and statistical analysis will be performed on CO_2 emissions over 2017, 2018, and 2019. Figure 7 shows CO_2 emissions through 2017, 2018, and 2019 over the 12 months.

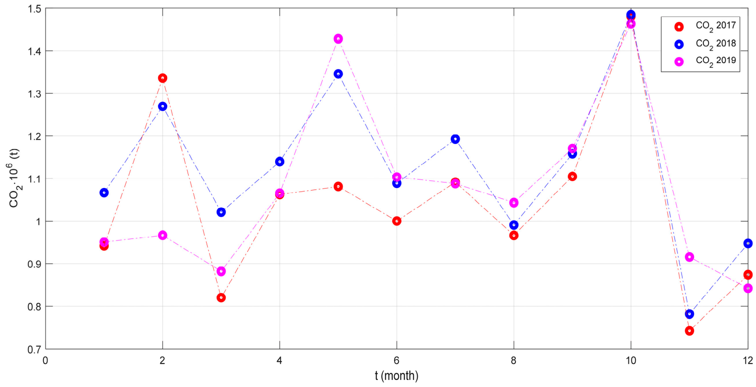

Figure 7. CO_2 emission in 2017, 2018, 2019 for Split city port.

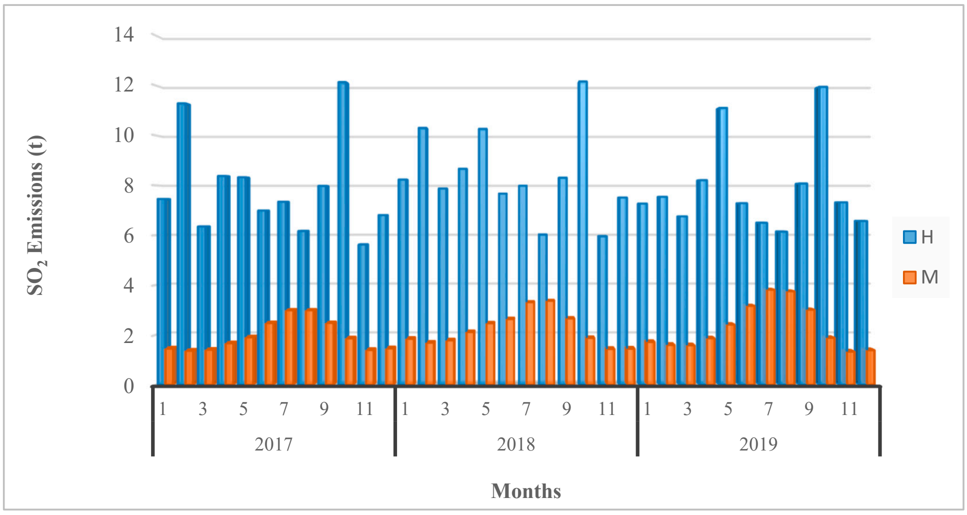

Figure 8. SO_2 emissions through years for hotelling and manoeuvring phase.

From Figure 7, it can be observed that all CO_2 emissions show seasonal character. Additionally, it can be observed that during the in-season period (April, May, June, July, August, and September) the CO_2 emission is constant. The average value in 2017 of CO_2 emissions is 961.67 t, in 2018 1037.48 t, and in 2019 it is 938.46 t. The total average value during the observed three years is 997.67 t.

To check the relationship between independent (month) variable and dependent variables (CO_2 emissions for 2017, 2018, and 2019), an F-test is performed, as shown in Table 6.

Table 6. F-test Two-Sample for Variances whether the selection of variables is acceptable, i.e., whether there are hidden correlations between them, and whether t is an independent variable.

	2017 Year		2018 Year		2019 Year	
	Month	**CO_2 Emission**	**Month**	**CO_2 Emission**	**Month**	**CO_2 Emission**
Mean	6.5	1.045	6.5	1.124	6.5	1.077
Variance	13	0.008	13	0.008	13	0.013
Observations	12	12	12	12	12	12
df	11		11		11	11
F	1527.375		1501.531		935.875	
p (F ≤ f) one-tail	7.367×10^{-16}		8.091×10^{-16}		1.085×10^{-14}	
F Critical one-tail	2.817		2.817		2.817	

From Table 6 it can be seen that all p values are significant, which implies that there are no hidden correlations between independent variable, i.e., month, and all dependent variables, i.e., CO_2 emissions for 2017, 2018, and 2019.

Next, trend analysis on the dependent variable, i.e., CO_2 emissions, has been performed using regression. The trend analysis is performed to check hypothesis two. Figure 9 shows a graphical presentation of trend analysis of CO_2 emissions through observed years, using Equation (9) and regressions.

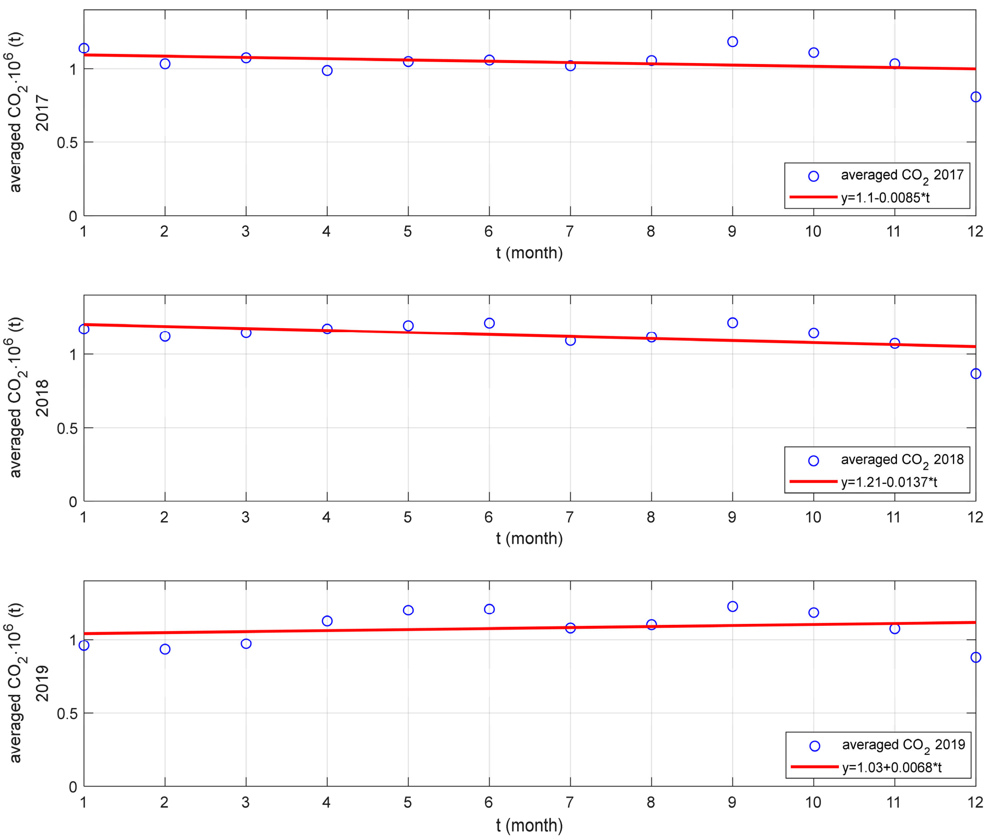

Figure 9. Trend presentation of CO_2 emissions for 2017, 2018, and 2019 of the Split city port.

From Figure 9, it can be observed that blue circles show the values after performing moving average filtering (Equation (9)) of CO_2 emissions for observed years. A period of three months is chosen as windows length (WL) for the moving average algorithm. The choice for WL = 3 is derived from the fact that in Republic Croatia, we observe three (3) months, which corresponds with in-season and off-season periods and to eliminate extreme values. Furthermore, the red line shows the trend (regression) of CO_2 emissions for the observed years. From the trend of CO_2 emissions in 2017, it can be observed that the emissions are constant, although the slope constant has a small negative value (−0.0085). Additionally, the same conclusion could be drawn for 2018. Contrary, for 2019, it can be seen that the slope constant has a small positive value (+0.0068), but since the constant is negligible, it can be concluded that CO_2 emission is constant over the year. Overall, the average emission of CO_2 stays constant, although the number of vessels during 2019 is increased.

To get further insight into CO_2 emission, for observed years, a correlation analysis is performed (Equations (6)–(9)), as shown in Table 7.

Table 7. Correlation matrix of CO_2 emissions for 2017, 2018, and 2019 of the Split city port.

	2017	**2018**	**2019**
2017	1		
2018	0.906	1	
2019	0.670	0.813	1

From Table 7, it can be observed there are strong correlations between all variables. For example, the correlation coefficient between the CO_2 emission from 2017 and CO_2 emission from 2018 is 0.906. Additionally, the "weakest" correlation is between the CO_2 emission from 2017 and CO_2 emission from 2019 (0.670). Further, ANOVA analysis is performed to check the hidden correlations within variables and see. The ANOVA analysis (F = 0.521, Fcrit = 3.285, p = 0.598) shows there are no variations between variables, which implies that all variables come from the same population. That can be explained by the fact that the Split city port operates within full capacity.

It is obvious that some organizational and technological solutions have to be applied to reduce harmful gas emissions, such as better voyage planning (more vessels in less time, especially during the season), usage of more environmentally friendly fuel, etc.

Besides these measures, it is important to find new improvements and solutions such as better cooperation with agents, cargo suppliers. i.e., the creation of integrated management. In terms of technological options, one should be open to renewable sources (fuel cells, wind energy, solar, . . .) if possible, use environmentally friendly materials of more environmentally efficient technology and find more efficient solutions when building a ship.

6. Conclusions

This paper investigates the ship emissions of pollutants and gases developed by line ships during manoeuvring and hotelling phases in cities that have ports in their centres. The analysis was conducted on the example of the Port of Split.

In the hotelling phase, when the ship is on the berth, the auxiliary engines have higher contribution to emissions than during the "at sea" phase. During manoeuvring phase propulsion engines are operating at low loads and auxiliary engine loads are at their highest load for additional onboard equipment such as thrusters. At berth propulsion engines are usually off and auxiliary engine loads are high during discharging cargo, cars, etc. it is presumed that vessels have their auxiliary engines on during the whole of the time spent in the port.

Through the manoeuvring, it can be observed the emissions show seasonality. That seasonality corresponds to increasing the ferry lines number from the end of May, with the largest arrivals in July, August, and September. Hotelling phase emissions are not shown seasonal patterns, but they depend on ship's number and port retention.

Comparing all emissions, carbon dioxide (CO_2), nitrogen oxides (NO_X), volatile organic compounds (VOC), sulphur dioxide (SO_2), and particulate matter (PM) it can be seen they are linearly correlated. From the data, it is evident that only CO_2 emission had a major impact on pollution.

Trend analysis for CO_2 emissions in 2017, 2018, and 2019 shows that the average emissions are constant, despite the number of vessels and staying time in the port.

Correlation analysis shows there are strong correlations between the CO_2 emission variables. Additionally, the ANOVA test confirms the findings. That implies all variables come from the same population, which points out that the Split city port operates within full capacity.

The conducted analysis shows that the variables observed during the manoeuvring and hoteling phases in the city port must be taken into account when developing city strategies to make maritime transport (line ships) more efficient, which could contribute in the future to reduce emissions.

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6.2 Article II

The maritime industry focus on enhancing energy efficiency and reducing GHG emissions in shipping involves both, technological and operational measures. Technological measures include the development of more efficient engines, the usage of alternative fuels, and the integration of renewable energy sources. Operational measures involve optimizing ship routes, reducing speed, and fuel management. The adaptation of existing vessels to incorporate renewable energy sources is a crucial step towards achieving decarbonization goals in the maritime industry. Croatia has significant potential for utilizing solar energy due to its Mediterranean climate.

As the maritime industry continues to evolve, the integration of renewable energy technologies will play a vital role in ensuring sustainable and environmentally friendly maritime operations. The case study of Split's port demonstrates the potential for reducing GHG emissions and improving energy efficiency through the use of photovoltaics systems. Split's port, the largest in Dalmatia, is close to the city center and has a significant impact on local air quality due to emissions from ships during maneuvering and hoteling. The implementation of such hybrid systems complies with international regulatory frameworks. Solar panels installed on ship decks and superstructures generate electricity and reduce the work of diesel generators. These renewable energy solutions not only reduce fuel consumption and emissions but also enhance the overall sustainability of maritime operations.

This research focuses on the application of photovoltaic (PV) systems on ship retrofits. The research analyzes three representative vessels, each representing a category: two Ro-Ro passenger ships and one high-speed passenger ship, each with different sizes and power configurations. By analyzing the energy needs and operational profiles of different vessel types, the study provides insights into the potential benefits and limitations of solar panel installations.

The study overcomes space limitations on ships by introducing an innovative design to maximize the installation area for solar panels. The study calculates the deck area and determines the optimal number of solar panels that can be installed. The solar panel installation on the selected ships involves designing a solid carrier for the forward and aft deck open spaces, allowing the placement of approximately 800 solar panels with a power output of 500 W each.

The solar radiation for the area is obtained using the iHOGA software, which also determines the suitable tilt angle for the solar panels to maximize energy output.

The hybrid power system proposed in the study, consisting of diesel generators, PV panels, batteries, and inverters. The research encompasses several cases based on the IHOGA simulator, covering all ship phases to minimize fuel consumption by diesel generators. Two operational modes are designed: Mode 1 allows surplus power to charge batteries or supply the port network, while Mode 2 addresses power deficits from alternative sources.

The research findings indicate that installing solar panels on ships can significantly reduce fuel consumption and emissions. The simulation results show that renewable energy sources can supply over 99% of the overall generator load energy for the Ro-Ro passenger ship, with minimal unmet load. The use of renewable energy reduces CO2 emissions by 1324.85 t/year and NOx emissions by 23.6 t/year for Ro-Ro passenger ship 1.

The economic analysis of the hybrid system components reveals a total system cost (NPC) of €2,891,024 for Ro-Ro passenger ship 1. This includes the costs of PV generators, battery banks, inverters, AC generator fuel, and installation. The long-term benefits of reduced fuel consumption and emissions make the investment in solar panel installations economically viable and environmentally beneficial.

During the hotelling phase, the load is entirely supplied by batteries, resulting in zero emissions at the port. This is particularly important for ports located near urban areas, where air quality is a critical concern. The ability to operate with zero emissions during port stays can significantly reduce the environmental impact of maritime operations and improve the quality of life for residents in coastal cities.

The study also explores the potential for excess energy generated by the solar panels to be fed back into the port's electrical grid. This not only enhances the overall energy efficiency of the maritime sector but also provides additional economic benefits by allowing ships to sell surplus electricity to the grid.

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Adaptation of Existing Vessels in Accordance with Decarbonization Requirements—Case Study—Mediterranean Port

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Abstract: This research investigates the application of photovoltaic (PV) systems on ship retrofits with the aim of reducing the emission of harmful gases. By using renewable energy resources, this research presents the potential for reducing greenhouse gas (GHG) emissions and improving energy efficiency in maritime operations, specifically within the Split coastal area. Overcoming the space restrictions on ships, an innovative design is presented to maximize the installation area for solar power. The research is conducted for several cases based on the IHOGA simulator, for all ship phases, and it aims to minimize fuel consumption by the diesel generators, thus emphasizing the use of renewable energy resources. A model with two operational modes is designed: Mode 1 allows surplus power to charge batteries or supply the port network, while Mode 2 covers power deficits from alternative sources. The implementation of renewables results in carbon dioxide (CO_2) and nitrogen oxide (NO_X) emission reductions. Furthermore, during the ship hotelling phase, the load is supplied entirely by batteries, resulting in zero emissions at the port.

Keywords: solar panel application on ships; fuel reduction; emission reduction; decarbonization; retrofit

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1. Introduction

1.1. Problem Background

Reducing fuel combustion, air pollution, and greenhouse gas (GHG) emissions is one of the world's biggest challenges in recent years. One of the reasons why society focuses on this issue is the negative impact of greenhouse gases on human health and the environment.

This issue is of fundamental importance to many industries, including maritime transport.

The maritime industry contributes 2.89% of global anthropogenic emissions, and this cannot be ignored [1]. Approximately 70% of ship emissions are predicted to occur within 400 km of land and can have a substantial impact on coastal air quality [2]. Moreover, maritime transport is an increasing source of air pollutants and greenhouse gas (GHG) emissions [1], and many predictions point to a trend of increasing maritime transport volumes in the future, which consequently implies an increase in air pollution and greenhouse gas emissions. As a result, energy efficiency management and fuel consumption control are key to reducing greenhouse gas emissions.

In this regard, legislation on maritime transport has been reorganized in recent years. The International Maritime Organization (IMO) adopted Annex VI of the MARPOL Convention in 1997, which sets regulations for preventing air pollution from ships [3]. In particular, Annex VI of MARPOL limits sulfur oxide (SO_x) and nitrogen oxide (NO_X) emissions from ship exhaust gases in addition to carbon dioxide (CO_2) emissions. In April 2018, the IMO agreed to a draft maritime greenhouse gas strategy, which required the maritime sector to reduce emissions by at least 50% by 2050 compared to the base year of 2018. By 2030, the carbon intensity of international shipping should decrease by at least 40% [4].

The European Union (EU) set goals of limiting global climate change to 2 °C (EC, 2007), which was later incorporated into the Europe 2020 Strategy for smart, sustainable, and inclusive growth. These objectives include a 20% increase in renewable energy use, a 20% reduction in fossil fuel use, and a 20% reduction in CO_2 emissions. Many of these objectives have yet to be met, despite the increased use of renewable energy. As a member of the EU, Croatia is obligated to fulfil these requirements. As a tourist destination with increased electricity consumption during the summer months, solar energy has a huge potential in Croatia [5]. The Croatian government adopted a new Energy Strategy for the period from 2030 to 2050 in February 2020. The strategy includes a wide range of energy policy initiatives aimed at improving energy security, increasing energy efficiency, reducing reliance on fossil fuels, increasing local production, and increasing renewable resources. According to the strategy, renewable energy resources will account for 36.4% of total energy consumption in 2030 and 65.6% in 2050 [6].

1.2. Energy Efficiency and GHG Reduction in Shipping

Due to the stricter environmental regulations, existing vessels must become more energy efficient to compete for the remaining period of their lifespan. The most important technical measure for new ships is the Energy Efficiency Design Index (EEDI), which promotes the use of more energy-efficient (lower polluting) equipment and engines. For each ship type and size segment, the EEDI requires a minimum energy efficiency level per capacity mile (e.g., ton mile) [7]. The Ship Energy Efficiency Management Plan (SEEMP) is a cost-effective operational measure that establishes a mechanism to improve a ship's energy efficiency for new and existing ships. The SEEMP also provides a method for shipping companies to manage ship and fleet efficiency performance over time by utilizing tools such as the Energy Efficiency Operational Indicator (EEOI) [8]. The EEOI allows operators to assess the fuel efficiency of a ship in operation and the impact of any operational changes, such as improved voyage planning, more frequent propeller cleaning, or the implementation of technical measures.

Several actions are being researched to improve the EEDI and EEOI indicators such as waste heat recovery, propeller upgrade, hull cleaning, speed reduction, route optimization, and usage of renewable energy sources [9]. Wind (e.g., soft sails, fixed wings, rotors, kites, and conventional wind turbines), solar photovoltaics, biofuels, wave energy, and the use of super capacitors charged with renewables are all potential renewable energy sources for shipping applications. These clean energy solutions can be incorporated into existing fleet retrofits or new shipbuilding and design [10].

The performance of the designed system is theoretically evaluated using a novel approach for the layout of solar arrays within a Ro-Ro-type marine vessel that navigated between Pendik/Turkey and Trieste/Italy in 2018. According to the methodology used, 7.76% energy efficiency was achieved, and the designed solar system met 7.38% of the stated vessel's fuel requirements. The release of 0.312 t of SO_x, 3.942 t of NO_X, 232.393 t of CO_2, and 0,114 t of PM into the atmosphere is prevented [11]. According to Qiu's research, a techno-economic analysis was performed on the hybrid power system. A mathematical model for predicting solar irradiation was proposed, and the six busiest international navigation routes were considered. The findings indicate that the hybrid power system is financially viable [12]. The latest research on the utilization of solar energy in ships is presented and analyzed in a study by Kurniawan to provide information for the researchers who developed the technology for solar-powered boats. The best way to use solar energy in a ship is to use a catamaran boat with a flat-top structure that allows for the placement of solar panels. Furthermore, the solar energy extracted from the panel can be optimized by using quadratic Maximization Maximum Power Point Tracking (MPPT), which is performed by the KY converter and converted to AC voltage by a multilevel inverter [13]. Initially, a brief description of a typical ship's electrical grid is presented by Kobougias, distinguishing the major components, reporting typical electrical magnitudes, and recommending the best installation locations [14]. The experiment was conducted on a passenger ship (85 t, 263 passengers); the hybrid PV/diesel green ship could operate independently as well as when connected to a smart grid [15]. The flexibility of boat demand in the Ballen marina on Sams, a medium-sized Danish island, was investigated in order to improve local grid operation. Based on the demand analysis, the optimal scheduling of boats and battery energy storage systems (BESS) is proposed using mixed-integer linear programming taking in consideration three representative weeks (peak tourist season, late summer, and late autumn) and using various combinations of high/low load and photovoltaic (PV) generation [16]. The KISS project is an example of a successful electric small craft with a performance and mission profile comparable to competitors using conventional propulsion. A concurrent design that considers the hull form, engine, propulsion system, and onboard energy storage has achieved such a goal [17]. The study investigated the factors that influence the viability of nautical tourism in a number of Mediterranean countries to identify the major barriers to greater use of renewable energy sources. Study findings support previous research indicating that using renewable energy sources, particularly photovoltaic (PV) modules, can result in significant energy consumption savings and that insufficient financial resources and a lack of knowledge are the main barriers to increasing the adoption of renewable energy sources and increasing energy efficiency in nautical tourism [18]. A case study in Croatia was conducted on retrofitting vessels with solar and wind energy. The study conducted a technical and economic analysis of the feasibility of using renewable energy sources (RES), specifically solar and wind energy, on an existing vessel. Using solar energy would result in 111.556 l of diesel fuel savings over a 25-year period [19].

1.3. Goal

The primary goal of this paper is to propose a new optimized hybrid ship power management to maximize ship energy efficiency and minimize both fuel combustion and greenhouse emissions for the port of interest.

In order to achieve this goal, a new configuration for the ship power plant of the existing Ro-Ro and high-speed passenger vessels is proposed, analyzed, and compared to the actual ship power configuration. Specifically, two configurations have been considered: the standard configuration consisting of the diesel generator system and the optimized hybrid solar-diesel generator configuration. For each of these configurations, realistic power calculations, emission reductions, and economic analyses were carried out.

This study is novel in focusing on renewable energy adoption on the board and analyzing the influence of the applied strategy on the GHG reduction in the case port. Improved Hybrid Optimization using Genetic Algorithm (iHOGA) PRO+ software [20] was used to perform the sizing of the renewable energy system consisting of solar panels and battery banks.

The paper is structured as follows: in Section 2 the seaport Split as a port of interest, the current configuration, and the energy needs of the considered ship are described; in Section 3 hybrid system performance is analyzed through the ships being in different phases (hotelling cruising or maneuvering). Finally, in the last section, the research findings are highlighted, summarized, and concluded.

2. Materials and Methods

Concerning the previously mentioned research problem of solar panel applications on ships, the following hypotheses are defined:

- By installing effective solar panels on ships, a significant amount of electricity can be generated, thereby reducing reliance on traditional fossil fuel-powered generators.
- Solar applications aboard ships can considerably decrease fuel usage.
- Ships fitted with solar panels can reduce the carbon footprint caused by the use of fossil fuels.

In confirmation of the hypotheses, the percentage of total load energy derived from renewable energy resources will be shown, as well as a comparison of fuel consumption and emissions of ships fitted with solar applications compared to standard ships. In order to perform a thorough analysis, factors such as ship size, solar panel efficiency, and weather conditions were taken into account.

2.1. Case Study: Area Description

Croatia is a Mediterranean country with developed maritime traffic. Split's port, located in the central Adriatic, is the largest in Dalmatia and is close to the city center. The port has 25 berths for passengers and Ro-Ro passenger ships traveling in national and international traffic [21]. A significant portion of the emissions from ships during maneuvering and berthing have an impact on city residents. Because of the coast indentation and the short distance between Split's city port and the islands, the spread of air emissions has a strong impact. Furthermore, as these regions' tourism grows, the number of boats will increase, consuming more fossil fuel and thus causing more pollution. Dalmatia is suitable for solar energy use due to its location, mild Mediterranean climate, and large number of sunny hours. Given the 2700 h of sunshine per year in the City of Split, it has an enormous potential that can be used to achieve this transformation, which is a hybrid solar–diesel generator system that may pique the interest of boat operators due to its environmental friendliness [22]. Transitioning from fossil fuel to hybrid with alternative energy sources could gradually reduce pollution and operational costs.

Split has been a transit city for decades as a result of its location. By a variety of metrics, recent tourism growth has highlighted Split as a top destination and a tourist record holder. According to the Split Tourist Board Statistics, the city of Split accounted for 711.071 tourist arrivals in 2022 [23]. In comparison to 2021, there has been a 58% increase in tourist arrivals. With its rich historical heritage and pleasant climate, it has become a popular tourist destination. It is served by all modes of transportation (road, air, rail, and maritime), and its hubs are located near the city center. Moreover, the railway station, bus station, and port are all 500 m from the city center, while the airport is less than 30 km away. The passenger port is located very close to the city center, and many vehicles gravitate to this area in order to board the ferry, especially during the summer time. Passenger traffic in Split's city port has increased over the last decade, with the exception of the corona crisis in the year 2020, as visible in Figure 1 [24]. The Split City Port saw a record annual turnover of 5.6 million passengers and 827,000 vehicles in 2019.

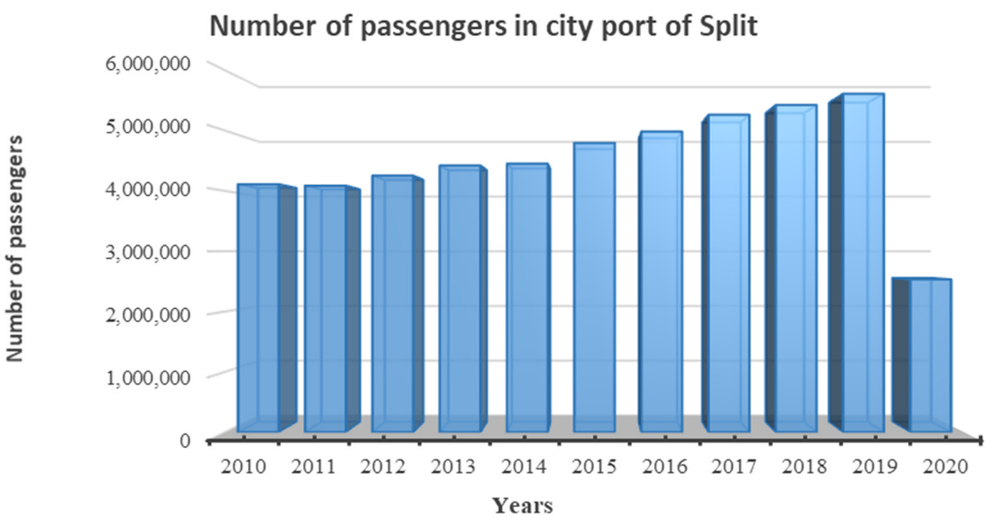


Figure 1. Number of passengers in city port of Split.

Previous research utilized an activity-based approach to estimate ship emissions in the City Port of Split [25]. The calculation focused on emissions during the ship maneuvering and hotelling phases. A comparison between the two phases revealed that emissions were higher in the hotelling phase for all pollutants, mainly due to the extended time spent in the port. Recent literature provides data on traffic and annual emissions t/year of NO_X and

PM_{10} for various ports, including Barcelona, Hong Kong, Copenhagen, Venice, Elsinore, St Petersburg, Las Palmas, Genoa, and Marseille [26]. Although these ports differ in size and the number of ship arrivals/departures, the aim was to consider emissions in urban cities with ports such as Split. For example, Hong Kong's minimum NO_X emissions amount to 20 t/year, while Marseille has significantly higher emissions at 1300 t/year [26]. The range of PM10 emissions in ports is between 1 t/year in Hong Kong and 80 t/year in Marseille. According to a study of PM_{10} emissions in Ancona's port, the majority of emissions (70%) occur during the hotelling phase [27]. These emissions are related to the PM_{10} emissions from the Split Port. Emissions during the maneuvering phase vary seasonally and are always lower than emissions during the hotelling phase. The total annual SO_2 emissions range from 118 to 127 t/year, far less than the 1405 t/year in Izmir Port [28]. Given that maneuvering emissions show seasonality, Split is a tourist town that relies on tourism, and large differences in arrivals during the winter and summer months two periods were observed: season and off season. Additional periods, such as pre- and post-season, could be introduced, but this will be part of future research. Exhaust gas measurements were taken on the ferry route between Split and the island of Brač for two ship phases: maneuvering and at sea. Measurements taken show that the exhaust emissions are higher during the maneuvering phase than during the "at sea" phase [29].

2.2. Vessel Description

In year 2022, 35 ships were observed with over 250 port calls per day during the season. Line ships which were observed during the year 2022 are divided into categories according to the power of the main engines. Those categories are:

- Main engine power less than 2000 kW–8 ships. The passenger capacity ranges from 80 passengers for the ship with a main engine power of 220 kW up to 1200 passengers for the ship with main engine power of 1968 kW;
- Main engine power between 2000 kW and 4000 kW–18 ships. The passenger capacity ranges from 250 passengers for the ship with main engine power of 2160 kW up to 1080 passengers for the ship with a main engine power of 3600 kW;
- Main engine power greater than 4000 kW–9 ships. The passenger capacity ranges from 316 passengers for the ship with a main engine power of 4000 kW up to 1300 passengers for the ship with a main engine power of 13,248 kW.

During this research, three vessels were selected, two of which were Ro-Ro passenger ships of different sizes and powers and one high-speed passenger ship. Each of them is a representative of one of the above three categories. The step-by-step approach is shown for one Ro-Ro vessel, while the results, CO_2 and NO_X reductions, and costs are summarized for all vessels. Table 1 provides selected ship specifications, and Table 2 provides port calls, port retention, and emissions in the period between 2017 and 2022 for selected ships. Table 1 shows vessel specifications such as hull material, year when ships are built, length overall, breadth, depth, and propulsion characteristics, provided from the Croatian Register of Shipping (CRS) website [30]. The ships port calls, port retention, and emissions in Table 2 are collected and estimated by the authors.

Table 1. Category-representative ship characteristics.

Ship Type:	Ro-Ro Passenger Ship 1	High Speed Passenger Ship	Ro-Ro Passenger Ship 2
Hull material:	Steel	Glass reinforced plastic	Steel
Year build:	2007	2019	2002
Length overall (m):	87.6	30.45	98.38
Breadth (m):	17.5	9	17
Draught (m):	2.400	1.832	2.7
Propulsion type:	Internal combustion engine	Internal combustion engine	Internal combustion engine

Table 1. *Cont.*

Ship Type:	Ro-Ro Passenger Ship 1	High Speed Passenger Ship	Ro-Ro Passenger Ship 2
Type of main propulsion engines:	Diesel, four stroke, single acting	Diesel, four stroke, single acting,	Diesel, four stroke, single acting
Number of main propulsion engines:	4	2	4
Builder:	CATERPILLAR Inc.	MTU	CATERPILLAR Inc.
License and type:	CATERPILLAR C32 ACERT	MTU 16V4000 M63L	CATERPILLAR 3508B
Total power output (kW):	1968	4480	3280
Number and total power of generators (kW):	3, 630	1, 70	3, 405

Table 2. Vessel port calls, port retention, and emissions in the period between 2017 and 2022.

Ferry	Year	Number of Calls	Port Retention (h)	Nox (g)	NMVOC (g)	PM (g)	SO_2 (g)	CO_2 (g)
Ro-Ro passenger ship 1	2017	44	9025.22	27,718,124	1,176,167	1,122,882	15,991,109	1.7×10^9
	2018	885	3768.36	11,573,327	491,092.7	468,844.3	6,676,871	7.08×10^8
	2019	826	3009.672	9,243,256	392,220.5	374,451.4	5,332,609	5.65×10^8
	2020	398	2556.312	7,850,905	333,138.6	318,046.1	4,529,335	4.8×10^8
	2021	864	3102.552	9,528,508	404,324.6	386,007.1	5,497,176	5.83×10^8
	2022	810	3352.896	10,297,361	436,949.4	417,153.9	5,940,742	6.3×10^8
Ro-Ro passenger ship 2	2017	1044	1262.09	2,715,559	143,878	131,459.1	1,610,475	1.7×10^8
	2018	974	2394.768	5,152,679	273,003.6	249,439	3,055,820	3.23×10^8
	2019	1056	2344.272	5,044,029	267,247	244,179.4	2,991,385	3.17×10^8
	2020	935	5116.536	11,008,944	583,285.1	532,938.4	6,528,905	6.91×10^8
	2021	983	4923.936	10,594,538	561,328.7	512,877.2	6,283,139	6.65×10^8
	2022	858	3031.68	6,523,084	345,611.5	315,779.8	3,868,545	4.09×10^8
High speed passenger ship	2017	167	3217.344	1,268,406	216,205.5	172,964.4	980,131.7	1.02×10^8
	2018	174	3038.184	1,197,774	204,166	163,332.8	925,552.4	96,638,557
	2019	101	1502.52	592,353.5	100,969.3	80,775.48	457,727.7	47,792,156
	2020	23	1099.464	433,452.7	73,883.98	59,107.18	334,940.7	34,971,751
	2021	533	4154.712	1,637,954	279,196.6	223,357.3	1,265,691	1.32×10^8
	2022	429	4026.624	1,587,456	270,589.1	21,6471.3	1,226,671	1.28×10^8

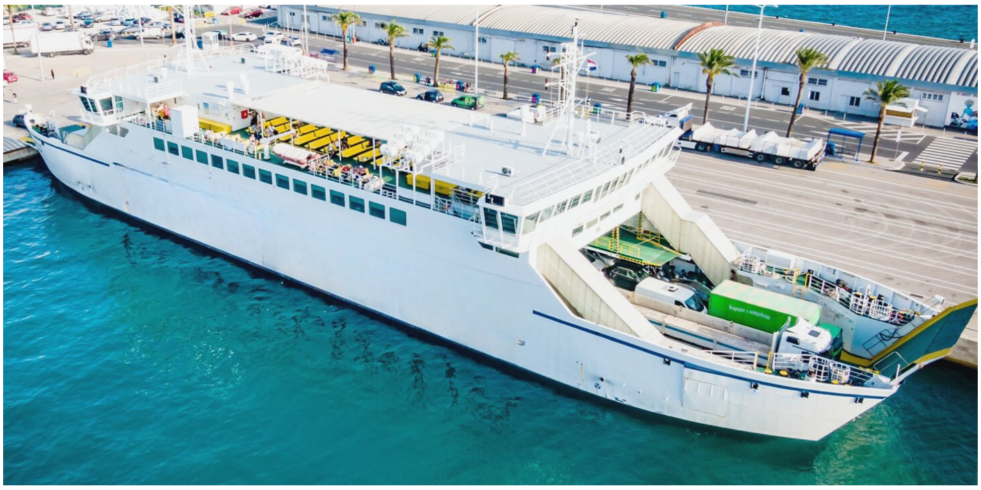
3. Hybrid System Components

In order to increase ship energy efficiency and minimize ship fuel consumption, an in-house developed software iHOGA has been applied. The iHOGA can simulate a ship power grid consisting of (i) an arbitrary number of prime and auxiliary generators, (ii) generators from renewable sources (photovoltaic panels in our case, wind, and hydroelectric generators), (iii) battery storage with chargers, and (iv) inverters or inverter-chargers.

The solar panel application was observed on three existing marine vessels, representative of one of the above-mentioned categories. A suitable deck area for locating the solar panels is selected together with a part of the deck selected, which can be projected so that solar panels can be placed on it on suitable supports. The amount of solar panels that can be installed is determined by the equation (1). Solar resources are gained for the area of interest.

In order to use all available areas for the placement of the solar panels on the Ro-Ro type of ship, a solid carrier is designed on the forward and aft deck open space parts, as visible in Figure 2. The detailed design of the solid carrier is not the subject of this work, and it would require additional efforts by designers and shipbuilders to determine in detail how the carrier should ultimately look.

(**a**)



(**b**)

Figure 2. (**a**) The Ro-Ro ship in present state. (**b**) The Ro-Ro ship with designed solid carrier on the forward and aft deck open space parts.

Deck area calculation is made following the formula [31]:

$$S = L_{OA} \times B \times N, \quad (1)$$

where:

S—surface (m^2);

L_{OA}—length over all (m);

B—breadth extreme (m);

N—0.91 for big tankers and bulk carriers, 0.88 for cargo liners, 0.84 for coasters, etc.

The calculated deck area for the Ro-Ro type of ship is 1287.7 m^2. Taking a solar panel area of 1.44 m^2, it is possible to place approximately 800 solar panels with a power of 500 W on the mentioned vessel. This possibility leaves enough space considering the estimation.

Solar Radiation (kWh/m^2) is determined by indicating the latitude and longitude of the selected location from the iHOGA software.

The suitable tilt angle for solar panels varies according to the geographical location, desired energy output, and use. When compared to a horizontal surface, the angle at which a solar panel is positioned might alter its efficiency and energy output. Tilted surfaces can be altered to face the sun more directly, thereby increasing exposure. Furthermore, inclined surfaces benefit from more direct sunlight for longer hours of the day. Figure 3 shows the monthly average daily irradiation over the back surface of the modules and the total direct irradiation over the tilt surface for the Port of Split.

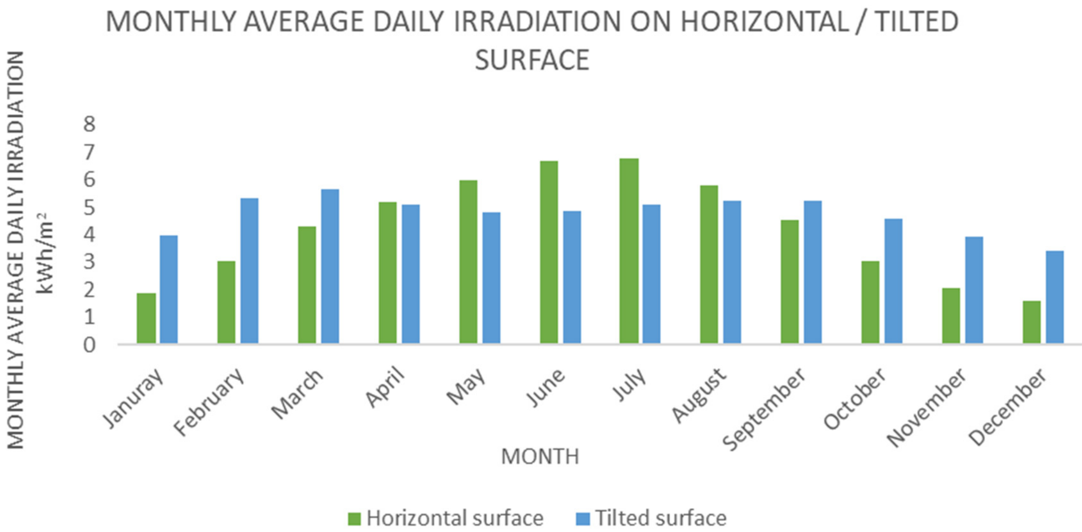


Figure 3. Split monthly average daily irradiation.

Three cases of ship operation were considered (maneuvering, at sea, and hotelling). The load in the three ship phases is used to determine the average daily load. Five types of different power solar panels, five batteries of different capacities, and suitable inverters are selected in order to gain the best possible solution.

Solar panels can have various characteristics that differentiate them from one another. Some key characteristics to consider are efficiency, power output, dimensions, temperature coefficient, and price. When selecting solar panels, it is crucial to consider these characteristics. Different PV solar panels are selected for this optimization in order to gain the best environmental and most economic solution. PV solar panel Power (kW), Voltage (V), Cost (k€), unit cost of operation and maintenance in year-C.O&M. (%/y), expected lifetime (years), normal operating temperature of the cell-NOCT (°C), coefficient of variation of the power with the temperature (%/°C), BIFACIALITY, CPV, and emissions of CO_2 ($kgCO_2$/kW) are shown in Table 3.

Table 3. PV solar panels characteristics.

Name	Power (kW)	Cost (k€)	C.O.&M. (%/y)	Lifetime (years)	NOCT (°C)	Power with temperature coef. (%/°C)	BIFACIALITY (0–1)	CPV	Emissions ($kgCO_2$/kW)
PV1	1	1	1	25	43	−0.4	0	NO	800
PV10	10	10	1	25	43	−0.4	0	NO	800
PV100	100	100	1	25	43	−0.4	0	NO	800
CPV10	10	12	1	25	43	−0.14	0	NO	800
PV10BIF	10	11	1	25	43	−0.4	0.7	NO	800

The complete power balance of electricity from the available technical documentation was reviewed. An estimate of the consumers and power in kW is determined for all ship phases in kW according to the ship voyage time tables, as shown in Table 4.

Table 4. Ro-Ro vessel consumers power in different phases.

Consumer	Power (kW)		
	At Sea	Maneuvering	Hotelling
Auxiliary machines of the engine and ship propulsion	92	100	72
Flanged machines	-	26	-
Ventilation and air conditioning	144	144	46
Total	236	270	118

According to the time spent in each phase and load, calculated energy use per day is 4.64 MWh/day for Ro-Ro passenger ship 1, 6.22 MWh/day for Ro-Ro passenger ship 2, and 1.2754 MWh/day for the high-speed passenger ship. In Figures 4–6, the daily load for one winter day and one summer day for all three ships is shown.

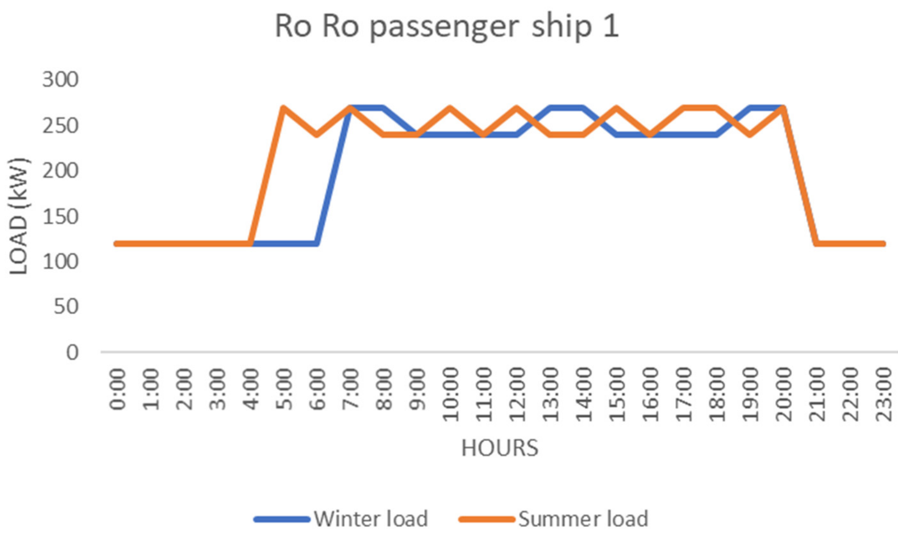


Figure 4. Ro-Ro passenger ship 1 daily load for one winter day and one summer day.

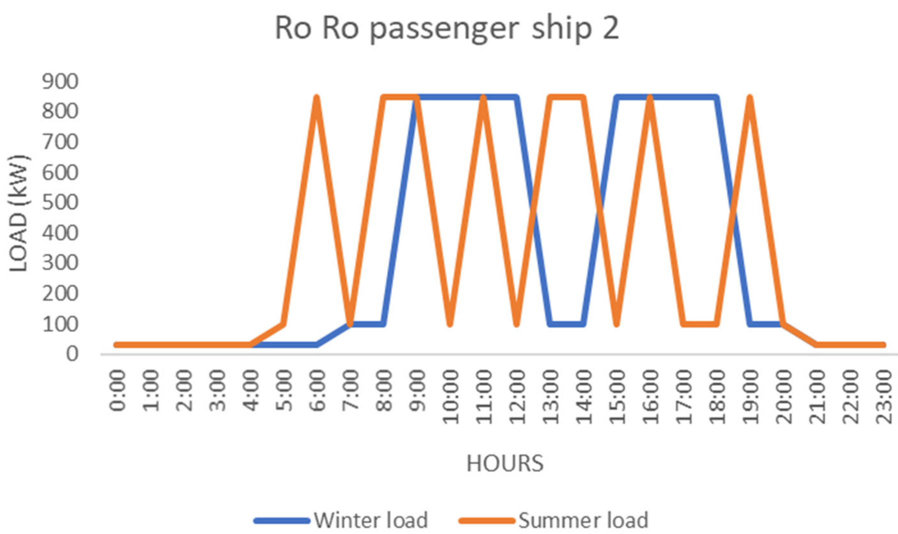


Figure 5. Ro-Ro passenger ship 2 daily load for one winter day and one summer day.

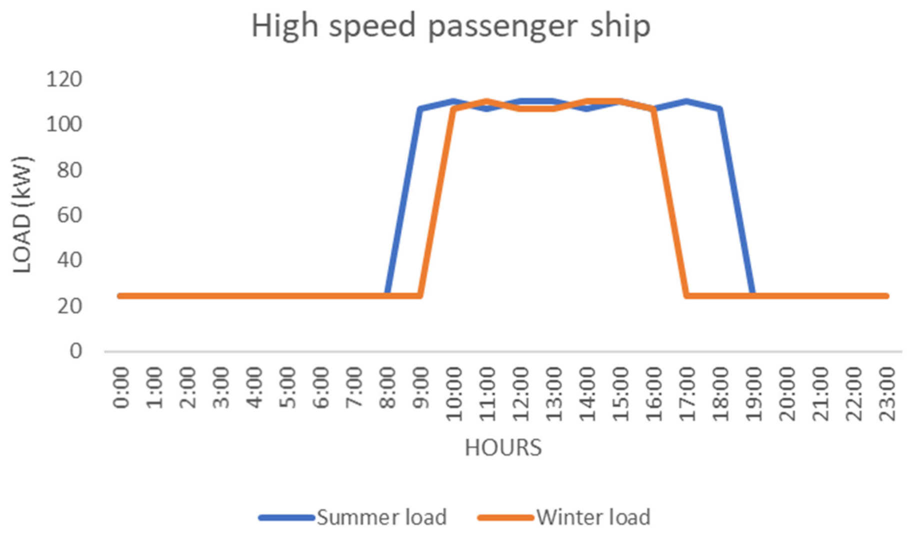


Figure 6. High-speed passenger ship daily load for one winter day and one summer day.

While considering the specific requirements of ships, such as the power demands and electrical system setup, and taking into account the amount of energy it can store as well as deliver and cost, five types of batteries were chosen, all of which were lithium-ion batteries. Cycle life depends on temperature, and the battery capacity depends on temperature. The remaining capacity at the battery end of life is set at 80%. The backup generator will charge the batteries after 14 days without full charge or after eight full cycles. Table 5 presents the battery Nominal Capacity (kAh), Voltage (V), Cost, (k€), Operation and Maintenance Cost in year–C.O.&M. (%/y), Minimum State of Charge (%), Self-Discharge Coefficient (%/month), Maximum allowed current (kA) Efficiency (%), and Floating Life (year).

Table 5. Battery characteristics.

Name	Nominal Capacity	Voltage	Cost	C.O&M	Minimum State of Charge	Self Discharge Coefficient	Maximum Allowed Current	Efficiency	Floating Life
	(kAh)	(V)	(k€)	(%/y)	(%)	(%/Month)	(kA)	(%)	(y)
Bat48 kWh	1	48	7.5	1	10	1	0.5	92	15
Bat96 kWh	2	48	15	1	10	1	1	92	15
Bat240 kWh	5	48	35	1	10	1	3	92	15
Bat480 kWh	10	48	70	1	10	1	5	92	15
Bat4800 kWh	100	48	600	1	10	1	50	92	15

By considering factors such as the size of solar system in terms of the power output, the compatibility with grid and other system components, and the cost, four types of inverter costs were selected to ensure the long-term efficiency of the solar system. Inverter Power (kVA), Lifetime (years), Cost (k€), Maximum charge current that can be supplied to the batteries (kA), Charger efficiency (%), Minimum operating DC voltage (V), Maximum operating DC voltage (V), and Maximum input power from renewables (kW) are shown in Table 6. The minimum inverter that can supply the AC load peak defined by the consumption is used in all combinations.

Table 6. Inverter characteristics.

Inverter Name	Power	Lifetime	Cost	Maximum Charge Current Which Can Be Supplied to the Batteries	Charger Efficiency	Minimum	Maximum Operating DC Voltage	Maximum Input Power from Renewables
	(kVA)	(Year)	(k€)	(kA)	(%)	(V)	(V)	(kW)
lnv-Ch100 kW	100	15	20	2.5	98	48	48	1.00×10^{15}
lnv-Ch300 kW	300	15	50	7.5	98	48	48	1.00×10^{15}
lnv-Ch200 kW	200	15	35	5	98	48	48	1.00×10^{15}
lnv-Ch400 kW	400	15	60	10	98	48	48	1.00×10^{15}

The Ro-Ro passenger ship 1 is fitted with three diesel generators that can work in parallel and can provide 345–480 kVA. Third generator is located astern and it can be completely separated from the main switchboard in order to supply fire pump in stern engine room.

In this study, improved Hybrid Optimization using the Genetic Algorithm (iHOGA) software is used for sizing and optimizing renewable energy resources connected to the ship power plant and for further analysis of implemented scenarios regarding GHG mitigation in the Split seaport. iHOGA uses genetic algorithms for solving a single-objective optimization or multi-objective optimization.

A flow diagram of the methods used by iHOGA in this study is shown in Figure 7.

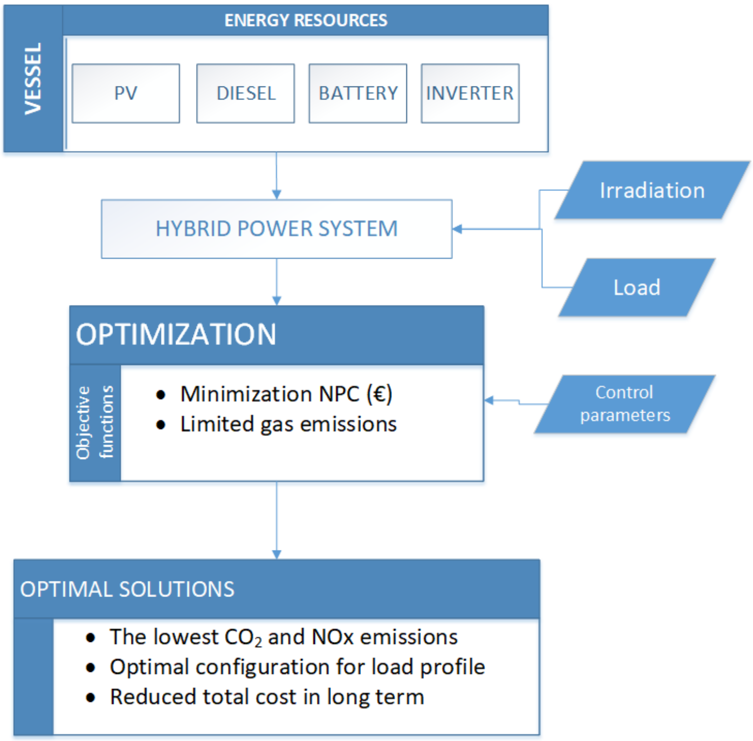


Figure 7. The flow diagram of the optimization components and outcomes.

The power to be provided by the solar power system is determined annually, based on the vessel load demand. Finally, the fuel savings, emission reductions, and economic aspects as a result of alternatively generated electricity are investigated.

Mathematical Backgrounds

In this study, multi-objective optimization is applied, with the objectives of minimizing annual gas emissions, considering only CO_2 and NOx emissions from fuel consumption, and the total cost during the lifespan of the system. The objective function can be expressed as follows:

$$minF = min[TC(x), AE(x)] \quad (2)$$

$$x = \{N_{PV}, a, N_{BAT}, b, N_G, c\} \quad (3)$$

where N_{PV}, N_{BAT}, and N_G are, respectively, the total number of PV panels, batteries, and AC generators. a, b, and c are the types of PV panel, the type of battery, and the type of AC generator, respectively.

The first objective of Equation (2) is the total cost TC. It is calculated using the iHOGA as the sum of investment costs and the discounted present values of all future costs during the system's lifetime and can be expressed as follows:

$$NPC = \sum_{k=1}^{n} \left(C_k + C_{REP}^k + C_{O\&M}^k + C_F \right) \quad (4)$$

where:

- C_k (€) is the initial cost of each component k (AC generator, PV, and battery);
- C_{REP}^k (€) is the replacement cost of different components during the system's lifetime (usually 25 or 30 years);
- $C_{O\&M}^k$ (€) is the annual cost for operating and maintening component k throughout the system's lifetime;
- CF (€) is the fuel cost of the AC generator.

The second objective of Equation (2) is annual gas emissions AE, including CO_2 and NO_X emissions from fuel consumption. AE can be calculated as follows [32]:

$$AE = \sum_i E_i = \sum_i S_{jklm} \times EF_j \quad (5)$$

$$E_i = \sum_{j,k,l,m} S_{jklm} \times EF_{jm}^i \quad (6)$$

where:

i is gas;
j is fuel type;
k is ship class;
l is engine type;
m is ship activity mode: cruising, maneuvering, hotelling;
E_i is total emissions of gas i;
S_{jklm} is daily consumption of fuel j in ship class k in mode m as a function of gross tonnage;
EF_{jm}^i is combustion emission factors of pollutant i from fuel j in engines type l in ship mode m.

Combustion emission factors vary by the following: engine type, engine rating (SSD, MSD, HSD), type of fuel (HFO, MDO, MGO, and LNG), activity mode, etc.

Table 7 reports on default emission factors proposed for the Ro-Ro, with a medium-speed diesel engine regarding ship mode.

Table 7. Emission factors of fuel in terms of kg/t of fuel consumed per air pollutant. Sources: IMO (2009) and IMO (2014).

Ship Mode	CO_2	NO_X
Hotelling	3200	23
Maneuvering	3200	51
Cruising	3200	57

In achieving this, additional constraints must be met:

$$P_{PV}(t) + P_{BAT}(t) + P_G(t) \geq P_{load}(t) \quad (7)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (8)$$

$$\left.\begin{array}{r} 0 \leq N_{PV} \leq N_{PVmax} \\ 0 \leq N_{BAT} \leq N_{BATmax} \end{array}\right\} \quad (9)$$

Constraint (7) ensures that for any given period t, the total power supply from the hybrid generation system is sufficient to supply the total demand. The relation (8) determines the maximum depth of battery discharging and the minimum depth of battery charging.

Two modes implemented in the iHOGA software may arise during the operation of the hybrid system:

MODE 1: If the power produced by the renewable sources is higher than the load charge, the Batteries are charged with the spare power from renewable sources. When the battery's SOC (State of Charge) reaches its maximum value, the charging process is terminated. Excess energy can be handed over to the port network while the ship is connected.

MODE 2: If the power produced by the renewable sources is less than the load discharge.

The power not supplied to meet the load will be supplied by the Batteries (if they cannot supply the whole, the rest will be supplied by the AC Generator). When the power to be supplied by AC Gen. is less than the critical power of the generator, the generator runs at full power (without excess), charging the Battery until 100% SOC is reached.

At the period when the ferry is in the hotelling phase, the load power is less, the battery SOC is at the upper boundary, and the controller shall disconnect both Ro-Ro ship diesel generators and discharge the battery in order to supply the load demand. This would provide zero emissions at the port.

The maximum unmet load allowed is set to 1%, meaning that the combinations in which the stand-alone system (without considering the AC grid) cannot supply at least 99% of the demand will be discarded. The minimum and maximum numbers of components allowed in parallel must be set.

When employing the optimization enumerative approach, the iHOGA assesses all potential component combinations and, for each component combination, all possible control strategy combinations. Each combination is simulated over the course of a year. If the simulation meets all of the restrictions, it calculates the Net Present Cost (NPC), taking into account all costs during the system's lifetime (25 years) and shifting all costs to the first year (taking inflation and interest rate into account). Combinations that do not match all of the restrictions are deleted.

4. Results and Discussion

After a series of simulations with different combinations of batteries, PV solar panels, and inverters, the selected hybrid system components in this case study include diesel generators, photovoltaic panels, batteries, inverters, and load in all ship phases (at sea, maneuvering, and hotelling). The hybrid power system provides two operating modes depending on the environmental conditions: battery charge status and load variation. The controller switches between Mode 1 and Mode 2, depending on the instructions. The goal of the optimization is to minimize CO_2 and NO_X emissions and NPC.

From the above-mentioned components, 128 PV panels PPV10BIF with a total power of 1280 kWp, 9 batteries Bat480 kWh, 10 kAh which provide a total energy of 4,32 MWh (0,7 d.aut), one diesel generator with the power of 200 KVA, and one inverter Inv-Ch400 kW with the power 400 kW are chosen for the Ro-Ro passenger ship 1. The energy balance for one year is shown in Table 8 in MWh/y.

Table 8. Energy balance for one year.

Overall Load Energy	1693.62 MWh/y From Renewable 99.23%
Unmet load	0.766 MWh/y (0.05% load)
E. Purchased from AC grid	0 MWh/y
Export Energy	288.826 MWh/y
E. sold to AC grid	123.367 MWh/y
Energy delivered by PV generator	2168.178 MWh/y
Energy delivered by AC Generator	12.237 MWh/y
Energy charged by Batteries	950.732 MWh/y
Energy discharged by Batteries	877.064 MWh/y

As visible in Table 8, 99.23% of the overall load energy comes from renewable energy resources. Unmet load is less than 0.05%. Figure 8 shows the hourly simulation for January 17 and August 08. The simulation is the same for all years. The load is met during summer and winter days. The power produced by the renewable sources is higher than load between 07:00 h and 17:00 h, and the batteries are charging in that period. Between 17:00 h and 07:00 h, the power produced by the renewable sources is less than the load, and the batteries are discharging.

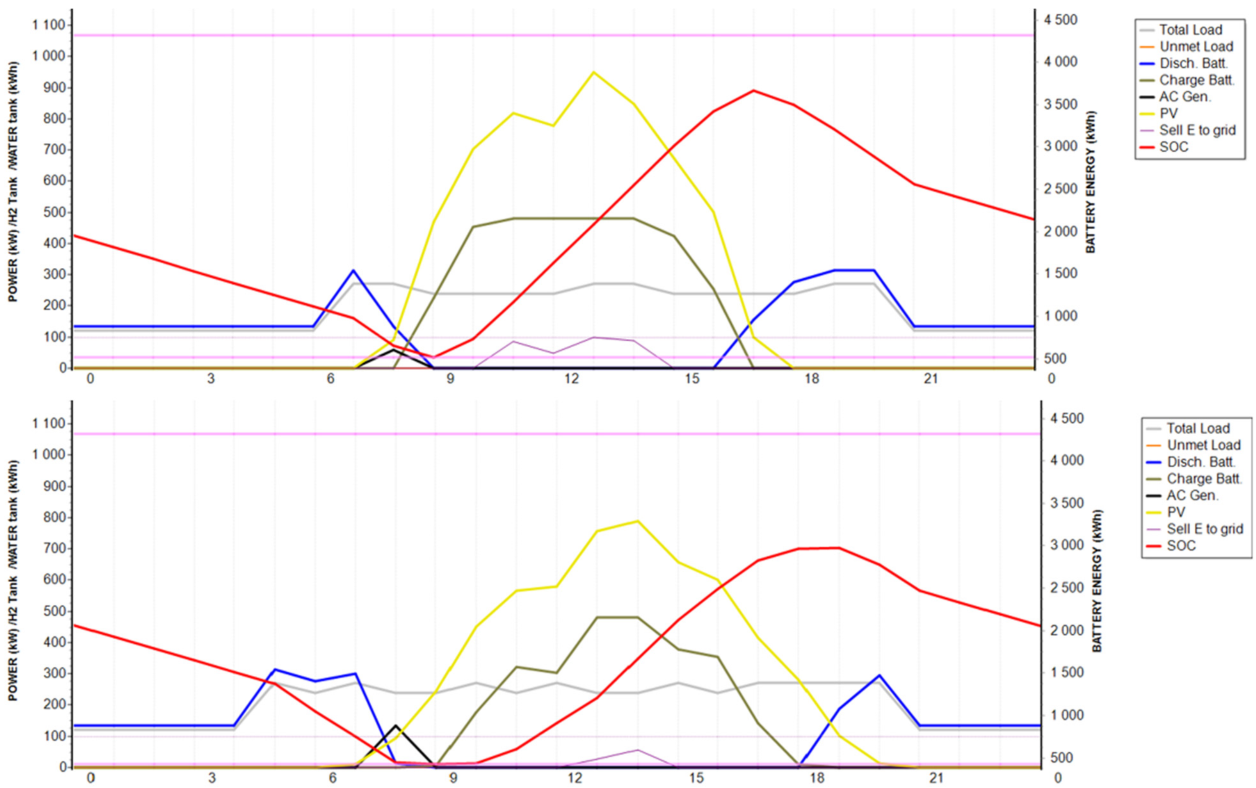


Figure 8. Hourly simulation for 17 January and 8 August 2022.

Significant environmental impacts were accomplished by incorporating such a solar system into the Ro-Ro vessel. The reduction in greenhouse gas emissions was calculated by eliminating the PV panels, batteries, and inverter from the list of components, and the initial load was only left on the diesel generators. As a result, the use of renewable energy resources reduces CO_2 emissions by 1324.85 t/year per year and NO_X emissions by 23.6 t/year per year for Ro-Ro passenger ship 1.

Prior to making a system investment, it is important to conduct an economic analysis. Total System Costs (NPC) is 2,891,024.00 €. Costs of components are shown in Table 9.

Table 9. Cost of hybrid system components.

PV Generator Costs (NPC)	1,608,407.00 €
Battery bank Costs (NPC)	1,034,998.00 €
Inverter Costs (NPC)	83,223.00 €
AC Generator Fuel Costs (NPC)	98,740.00 €
Installation + financing (NPC)	65,656.00 €
Total:	2,891,024.00 €

According to the results in Table 10, renewable energy resources account for between 90.1% and 100% of the total load energy depending on the ship. The primary goal of the optimization is to reduce the fuel consumption of diesel generators. As a result, using renewable energy resources reduces CO_2 emissions up by 1324.85 t/year and NO_X emission by 23.6 t/year for Ro-Ro passenger ship 1; CO_2 emission by 513.53 t/year and NO_X emissions by 9.15 t/year for Ro-Ro passenger ship; and CO_2 emission by 833.24 t/year and NO_X emission 14.84 t/year for high speed passenger ship. The installation of solar panels on ships is a long-term investment that costs between 849,468.00 € and 4,225,387.00 €.

Table 10. Optimization results for all vessels.

Vessel	Ro-Ro Passenger Ship 1	Ro-Ro Passenger Ship 2	High Speed Passenger Ship
PV solar panels	128 × PPV10BIF	246 × PPV10BIF	53 × PPV10BIF
Batteries	9 × Bat480 kWh, 10 kAh	9 × Bat480 kWh, 10 kAh	3 × Bat480 kWh, 10 kAh
Inverter	Inv-Ch400 kW	Inv-Ch400 kW	Inv-Ch200 kW
Renewables	99.23%	90.41%	100%
Unmet load	0.05%.	0.54%	0%
Cost	2891.024 k€	4225.387 k€	849.468 k€
CO_2 reduction	1324.85 t/year	513.53 t/year	833.24 t/year
NOx reduction	23.5989 t/year	9.1472 t/year	14.8420 t/year

During the observation of vessel movements in year 2022, on 10 August 2022, 56 ferry boats entered the port of Split. In the time period between 15:00 h and 15:45 h, seven ferries were in the departing maneuver, of which four vessels had a main engine power between 2000 kW and 4000 kW, and three vessels had a main engine power greater than 4000 kW. This is the largest number of vessels and maneuvers to depart in the same period of time in the port of Split. According to the results obtained for each category representative, installing photovoltaic panels on ships would lead to an approximate CO_2 emission reduction of 4553,82 t/year and NO_X emission reduction of 81,11 t/year.

Installing photovoltaic panels on all 36 ships that are arriving/departing from the port of Split, according to the results obtained for each category representative, would lead to an approximate CO_2 emission reduction of 27,341.39 t/year and NO_X emission reduction of 487.02 t/year. Following the IMO GHG Strategy of reducing the carbon intensity of international shipping by at least 40% by 2030 and aiming for 70% by 2050, a hybrid system implemented on all ships in the port of Split from 2023 would cut CO_2 emissions by 218,731.14 t and NO_X emissions reduction of 13,636.52 t would be achieved by year 2050.

Figures 9–11 show the behavior of solar applications on Ro-Ro passenger ships and a high-speed passenger ship depending on ship phases (hotelling—H, cruising—C, or maneuvering—M). In the hotelling phase, the power produced by renewable sources is less than the load, and batteries are discharging. Batteries can supply the whole load in hotelling phase, and the AC Generator does not work, providing zero emissions in the port. During the cruising and maneuvering phases, the power produced by the renewable sources is higher than the load, and batteries are charged with the excess power from renewable sources of energy.

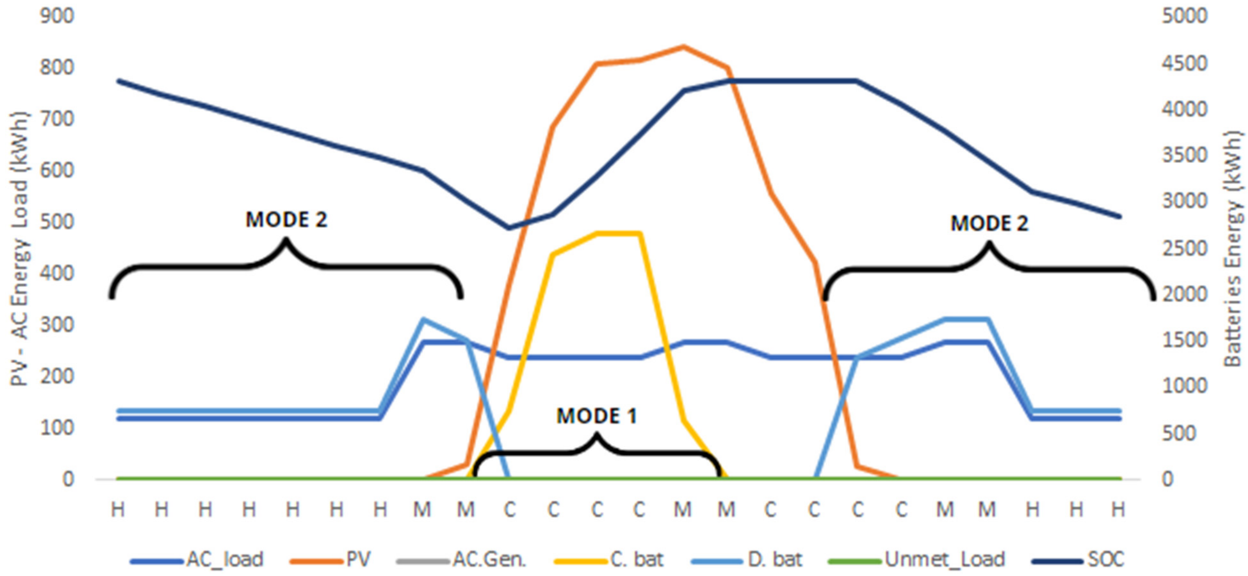


Figure 9. Solar application on Ro-Ro passenger ship 1 in different ship phases for one day.

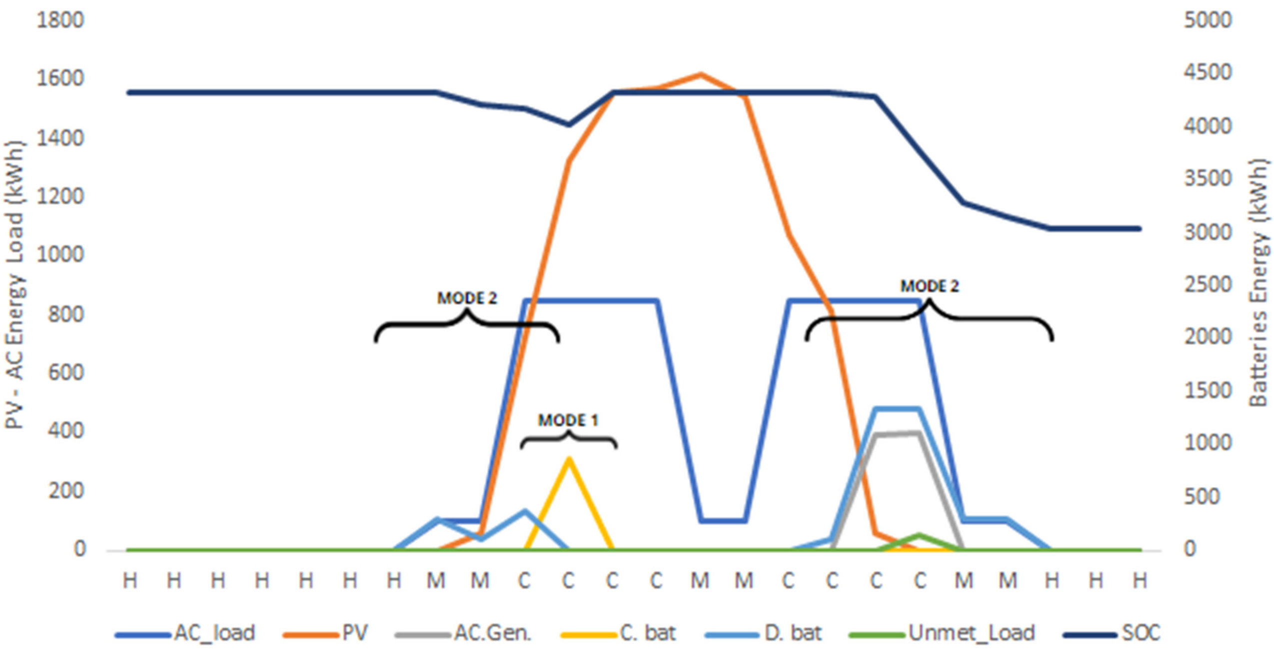


Figure 10. Solar application on Ro-Ro passenger ship 2 in different ship phases for one day.

A "hotelling phase" is a period when the ship is docked or at port. Solar power systems experience battery discharge during this period due to the time of day (night). Onboard systems and equipment like lights, air conditioning, refrigerators, and communication equipment are still operational. These technologies use electricity, putting a constant strain on the batteries. Furthermore, the ship berthed at the port may result in less direct sunshine exposure or increased shadowing from buildings nearby, decreasing the solar power output and causing the batteries to discharge to compensate for the shortage.

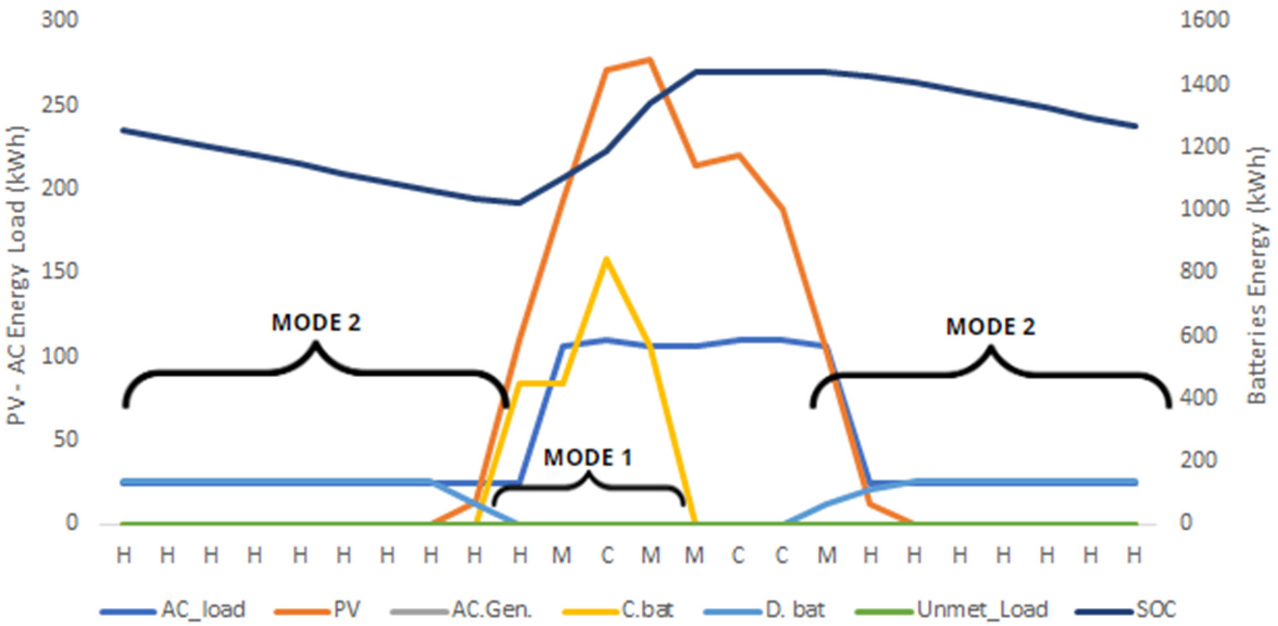


Figure 11. Solar application on high speed passenger ship in different ship phases during one day.

In the cruising and maneuvering phases, solar panels are likely to receive direct sunlight, leading to efficient power generation. The excess energy produced was used to charge the batteries.

The power demands of the ship's systems during the hotelling time shall be analyzed in order to optimize the operation of the solar power system and maintain zero emission in the ports. Examining the location and orientation of solar panels can help with maximizing sunshine exposure and minimizing shadowing effects.

5. Conclusions

Solar energy on ships is now recognized as a promising solution for reducing greenhouse gas emissions and achieving sustainability in the maritime industry. This research is focused on investigating the application of photovoltaic (PV) systems on two Ro-Ro ships and one high-speed vessel, with an emphasis on ship retrofitting. Despite the space limitations onboard ships, an innovative design is presented to allow an increased installation area for solar power systems. The proposed hybrid system consists of diesel generators, solar panels, batteries, and an inverter.

This research successfully achieved its hypotheses, demonstrating that renewable energy resources accounted for between 90.1% and 100% of the overall load energy. The primary objective of the optimization process is to minimize fuel consumption by diesel generators. Consequently, the incorporation of renewable energy resources significantly reduced emissions, ranging from 513.53 to 1324.85 t/year for CO_2 emissions and 9.15 to 23.6 t/year for NO_X emissions.

Despite the initial capital expenses, the outcomes of this study indicate that adapting the solar system to Ro-Ro ships and high-speed vessels would lead to a more sustainable future in the shipping industry.

Furthermore, during the ship hotelling phase, where the vessel is berthed at the port, the load is supplied solely by batteries, resulting in zero emissions. This demonstrates the capability of the battery-powered system to provide a clean and environmentally sustainable power source while the ship is stationary.

Given the worldwide scope of the maritime industry, international collaboration, standardization, and legislative measures are critical for knowledge sharing, as well as the formation of common frameworks for solar application standards and legislative efforts.

Future research should focus on additional factors that influence emission reduction, such as route optimization, alternative types of renewable energy, clean fuel, and new technology with different approaches to new and existing vessels.

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6.3 Article III

The International Maritime Organization (IMO) has adopted strategies to reduce GHG emissions from international shipping, including technical and operational measures. Among solutions for compliance, propeller optimization emerges as a long-term strategy with significant potential to reduce ship vibrations, fuel consumption, and the carbon footprint of maritime transport.

A ship propeller is a device that uses rotational motion to generate propulsion and propel a ship across water. It consists of several blades connected to a central hub that is positioned on a shaft powered by the ship's engine. A propeller typically has between three and five blades. More blades often result in smoother operation, although they may impact the efficiency. The shape, size, and pitch (angle) of the blades are crucial to achieve best performance and efficiency. Propellers are employed in a variety of vessels, so during the selection of propeller, operating conditions and specific performance needs should be taken into account.

Studies show that optimized propellers can significantly impact a vessel's performance. Optimized propellers may significantly decrease fuel consumption by increasing the ship's propulsion efficiency. By increasing fuel efficiency, optimized propellers reduce air pollution which aligns with environmental requirements and sustainability goals. International maritime regulations require ships to achieve specific efficiency and environmental criteria. Optimized propellers contribute to meeting these limitations. Optimized propellers increase the speed and maneuverability of a ship while reducing noise and vibration. By improving propeller efficiency, optimization can extend the lifespan of the propeller and resulting in lower maintenance costs. Overall cost reductions in terms of fuel, maintenance, and operating efficiency can be realized by optimizing ship propellers.

Propeller optimization, a crucial aspect of ship performance, involves creating an initial design plan and refining it to achieve the best compromise between goals and limitations. The international standard ISO 484-2:2015 specifies the tolerances for fabricating propellers in all geometric dimensions, considering criteria such as pitch, diameter, chord length, rake, thickness, and blade separation. The regulation categorizes propeller tolerances into four classes: Class III: Wide tolerances, Class II: Medium accuracy, Class I: High accuracy, Class S: Very high accuracy.

The impact of optimized propellers on ship vibrations and fuel consumption is evaluated through a case study on a Ro-Ro passenger ship. Optimized propeller design reduces vibrations, which enhances propeller efficiency and decreases fuel consumption, thereby reducing GHG emissions.

Prop Scan technology is used to optimize propeller efficiency by examining and refining propellers to improve efficiency, minimize vibrations, and enhance overall ship handling. The system uses high-precision 3D scanners and software to analyze propeller surfaces, identify flaws, and recommend design changes. Technicians then manually reshape and refine the blades based on these recommendations. This process ensures that the propeller meets required standards and functions optimally.

During sea trials, fuel consumption and vibrations were measured before and after optimization. Results showed a significant drop in fuel consumption and reduced vibrations, highlighting the effectiveness of propeller optimization.

Post-optimization results indicated a 1.41% reduction in fuel consumption, translating to substantial fuel savings and a significant reduction in CO_2 emissions. Besides CO_2 reduction, optimization aids in decreasing particulate matter and nitrogen oxide emissions, assisting firms in meeting regulatory requirements and demonstrating environmental responsibility.

Besides propeller optimization, the paper performs a SWOT (strengths, weaknesses, opportunities, threats) analysis comparing it with solar and wind power applications on ship.

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Article

Propeller Optimization in Marine Power Systems: Exploring Its Contribution and Correlation with Renewable Energy Solutions

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Abstract: The goal of increasing fuel efficiency and decreasing greenhouse gas (GHG) emissions has increased interest in the application of renewable energy sources and the usage of new technologies in the maritime industry. In order to implement the most suitable source, factors such as voyage duration, storage availability, and the condition of existing vessels as well as those that are still under construction should be taken into account. Propeller optimization is proposed as a long-term solution. This paper investigates the environmental aspects of propeller optimization, focusing on its potential to reduce ship vibrations fuel consumption, and, therefore, the ship's carbon footprint. The case study presents propeller optimization on a Ro-Ro passenger ship. The data collected during sea trials before and after propeller optimization will be compared. Expected fuel oil consumption will be correlated to the CO_2 emission reduction. Besides propeller optimization, the paper performs a SWOT (strengths, weaknesses, opportunities, threats) analysis comparing it with solar and wind power applications on ships.

Keywords: propeller optimization; solar power application; wind power application

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1. Introduction

1.1. Problem Background

In general, maritime transport is strongly related to global trade. Any rise in global trade is expected to increase demand for maritime transport. The global fleet has nearly doubled in size by deadweight tonnage since 2007 and, at the end of 2022, accounted for roughly 61,000 vessels. Growth has been linear, increasing by 3% in the most recent year [1]. As a result, emissions from ships are projected to rise. The International Maritime Organization (IMO) strives to contribute to the global fight against climate change, calling for immediate action by adopting a strategy for the reduction of greenhouse gas (GHG) emissions from international shipping. The 2023 IMO GHG Strategy calls for a reduction in the carbon intensity of international shipping through increased energy efficiency in new ships as well as the adoption of zero or near-zero GHG emission technologies, fuels, and/or energy sources [2]. Technical and operational approaches to increase ship energy efficiency are consolidated through the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Ship Energy Efficiency Management Plan (SEEMP) [3,4]. Examples of solutions for compliance with these measures are visible in Figure 1.

The EEDI is a technical measure encouraging the adoption of more energy-efficient equipment and engines in the construction of new ships to reduce pollution, while the SEEMP is a cost-effective operational mechanism. All existing ships of 400 GT and above are obliged, with specified exceptions, to compute their reached Energy Efficiency Existing Ship Index (EEXI), which indicates the ship's "technical" or "design" efficiency. The Carbon Intensity Indicator (CII) rating represents a ship's operational energy efficiency (in terms of how efficiently a ship transports goods or passengers, expressed in grams of CO_2 emitted per transport work and nautical miles), using fuel oil consumption data from the IMO DCS and the SEEMP as a management tool.

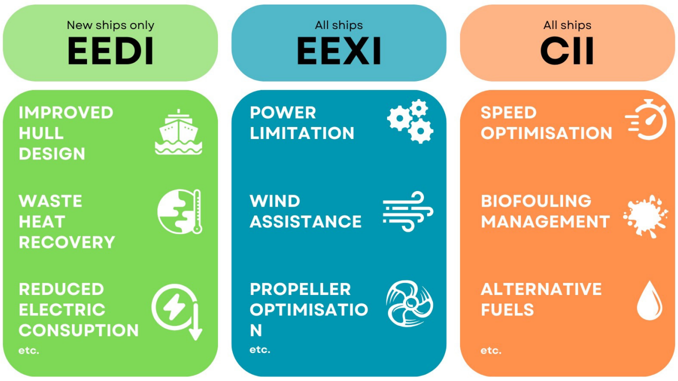

Figure 1. Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII) are examples of solutions for compliance.

1.2. Energy Efficiency and GHG Reduction in Shipping

Energy efficiency improvements can be achieved through propulsion system optimization and alternative fuel usage [5–11], improved hull designs [12,13], and operational measures such as lower speed [14], voyage optimization [15], etc., that can achieve significant reductions in fuel consumption and resulting CO_2 emissions. The connection between ship propeller design, vibrations, and fuel consumption is an essential aspect of ship performance. Ship propeller optimization is crucial for improving marine vessel efficiency, maneuverability, and overall performance. The typical approach involves creating an initial design plan and refining it by achieving the best compromise between goals and limitations. This process naturally evolves into an optimization task [16]. This study shows that propellers have a significant impact on a vessel's performance, leading to an increase in the trim angle and a decrease in resistance. These effects result from a notable decrease in pressure near the propellers [17]. Engineers can achieve optimal power transfer, reduce fuel consumption, and limit the environmental effect by fine-tuning the design and features of ship propellers. The results of the method for improving the performance of marine propellers, particularly the wide chord tip (WCT) propeller, which maximizes propeller performance by altering enlarged regions of the propeller blade, can improve efficiency by more than 2% [18]. Hydrodynamic optimization of propellers using gradient and non-gradient-based algorithms revealed a nearly 13% increase in the efficiency and a nearly 15% drop in the torque coefficient for the first propeller, as well as a nearly 10% increase in the efficiency for the later propeller are attainable [19]. Research results indicate that it is possible to create a medium-sized flexible composite propeller that will reduce fuel consumption while withstanding the imposed loads. The design and optimization of a flexible composite material marine propeller results in a 1.25% reduction in fuel consumption for the combined scenario, equating to a 4.7% drop in cruising speed [20]. A comprehensive test system for ship-model testing in real wind, wave, and current flow settings was created to determine the 25-m-long ship performance in actual sea conditions. This platform was used to test the effects of an energy-saving technology and the results proved the reliability of the proposed approach [21]. The measurements and analyses performed, when compared to the ship's output performances before and after propeller optimization, demonstrate a successful procedure for optimizing a fixed-pitch propeller and the justification for using Prop Scan technology [22]. Berg Propulsion, a Swedish company specializing in propellers, claims significant success by redesigning propulsion systems on existing ships, managing to achieve remarkable fuel savings of up to 22% in a recent case through their redesign efforts [23]. The optimization method of trimaran hull form for resistance reduction and propeller intake flow improvement focuses on two main goals: reducing the total resistance and improving the propeller intake flow, making it a multi-objective optimization challenge. The optimization outcomes reveal a 13.3% decrease in resistance and a 7.58% enhancement in the wake coefficient for the obtained hull form [24]. Shifting the propeller toward the rear and expanding its area revealed significant potential for reducing power requirements. This adjustment enables a larger propeller diameter without the risk of transmitting pressure pulses to the hull. This enhancement in efficiency can consequently diminish environmental effects and costs [25]. A thorough analysis aimed to enhance the energy efficiency of large shipping vessels by optimizing the propeller boss cap with fins (PBCFs) in a cost-effective manner. After achieving an optimal PBCF design, it was integrated into a model-scale modern propeller/rudder system that initially lacked PBCFs. Operating under the designed conditions, this implementation provided an efficiency improvement of 0.728 percentage points, equivalent to a 1.043% increase over the original propeller/rudder system [26]. Designing propellers to enhance efficiency and minimize cavitation issues demands significant computational resources, especially during the initial planning stage. While the boundary element method (BEM) is commonly used at this stage due to its lower computational demands, it often brings about higher uncertainties [27]. Adjusting the propeller's shape for better efficiency also alters its behavior in terms of cavitation, vibrations, and internal noise. Consequently, the only viable approach is to discover a balanced design specific to each ship and its particular requirements. The purpose of optimization is to find the proper propeller geometry that decreases the power required to obtain a given thrust. The use of a cross-section airfoil angle of attack as a function of blade span as a design variable strengthens the optimization process by preserving the airfoil properties from calculation at supercritical angles of attack and reducing the amount of calculations performed throughout the optimization. The development algorithm was confirmed both experimentally and numerically using the CFD approach. The study demonstrates that the improved propeller geometry outperforms commercial alternatives on the market [28]. Recently, there has been significant work on automated optimization methods for blade design support [29]. Despite promising outcomes, applying this approach in industrial settings has proven challenging due to difficulties in setting up the optimization algorithm to reach a converged solution. Given these challenges, the traditional manual design process appears more reliable and efficient than grappling with a fully automated optimization approach. A summary of the literature findings, together with authors and year published, is published in Table 1.

Table 1. Chronological presentation of the literature findings regarding ship efficiency.

Author/Authors and Year	Title	Effect on Energy Efficiency
Lee et al., 2010 [18]	Performance optimization of marine propellers	Method for improving wide chord tip (WCT) propeller efficiency by more than 2%
Blasques et al., 2010 [20]	Hydro-elastic analysis and optimization of a composite marine propeller	The design and optimization of a flexible composite marine propeller results in a 1.25% reduction in fuel consumption
Knutsson, Larsson, 2011 [25]	Large Area Propellers	Potential of propeller adjustments for efficiency enhancement
Vetma et al., 2012 [22]	Optimization of marine propellers with constant pitch	Optimizing marine propellers using Prop Scan increased ship speed, while fuel consumption decreased
Lützen, Kristensen, 2012 [12]	A Model for Prediction of Propulsion Power and Emissions: Tankers and Bulk Carriers	A new model for prediction of the propulsion power of ships
Kristensen, Lützen, 2012 [13]	Existing Design Trends for Tankers and Bulk Carriers: Design Changes for Improvement of the EEDI in the Future	Analysis showed that the design trend of bulk carriers and tankers has moved in the wrong direction from an energy-saving point of view
Vesting et al., 2013 [16]	Parameter Influence Analysis in Propeller Optimisation	Propeller optimization process
Taheri, Mazaheri, 2013 [19]	Hydrodynamic Optimization of Marine Propeller Using Gradient and Non-Gradient-based Algorithms	Optimization of marine propellers using gradient and non-gradient-based algorithms revealed a nearly 13% increase in efficiency and a nearly 15% drop in torque coefficient for the first propeller, as well as a nearly 10% increase in efficiency for the later propeller

Table 1. *Cont.*

Author/Authors and Year	Title	Effect on Energy Efficiency
Faitar, Novac, 2016 [8]	A new approach on the upgrade of energetic system based on green energy	Comparative analysis of the EEDI and EEOI
Ančić et al., 2018 [9]	Energy efficiency of ro-ro passenger ships with integrated power systems	Energy efficiency of ro-ro passenger ships with IPS
El Geneidy et al., 2018 [11]	Increasing energy efficiency in passenger ships by novel energy conservation measures	Increasing energy efficiency in passenger ships
Zaccone et al., 2018 [15]	Ship voyage optimization for safe and energy-efficient navigation: A dynamic programming approach	Ship voyage optimization method, aiming to select the optimal path and speed on the basis of weather forecast maps in accordance with a minimum fuel consumption
Radonja et al., 2019 [14]	Methodological approach on optimizing the speed of navigation to reduce fuel consumption and increase energy efficiency of the cruising ship	Fuel savings can be achieved by optimizing cruising speeds during travel
Litwin et al., 2019 [5]	Experimental Research on the Energy Efficiency of a Parallel Hybrid Drive for an Inland Ship	Energy efficiency improvements of a parallel hybrid drive
Roshan et al., 2020 [17]	Hull–propeller interaction for planing boats: a numerical study	Propellers have a significant impact on a vessel's performance, leading to an increase in trim angle and a decrease in resistance
He et al., 2021 [7]	Two-phase energy efficiency optimization for ships using parallel hybrid electric propulsion system	Two-phase energy efficiency optimization for ships using parallel hybrid electric propulsion system reduces energy consumption by between 2.60% and 9.86%
The maritime executive, 2021 [23]	No name	Redesigned propeller blades increase fuel efficiency by up to 22%
Ammar, Seddiek, 2021 [10]	Evaluation of the environmental and economic impacts of electric propulsion systems onboard ships: case study passenger vessel	Gas turbine electric and steam propulsion systems demonstrate higher energy efficiency compared to Diesel engines, boasting improvements of 9.3% and 27.55%
Elkafas, Shouman, 2022 [6]	A Study of the Performance of Ship Diesel-Electric Propulsion Systems From an Environmental, Energy Efficiency, and Economic Perspective	The suggested electric propulsion system reduced emission rates compared to the conventional system, showing decreases of 10% for carbon dioxide, 21% for nitrogen oxides, and 88% for sulfur dioxide emissions.
Doijode et al., 2022 [27]	A machine learning approach for propeller design and optimization	Challenges in propeller design and computational demands
Hamed, 2022 [24]	Multi-objective optimization method of trimaran hull form for resistance reduction and propeller intake flow improvement	Trimaran hull form optimization outcomes reveal a 13.3% decrease in resistance and a 7.58% enhancement in wake coefficient for the obtained hull form
Yin et al., 2023 [26]	Improve Ship Propeller Efficiency via Optimum Design of Propeller Boss Cap Fins	Optimization of propeller boss cap with fins provided an efficiency improvement of 0.728 percentage points
Gypa et al., 2023 [29]	Propeller optimization by interactive genetic algorithms and machine learning	Difficulties in blade design optimization

2. Materials and Methods

This paper aims to evaluate the impact of optimized propellers on ship vibrations and fuel consumption and explores how they can reduce the environmental impact of maritime transportation.

Concerning the previously mentioned research problem of ship propeller optimization, the following hypotheses are defined:

- Optimized propeller design reduces vibrations;
- Vibration reduction enhances propeller efficiency and decreases fuel consumption;
- Propeller optimization reduces greenhouse gas (GHG) emissions from shipping.

To confirm these hypotheses, fuel consumption and vibrations on the Ro-Ro passenger ship during sea trials will be measured before and after ship propeller optimization on the same route. This data will be compared and expected fuel savings will be correlated to the CO_2 emission reduction.

Furthermore, a SWOT analysis will compare propeller optimization efficiency to other technologies (solar and wind power applications). The process is shown in Figure 2.

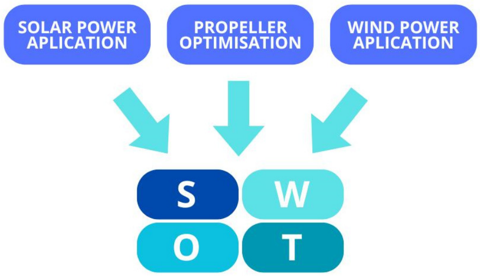

Figure 2. SWOT analysis block diagram.

3. Propeller Optimization—Case Study

The specific geometry of the propeller enhances the power transformation. The power produced is the product of the propeller thrust (T_p) and the advanced velocity (u_a). The thrust power produced by the propeller is defined as [30]:

$$P_t = T_p \times u_a \tag{1}$$

The shaft power is the product of the shaft torque and the shaft's angular velocity. In this paper, the shaft torque is referred to as the propeller torque (Q_p) and the shaft angular velocity is referred to as the propeller angular velocity (ω). Therefore:

$$P_S = Q_P \times \omega \tag{2}$$

Efficiency is defined as the ratio of useful and produced power used throughout the process:

$$\eta = \frac{P_{produced}}{P_{consumed}} \tag{3}$$

Therefore, propeller efficiency can be defined as:

$$\eta prop = \frac{P_t}{P_s} = \frac{T_p \times u_a}{Q_p \times \omega} \tag{4}$$

Propeller optimization can significantly improve efficiency by maximizing thrust while minimizing energy consumption. Vibrations in a ship's propulsion system can cause a variety of problems, including decreased efficiency, component failure, and discomfort for passengers and crew. Typically, propeller-induced vibrations are influenced by the: angular speed of the propeller (represented as revolutions per minute—rpm), propeller blade design, and hull and shaft alignment.

To reduce vibrations and fuel consumption, the propeller design must be optimized, taking into account the ship's operational conditions, size, and intended use. Proper propulsion system maintenance and alignment, as well as frequent cavitation checks, are critical for decreasing vibrations and improving fuel economy. Finally, the relationship between the ship propeller design, vibrations, and fuel usage is complicated and dependent on a variety of factors. These parameters can be optimized to save money, increase performance, and reduce environmental impact.

The ship's propeller design is one of the most critical aspects affecting fuel consumption and vibrations. A well-designed propeller can significantly impact the ship's performance. Tolerances for the fabrication of propellers in all geometric dimensions are provided by the international standard ISO 484-2:2015 [31]. This standard takes into account all propeller criteria such as pitch, diameter, chord length, rake, thickness, and blade separation. The size of various radii must be varied depending on the type of propeller manufactured according to the regulation. The ISO-484 standard has 4 classes of tolerance for propeller classes, where class III has wide tolerances, class II stands for medium accuracy, class I stands for high accuracy, and class S has very high accuracy. Pitch tolerances are shown in Table 2.

Table 2. International Standard Organization ISO-484-2 tolerances on pitch.

Pitch		Class			
		S	**I**	**II**	**III**
Local pitch	Pitch of one portion of one blade	±1.5%	±2%	±3%	-
Section pitch	Average pitch of one radius of one blade	±1%	±1.5%	±2%	±5%
Blade pitch	Pitch of single blade	±0.75%	±1%	±1.5%	±4%
Propeller pitch	Average pitch of all blades	±0.5%	±0.75%	±1%	±3%

3.1. Prop Scan System

Prop Scan is a sophisticated technology used in the marine industry to optimize ship propeller efficiency [32]. It is a computerized system that examines and refines propellers to improve efficiency, minimize vibrations, and improve overall ship handling. The Prop Scan system for inspecting and diagnosing propellers consists of a workstation with a propeller base and a measuring sensor, all connected to the computer. This method makes use of a specific process that analyzes propeller surfaces. A high-precision 3D scanner i = was employed to capture propeller geometry, along with the corresponding software, to define the propeller shape. Measurements were taken on the radius $\bar{r}$, along the curve PQ, at any angle α, to determine the radius and the height difference (Δh) in addition to the reference plan. This measurement provided the section pitch. This value was compared to the intended value and classified into tolerance classes. The pitch per radius and per blade was calculated for each radius by multiplying the difference in height among the furthest distant measuring sites at each radius [33]:

$$P = h \times \frac{360}{\alpha} \quad (5)$$

Measurement was made on the pressure face of the blade, which involved selecting around 5 evenly distributed places between the leading and tailing edges for the initial measurement. The propeller was measured at different radii, with each radius measured as a fraction of the full radius (R = 0.2 × R, 0.3 × R, 0.4 × R, 0.5 × R, 0.6 × R, 0.7 × R, 0.8 × R, 0.9 × R, 0.95 × R, 0.975 × R, 0.985 × R). Furthermore, the average values can be compared and a tolerance class defined [22,33].

These data were then entered into software that analyzes, simulates, and determines the most efficient design changes.

Computational fluid dynamics (CFD) methods were used to simulate and calculate fluid behavior. The numerical approach was based on Reynolds averaged Navier–Stokes equations [33].

The Prop Scan system software processed the data and displayed the propeller blade shape in a linear and bar graph. Prop Scan detects flaws or abnormalities in the propeller surfaces. Minor damages or abnormalities can have a substantial impact on a propeller's performance, generating vibrations, lower fuel economy, and inefficient vessel handling. Prop Scan technology enables rigorous scanning and inspection, allowing professionals to identify and rectify these flaws with great precision. Following the diagnostics, some changes to the propeller, or rather a pitch correction, had to be made in accordance with the base set of the propeller blade's new design (linear diagram). Technicians altered the propeller blades using specialized machinery based on the software's recommendations. To obtain the appropriate standards, they manually reshaped and refined the blades. After the repairs were completed, the propeller was scanned again to ensure that the changes were made correctly. This approach ensures that the propeller satisfies the requirements and functions properly.

Figure 3 shows the Prop Scan workstation and propeller.

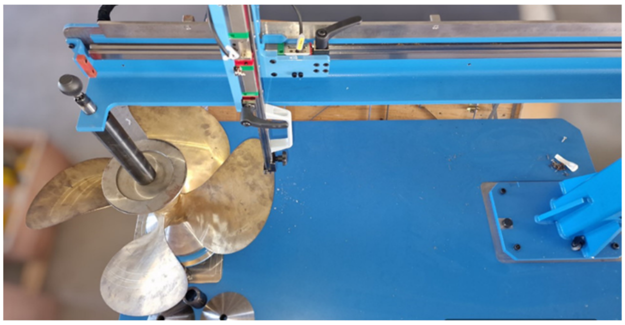

Figure 3. Prop Scan workstation.

3.2. Measurements and Data Collection

Propeller optimization was performed on a Ro-Ro passenger ship. Specifications such as the year when the ship was built, the length of the hull, the ship's breadth, depth, gross tonnage, and propulsion characteristics were provided from the yacht Certificate of Registry and presented in Table 3.

Table 3. Ro-Ro passenger ship specifications.

Year built	1993
Length of hull	116.00 m
Breadth	18.90 m
Draft	5.140 m
Gross tonnage	9487
Propulsion type	Diesel engine × 2
Manufacturer	MAN, Augsburg, Germany
Model	MAN 8L
Total power	1750.00 kW × 2

During sea trials, fuel consumption and vibrations on the engine were measured. Propeller optimization was conducted by the Adriatic Propeleri company [34]. On the day of the sea trial, all working parameters were measured in two different directions in order to avoid the effect of the wind and sea current. At the beginning of the trip, the ship's speed and fuel consumption were recorded using the ship's instruments at the nominal number of revolutions. This was followed by a ten-minute drive against the sea current and ten minutes in the direction of the sea current in the area of the Zadar channel in order to make a comparison after the optimization process. The results before propeller optimization are presented in Tables 4 and 5.

Table 4. Ship speed and fuel consumption before propeller optimization.

Before Optimization—Class 2			
Revolutions per Minute (RPM)	**380 (±1)**		**Measurement Error**
Course	86°	266°	±1°
Speed (knots)	14.25	14.62	±0.02
Average speed in both directions (knots)	14.43		±0.05
Consumption (Lh)	876.2	906.3	±0.4
Average consumption in both directions (L/h)	891.3		±0.8

Table 5. Ship vibrations before propeller optimization.

Ro-Ro Passenger Ship Vibration Measurement at 380 min^{-1} (Average of Both Directions)			
Direction	**X [m/s^2] (Up-Down)**	**Y [m/s^2] (Port-Starboard)**	**Z [m/s^2] (Bow-Stern)**
RMS exp	0.02130	0.02402	0.03447
RMS lin	0.09295	0.07887	0.1399
Peak	0.06951	0.07820	0.2477
Peak-Peak	0.1667	0.1444	0.2320
Min	−0.09295	−0.07888	−0.1399
Max	0.07371	0.07032	0.1077
Average	−0.000434	−0.00002019	−0.002849
Vibration spectrum (maximum amplitude)			
X peak	0.1017@ [7 Hz]		
Y peak	0.02108 @ [31 Hz]		
Z peak	0.03088 @ [7Hz]		

4. Results after Optimization of the Ship Propeller

After propeller optimization, fuel consumption and vibrations were measured. The measurements were conducted according to the same principles as before the propeller optimization, allowing for comparison of the results. The results after propeller optimization are presented in Tables 6 and 7. Vibrations before and after optimization (X, Y, Z-direction separately) are shown in Figure 4.

Table 6. Ship speed and fuel consumption after propeller optimization.

After Optimization—Class S			
Revolutions per Minute (RPM)	**380 (±1)**		**Measurement Error**
Course	185°	5°	±1°
Speed (knots)	14.71	14.54	±0.02
Average speed in both directions (knots)	14.63		±0.05
Consumption (L/h)	865.2	892.1	±0.4
Average consumption in both directions (L/h)	878.7		±0.8

Table 7. Ship vibrations after propeller optimization.

Ro-Ro Passenger Ship Vibration Measurement at 380 min^{-1} (Average of Both Directions)			
Direction	**X [m/s^2] (Up-Down)**	**Y [m/s^2] (Port-Starboard)**	**Z [m/s^2] (Bow-Stern)**
RMS exp	0.02448	0.02310	0.036866
RMS lin	0.02435	0.01968	0.1050
Peak	0.074526	0.06702	0.2000
Peak-Peak	0.1464	0.1275	0.1623
Min	−0.07188	−0.06702	−0.09495
Max	0.074526	0.06754	0.1051
Average	−0.0006371	−0.0003775	0.001191
Vibration spectrum (maximum amplitude)			
X peak	0.0211 @ [7 Hz]		
Y peak	0.01024 @ [12,5 Hz]		
Z peak	0.03296 @ [7 Hz]		

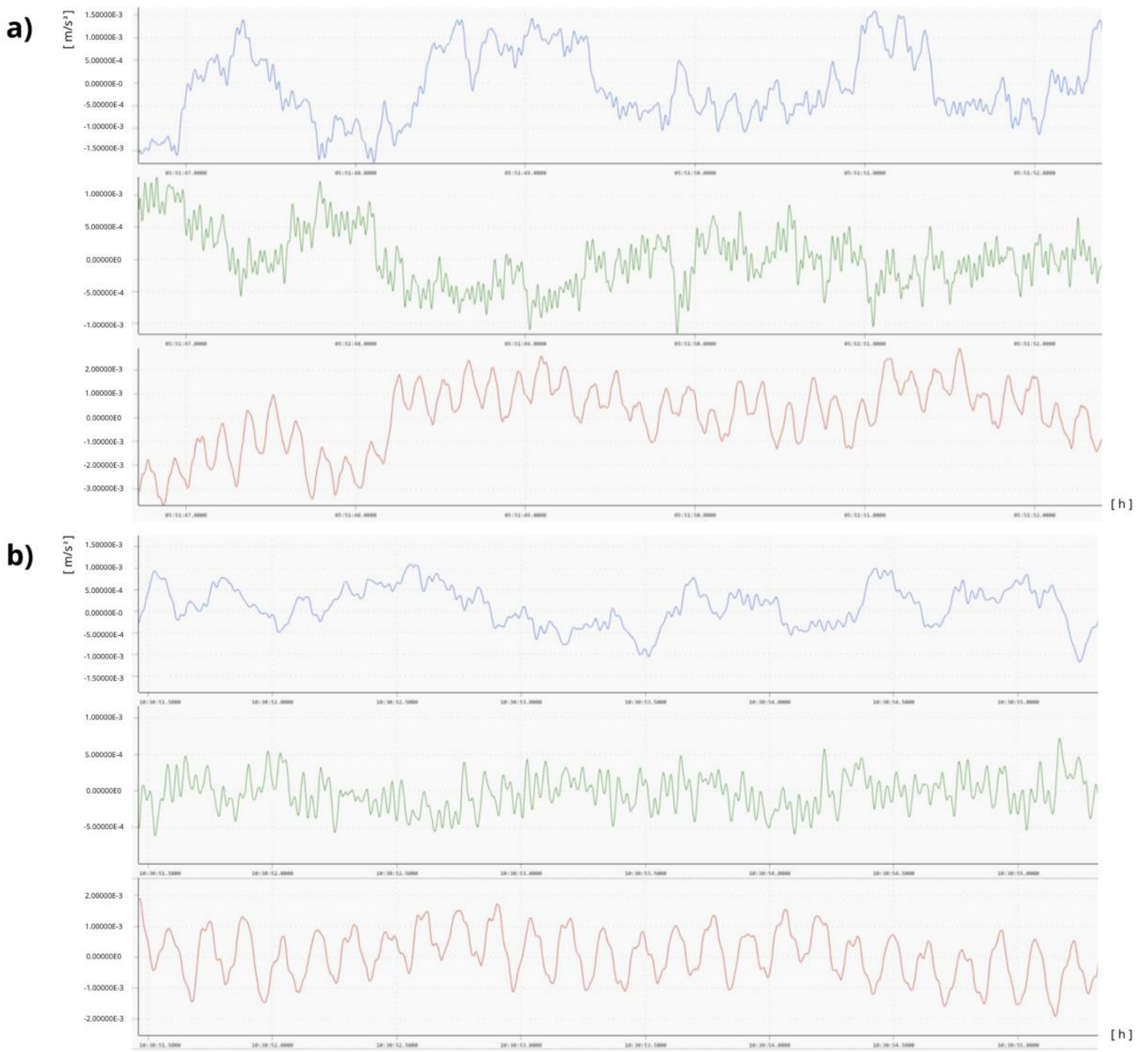

Figure 4. Vibrations before (**a**) and after (**b**) optimization (X, Y, Z-direction separately).

Comparing the results before and after propeller optimization, there was approximately a 1.41% drop in fuel consumption. Achieving a 1.41% reduction in fuel consumption through propeller optimization not only leads to cost savings but also has effects on emissions and the environment. Reduced greenhouse gas emissions are one of the most direct and immediate benefits of reduced fuel consumption. When fossil fuels are burned for propulsion, carbon dioxide (CO_2) is created, which is a key contributor to climate change. The Ro-Ro passenger ship consumes approximately 2,540,456 L of marine diesel oil (MDO) annually according to the Coastal liner shipping agency, which is the main regulatory body of the Republic of Croatia for issues of liner passenger traffic on the Adriatic. Propeller optimization results in substantial fuel savings, amounting to around 35,852.45 L per year [35]. Considering the average CO_2 emissions factor of 3.151 tons CO_2 per fuel ton for marine diesel oil (MDO) and converting the fuel savings from liters to metric tons, and taking into account the density of marine diesel oil, the Ro-Ro passenger ship's annual fuel savings contribute to a reduction of approximately 96,098.26 tons of CO_2 emissions [36].

Aside from CO_2 reduction, propeller optimization can aid in the reduction of particulate matter and nitrogen oxide emissions. Many countries have rigorous regulations in place to limit transportation emissions. A 1.41% reduction in fuel consumption achieved by propeller optimization can assist firms in meeting and exceeding these legal criteria, avoiding penalties and exhibiting environmental responsibility.

The cost of propeller optimization varies depending on different parameters such as the size and type of vessel, the existing status of the propeller, and the level of customization necessary. Overall, the cost of propeller optimization can fluctuate based on individual requirements and constraints of the optimization project. Fuel savings, improved performance, and environmental benefits are all advantages of optimization. Vessels with optimized propeller systems may obtain a competitive advantage in the market by offering lower operating costs, superior performance, and enhanced environmental credentials. Propeller optimization is a long-term investment that can yield benefits throughout the vessel's lifecycle. Assessing the long-term economic feasibility of optimization techniques requires considering factors such as future fuel price predictions, technological advancements, and increasing regulatory requirements.

The propeller optimization result of a 1.41% decrease in fuel consumption falls within a comparable range to the other discussed techniques. For instance, the optimization of the flexible composite marine propeller resulted in a 1.25% reduction in fuel consumption, while the optimization of the propeller boss cap led to a 0.728 percentage point increase in efficiency. Similarly, optimizing marine propellers using algorithms can yield significant efficiency gains of approximately 13% in certain conditions, contributing distinctly to improving propeller performance and fuel efficiency in the marine industry, with vessel type and operational conditions determining its effectiveness.

Furthermore, such optimization efforts help to achieve the industry's sustainability goals by lowering greenhouse gas emissions and minimizing its environmental impact. Propeller optimization not only saves fuel but also enhances vessel performance, reliability, and market competitiveness. It enables maritime businesses to operate more efficiently and maintain competitiveness in a global market where fuel prices and environmental concerns hold high importance for the industry.

To compare results among ships of different sizes and demonstrate the efficiency of Prop Scan technology propeller optimization, a study on propeller optimization on an 18.34 m long fishing ship was reviewed. After optimizing the propeller from class II to class S, the fishing ship consumed 15.66% more fuel for the same number of diesel engine revolutions. Additionally, preoptimization vibrations were significantly reduced. This fishing ship has reached the same speed with fewer diesel engine revolutions.

Potential limits of propeller optimization include challenges in obtaining approvals for ship retrofitting, as upgrading existing vessels may need regulatory approval. Obtaining these permits can be a lengthy process involving compliance with environmental, safety, and classification society requirements. The effectiveness of propeller optimization depends on the vessel type, size, and speed and the propeller condition. While propeller optimization can lead to significant fuel savings and performance advantages for some vessels, others may not experience such substantial results. Additionally, inaccurate or inadequate data might undermine the effectiveness of optimization attempts, resulting in unsatisfactory outcomes. While propeller optimization contributes to fuel saving and emission reduction, its environmental impact may be lower compared to renewable energy sources such as wind, solar, or hydrogen propulsion.

5. Comparing Photovoltaic Panels Application, Wind Application, and Propeller Optimization

The aim of propeller optimization is to increase efficiency, consequently reducing fuel consumption. A 1.41% reduction in fuel consumption is noteworthy and directly translates into lower CO_2 emissions. This is consistent with worldwide efforts to reduce greenhouse gas emissions and to combat climate change. Furthermore, the effects of optimization extend beyond CO_2 reduction; it can also aid in diminishing particulate matter and nitrogen oxide emissions, thus enhancing environmental sustainability. Propeller optimization has various strengths, including the potential for increased ship efficiency and environmental benefits from lower emissions. The capacity to customize designs for specific ships is another benefit. However, weaknesses such as optimization costs, process complexity, and potential integration issues may prevent wider implementation. Opportunities arise from the increasing demand for environmentally friendly transportation solutions and potential legislative incentives promoting the integration of solar applications with maritime fleets Threats include the need to handle technical uncertainty and reluctance to change within the maritime industry.

Solar power installation, on the other hand, provides a renewable energy source that does not rely on fossil fuels. Utilizing solar energy on ships is widely recognized as a viable approach to reducing greenhouse gas emissions and advancing marine sustainability. Comparing the CO_2 reduction achieved through the optimization of ship propellers with the CO_2 reduction achieved through the implementation of solar applications, the solar application results in a substantially higher reduction compared to the optimization of fuel consumption alone. For instance, propeller optimization on Ro-Ro passenger ships results in an annual fuel saving equivalent to approximately 96,098.26 kg of CO_2 emissions, whereas the implementation of solar applications on the same ships leads to a reduction of 513,530 kg of CO_2 emissions per year [37]. Both propeller optimization and solar power usage on ships contribute to environmental aims. Solar power minimizes reliance on traditional fuel sources, resulting in cleaner mobility. Both technologies enable customization. Solar applications can be tailored to a ship's energy requirements and available space. The growing market demand for sustainable and energy-efficient maritime technologies presents a common opportunity for both solar energy application and propeller optimization. Propeller optimization aims to improve the efficiency of traditional propulsion systems, whereas solar power applications use photovoltaic panels to directly harness energy from the sun. Both technologies face integration issues but they are fundamentally different. Propeller optimization may include changes to current propulsion systems but solar power applications must take into account space restriction. Solar power applications are weather dependent since energy generation depends on sunlight availability. Propeller optimization, on the other hand, requires less reliance on external weather conditions once accomplished.

Wind-powered ships use innovative sail technologies, providing a greener alternative by considerably reducing dependency on traditional fossil fuels. By harnessing the force of the wind, they aim to reduce carbon emissions. Although the unpredictability of the wind poses challenges, ongoing advancements in sail designs and navigation systems are steadily enhancing their efficiency, thus establishing more effective marine transportation. The study investigating the carbon footprint (CF) of Croatia's Ro-Ro passenger fleet in the Adriatic Sea revealed that 27 Ro-Ro ships emit approximately 29,000 tons of CO_2 per year [38]. The investigation separates two lines that contribute much more to overall emissions. Through the utilization of a wind density map on the specific routes and the installation of appropriate wind turbines on Ro-Ro ships, tailpipe emissions could be reduced by approximately 24.3 kg CO_2/h, or 213 tons, annually, resulting in a CF reduction of around 17%. However, on the other route, where the mean annual wind power density is substantially lower, the reduction in CF is less than 3.2%, making it unsuitable for this route. Wind energy usage on ships, like solar power, includes using a renewable source for ship propulsion. Wind-assisted technology can considerably improve fuel efficiency by using wind power to supplement existing propulsion systems. Wind energy usage, like solar energy usage and propeller optimization, allows for modification to accommodate a variety of ship types and sizes. However, barriers to wider use include high initial investment costs, required changes to ship design for effective wind collection, and limited wind conditions. Table 8 illustrates the SWOT analysis of propeller optimization, wind power application, and solar power application.

Table 8. SWOT analysis for propeller–wind–solar propulsion.

	Solar Power Application	Wind Power Application	Propeller Optimization on Ships
STRENGTHS	- Renewable energy source - Long lifespan - Low operational costs once installed - Other applications besides ship propulsion - Potential for combination with energy storage systems to provide continuous power supply - Reduced dependence on fossil fuels - Can be combined with other renewable energy sources	- Renewable energy source - Zero greenhouse gas emissions during operation - Potential to save considerable amounts of fuel and reduce emissions - Reduced dependence on fossil fuels - Can be combined with other renewable energy sources - Can be linked into current ship systems without requiring significant modifications	- Retrotiffing ships - Improves fuel efficiency and lowers greenhouse gas emissions - Reduces vibrations - Can be used with hull optimization to obtain overall performance advantages - Promotes compliance with international emission and environmental requirements
WEAKNESSES	- Energy generation dependent on weather conditions and availability of sunlight - Lower efficiency in high-latitude places with less sunlight - Initial installation expenses - Energy storage capacity is limited - Exposure to shading from onboard structures and equipment - Decrease in solar panel efficiency over time - Difficulties in integrating solar power into current ship systems and layouts	- Weather conditions dependence - Space requirements may limit cargo capacity and deck space - Temperatures can reduce efficiency - Noise and vibrations - Applicability is limited to specific ship types - High initial investment - Concerns about birds colliding with turbine blades	- Difficulties in obtaining permits and approvals for retrofit projects - Possible rise in maintenance expenditures - Efficiency benefits may vary based on the vessel type and operating conditions - Requires knowing the present state of propeller - Lower emission reduction than renewable energy sources
OPPORTUNITIES	- Technological advances in solar panel efficiency and energy storage - Integration of various renewable energy sources into hybrid systems - Increased energy security and resilience to fuel price volatility - Potential from excess energy exported to the grid - Developing energy storage technology in ports	- Continued improvement of turbine design and efficiency - Collaboration with maritime sector to install wind propulsion technologies - Continuous innovation in materials and production methods to reduce costs - Opportunities for job generation in the renewable energy sector - Integration of various renewable energy sources into hybrid systems	- Market demand for environmentally friendly shipping options - Improving the availability of data analytics and optimization tools for propeller design - Opportunities for collaboration with shipyards on integrated ship design and optimization
THREATS	- Impacts of climate change and weather dependence - Policy uncertainty and regulatory obstacles - Risk of panel damages - Sensitivity to contamination - Reduced government incentives - Competition with other renewable energy sources - Supply chain vulnerabilities	- Limited global wind patterns - Technological limitations in wind propulsion - Competition with other renewable energy sources	- Resistance from shipowners and operators to adopt new technologies - Rapidly evolving regulatory landscape affecting compliance requirements - Competition with other efficiency optimization solutions

6. Conclusions

Propeller optimization aims to improve the efficiency of existing systems on ships, resulting in lower fuel consumption and emissions. This paper presents a case study on the propeller optimization of Ro-Ro passenger ships. This research examined data from sea trials conducted both before and after propeller optimization to provide insights into ship vibrations and fuel consumption. The propeller optimization, resulting in a transition from Class 2 to Class S in ISO 484-2:2015 standard, led to a 1.41% reduction in fuel consumption, achieving the dual goal of enhancing fuel efficiency and reducing the vessel's environmental impact. Furthermore, the results of this case study align with regulatory and policy frameworks governing maritime operations, underscoring its significance in meeting environmental standards. The demonstrated efficacy of propeller modification in decreasing CO_2 emissions is consistent with the primary goals of international agreements such as the International Maritime Organization's (IMO) greenhouse gas emission regulations for ships.

Propeller optimization is one of several methods that show promise for developing sustainable practices in the maritime industry. Combining solar power application, wind power application, and propeller optimization holds the potential to yield even more significant outcomes. Previous research on the implementation of photovoltaic (PV) systems on Ro-Ro ships and a high-speed vessel revealed that renewable energy sources could reduce CO_2 emissions from 513.53 to 1324.85 t/year and NOX emissions by 9.15 to 23.6 t/year. The carbon footprint can be reduced between 3.2% and 17% by installing suitable wind turbines on ro-ro ships depending on the route.

Future research will explore the effects of various parameters contributing to optimal energy resources management, aiming to reduce the emission of harmful gases and enhance energy efficiency. The primary scientific contribution will involve determining the optimal number of vessels retrofitted with renewable energy sources to enhance energy efficiency. Furthermore, we will identify parameters that affect energy efficiency and emissions of harmful gases in the surrounding area and develop an optimization algorithm that determines the acceptable number of renewable resources, minimizing gas emissions and fostering optimal energy efficiency management.

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7. MODEL AND SUMMARY OF RESULTS

The developed model aims to quantify CO_2 emission savings achieved through the integration of solar panels on ships and propeller optimization. The assessment begins with the estimation of baseline emissions, representing the total emissions produced without any implemented savings measures. Subsequently, the model calculates the emission reductions from the installation of solar panels and incorporates the additional emission savings resulting from the optimization of the vessel's propeller. A block diagram of the methods used is presented in Figure 1.

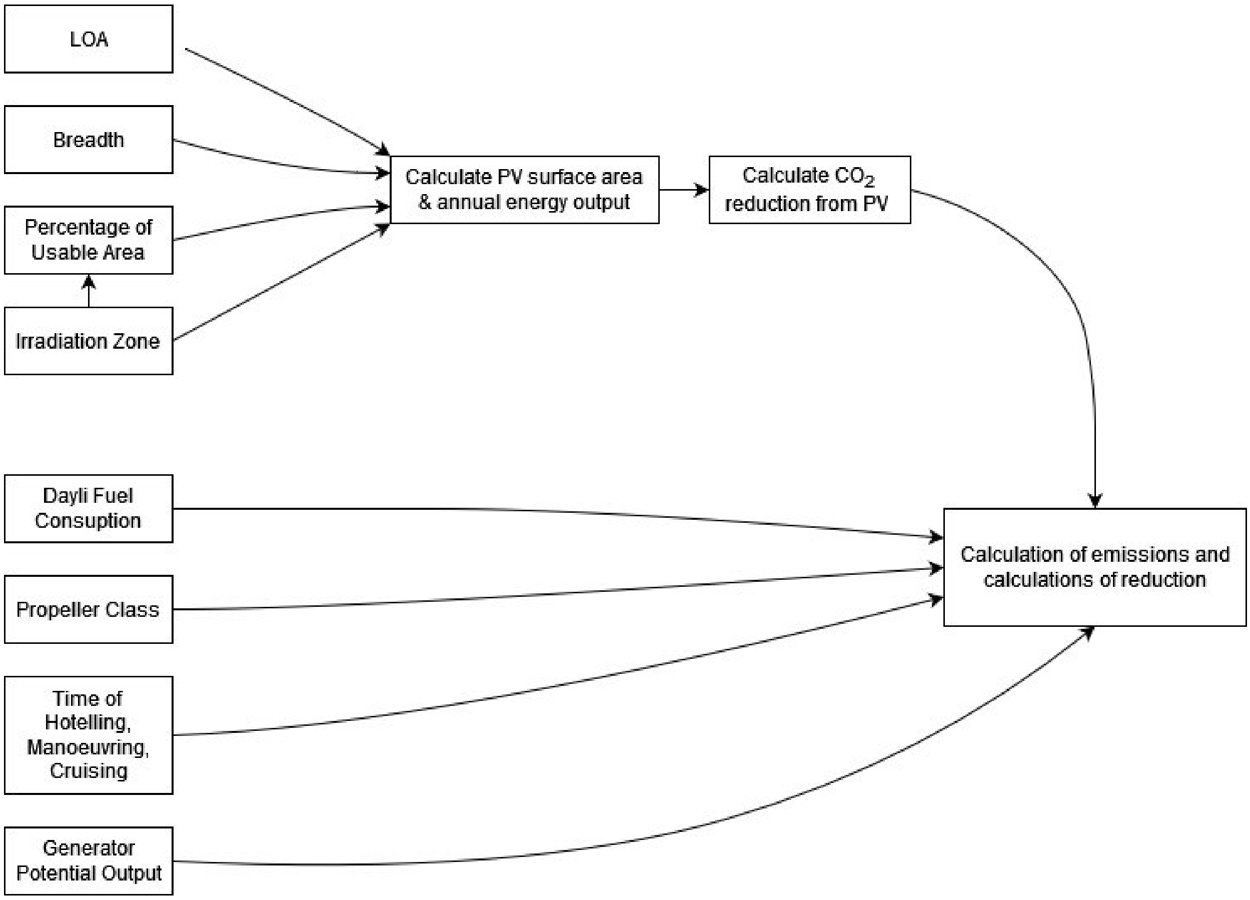

Figure1. The block diagram of the model

For developing the CO_2 Emissions Calculator software, PyCharm 2022.3.3 (Community Edition), which is an integrated development environment (IDE), and Python 3.10.2 were used [43]. Since the objective was to create an application that calculates the reduction of CO_2 emissions, library extensions were used for creating the Graphical User Interface (GUI). The "customtkinter" library extends "tkinter" by providing more customizable widgets, giving it a more aesthetic view. The "tkinter" library itself is the standard toolkit for creating graphical user interfaces in Python, offering a basic widgets and layout management tools. The "webbrowser" library enables web browsing capabilities within a GUI application, allowing users to open URLs in their default web browsers. "matplotlib.pyplot" is a plotting library , while "FigureCanvasTkAgg" bridges "matplotlib" and "tkinter", enabling the embedding of "matplotlib" plots directly within a "tkinter" GUI for interactive data visualization. On Figure 2 is presented CO_2 emission calculator interface.

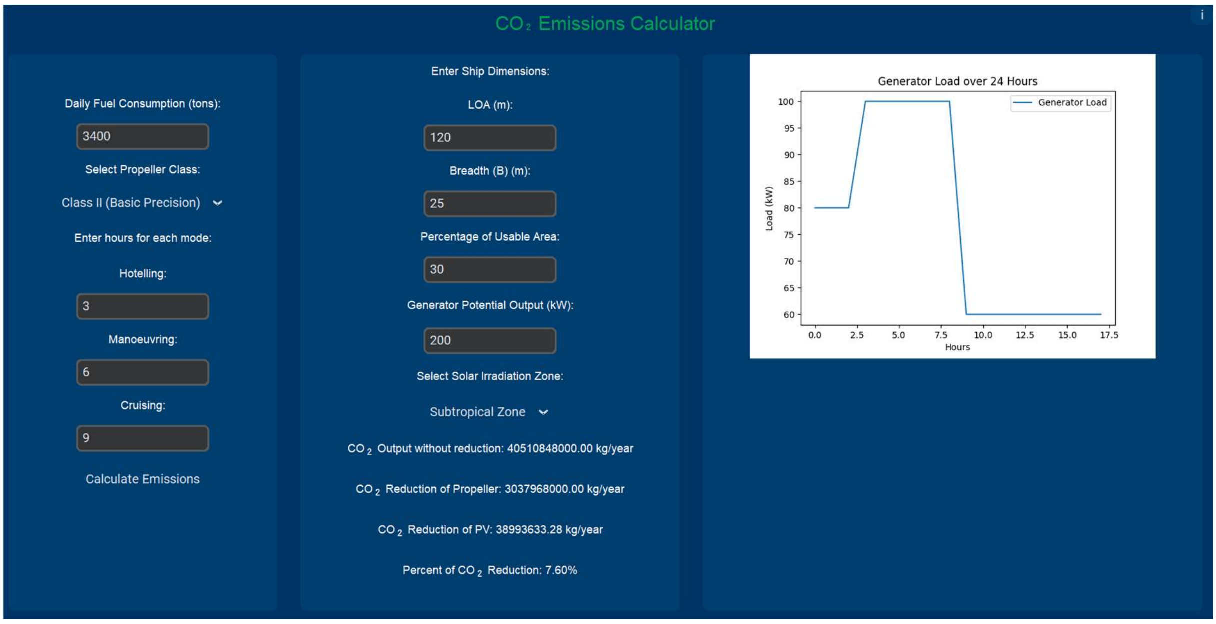

Figure 2. CO_2 emission calculator interface

7.1 Estimated Baseline Emissions

The initial step involves estimating the emissions generated by the vessel under standard operating conditions, without the implementation of any energy-saving technologies. These baseline annual gas emissions (EM_i) from fuel consumption are calculated as follows [4]:

$$EM_i = FC_i \times EF_f \quad (1)$$

where:

FC_i is fuel consumption (l)

EF_f is emission factor (grams of pollutant / gram of fuel)

CO_2 fuel-based emission factor for marine diesel oil (MDO) all ship phases (hoteling, maneuvering and cruising) is 3.206 g CO_2 / g fuel. The weight of 1 liter of diesel can vary slightly depending on its temperature and composition. However, on average, the density of diesel fuel is approximately 840 g / liter.

7.2 Emission Savings from Solar Panels

The model then incorporates the emission reductions achieved through the installation of solar panels. Solar panels contribute to emission savings by reducing the vessel's reliance on conventional fuel sources, thereby decreasing the overall fuel consumption. The model calculates these savings by determining the available deck area for solar panel installation, generator load, amount of energy produced by the solar panels and the corresponding reduction in fuel use and associated emissions.

A suitable deck area is selected together with a part of the deck, which can be projected so that solar panels can be placed on it on suitable supports. To maximize the use of available spaces for solar panel installation on a Ro-Ro type ship, a solid support structure is designed for the open areas on both the forward and aft decks. The deck area is calculated using the following equation [44]:

$$A = L_{OA} \times B \times N \tag{2}$$

where:

A is surface (m_2);

L_{OA} is length over all (m);

B is breadth extreme (m);

N -is coefficient (0.91 for big tankers and bulk carriers, 0.88 for cargo liners, 0.84 for coasters, etc.).

An average solar panel area of 1.44 $m^2$is taken in calculation. By entering ship length over all and breadth it calculates the maximum capacity for solar panel installation. The application allows the user to determine the percentage of the deck area which will be covered with solar panels.

The optimal tilt angle for solar panels depends on the geographic location, the intended energy output, and the specific application. In application are integrated several irradiation zones from which can be chosen the one adequate for ship location as visible in Figure 3.

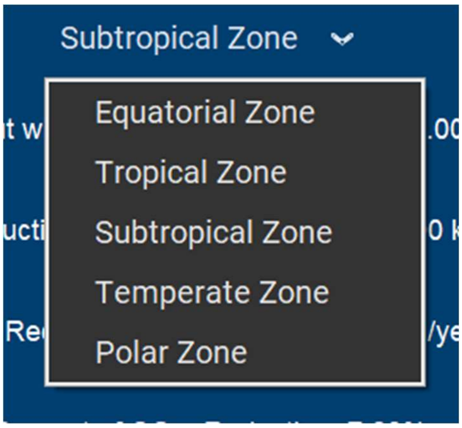

Figure 3. Solar Irradiation Zones

To calculate the total annual energy output in kilowatt-hours (kWh) from a solar panel system, first step is determining the energy output. The formula for the energy output is [45]:

$$E = A \times r \times H \times PR \quad (3)$$

Where:

E is energy (kWh);

H is annual average solar irradiation (kWh/m²);

A is the total area of the solar panels (m^2);

r is solar panels efficiency;

PR is performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75).

In order to determine ship generator daily load it is necessary to determine how much time it spends in each phase (hoteling, maneuvering and cruising). Application allows manually entering hours in each phase, but limiting total hours to 24h. According to the engine operation for the different activities, load of maximum continuous running (MCR) for auxiliary engine operation is 30% for cruising, 50% maneuvering and 40% for hoteling phase. By multiplying generator power, time spent in each phase and load factor is given ship generator daily load. Generator daily load is also presented as graph in application.

In order to calculate CO_2 savings from solar system following formula is used [46]:

$$E_{365} = E \times EF \tag{4}$$

where:

E_{365} is the annual CO_2 emission;

E is the energy output in a year;

EF is the CO_2 emission factor per MWh.

This calculation provides the total CO_2 savings achieved by using solar panels instead of a traditional diesel generator. The emission factors for diesel is 266, 76 kg / MWh.

7.3 Emission Savings from Propeller Optimization

In order to calculate the fuel savings from propeller optimization fuel consumption is multiplied by percentage of saving from propeller optimization. The optimization savings vary depending on the transition from a given class to Class 0, as outlined below and shown in Figure 4:

Fuel Savings Percentages:

From Class III to Class 0: up to 20% (average 10%)

From Class II to Class 0: up to 15% (average 7.5%)

From Class I to Class 0: up to10% (average 5%)

From Class S to Class 0: up to 5% (average 2.5%).

The annual CO_2 savings from the propeller are calculated by multiplying the daily fuel consumption by the fuel savings achieved through optimization. This result is then multiplied by 365 to account for the entire year. Finally, this value is multiplied by the CO_2 emission factor, which represents the amount of CO_2 emitted per liter of fuel burned. The average CO_2 emissions factor of 3.151 tons CO_2 per fuel ton for marine diesel oil (MDO) The fuel savings are converted from liters to metric tons by considering the density of marine diesel oil.

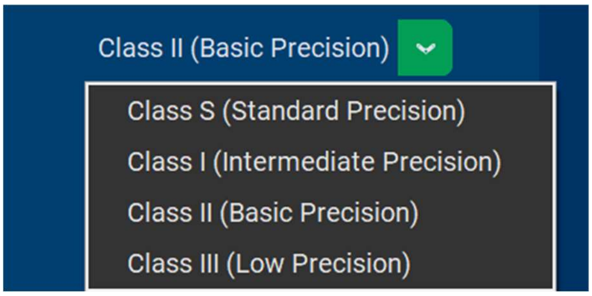

Figure 4. Propeller Class drop down menu

7.4 Results

As a result of all interaction procedures, the application provides a detailed analysis of the contributions from different reduction strategies, offering valuable insights into the overall reduction of CO_2 emissions.

Case 1: The CO_2 output without reduction. This value represents the baseline emissions, which is the amount of CO_2 emitted under normal operating conditions without propeller optimization or reduction measures. It serves as a reference point for evaluating the effectiveness of various CO_2 reduction strategies.

Case 2: The CO_2 reduction achieved through propeller optimization. This is calculated by diminishing the CO_2 savings resulting from the optimization of the propeller from the baseline emissions.

Case 3: The CO_2 reduction resulting from the photovoltaic (PV) system. This value represents the amount of CO_2 emissions reduced due to the use of solar energy.

Case 4: The percentage of CO_2 reduction. This is calculated as the ratio of total CO_2 savings (from propeller optimization and the photovoltaic system) to the baseline emissions, expressed as a percentage. This provides a representation of the reduction in total CO_2 emissions compared to the baseline emissions. Different cases are visible on Figure 5.

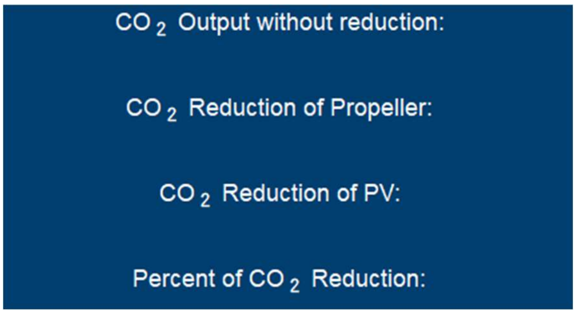

Figure 5. Results of the contributions from different reduction strategies in the overall reduction of CO_2 emissions

8. CONCLUSION

Emissions of harmful gases can be mitigated through the use of alternative fuels, renewable energy sources, fuel cells, and other similar technologies. This paper specifically focuses on the optimization of propellers and the utilization of solar energy. The thesis addresses key factors related to maritime traffic emissions, focusing on the impact of different parameters that contribute to effective energy resource management. The goal is to reduce harmful gas emissions and improve energy efficiency by integrating solar power application on ships and propeller optimization, while also proposing a model based on research results which is applicable for emission estimation in ports.

Maritime traffic significantly impacts local air quality and environmental health due to emissions from ship operations. These emissions include harmful gases such as CO_2, NOx, and SOx, which have a bad effect to both human health and the environment. The methodology involved in this research includes detailed data collection on ship activities through years, estimating emissions using specific factors, and conducting statistical analysis to identify emission patterns over time.

The use of renewable energy technologies on ships, such as solar panels, helps to reduce fuel consumption and emissions. The research revealed that solar arrays can efficiently supplement ship energy needs, particularly during the hotelling phase, resulting in significant reductions in CO_2 and other pollutant emissions what is improving quality of living in port cities with frequent vessel traffic.

Furthermore, optimizing ship propeller has demonstrated promising results in increasing fuel efficiency and lowering emissions. Optimized propeller design reduces the energy required for propulsion, leading to less fuel consumption and lower emissions. This approach contributes to environmental sustainability in maritime operations.

The model proposed in this thesis is not limited to Port of Split, but enables to ports across the world to measure, control, and mitigate ship emissions efficiently. Significant progress can be made toward environmental sustainability in maritime transportation by incorporating solar power application and propeller optimization. By presenting the CO_2 savings in four detailed cases, the application highlights the individual contributions of propeller optimization and PV application on ships and also demonstrates the cumulative effect of these strategies. The proposed model for emission estimation can be adapted globally, making it a significant contribution to the field of maritime environmental management. The research did not consider the structural characteristics, temperature coefficients, or thermal effects, as well as other parameters that need to be thoroughly investigated and anticipated in the vessel design if the shipowner decides to opt for such innovative solutions. The continued focus on research, technological advancement, regulatory support and legislative assistance will be essential for driving the maritime industry toward a more sustainable future.

Implementing shore power facilities and growing renewable energy capacity to support vessel operations are recommended as ways to improve port infrastructure. Governments policies have the potential to impact CO_2 emission reductions in the maritime sector through adaptation of strategies and support mechanisms. When providing state subsidies and concessions for ferry and fast ferry lines of on specific maritime routes, one of the criteria that will be evaluated incudes the usage of renewable energy sources and new technologies. Funding the development of low-emission ships, such as those powered by hydrogen, ammonia, or electric batteries is of high importance. Port authorities could provide financial incentives, such as reduced port fees to vessels with low CO_2 emissions or vessels using alternative fuels. Implementing a carbon fee on maritime fuels will encourage shipping companies in usage of cleaner technologies and alternative fuel. Reductions in taxes, and offering lower interest on the loan for retrofitting existing ships for companies investing in green technologies places emphasis on sustainability. New technologies and hybrid systems, as well as the complexity of infrastructure, require the application of artificial intelligence (AI) technologies in the maritime sector, which can help reduce emissions from ships by optimizing their operation. AI systems use real-time weather and traffic data to calculate the most efficient route and monitor fuel consumption in real-time and scenarios can be verified through digital twins before final development.

By integrating renewable energy sources, optimizing ship design, and implementing regulatory frameworks, the maritime industry can significantly reduce its environmental footprint. This research serves as a step toward achieving these goals and highlights the potential for substantial improvements in both local and global environmental sustainability innovative maritime practices.

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Inspections of ships before purchase and valuation

- Examination of plastic hulls and measurement of capillary moisture (Osmosis)
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- Measuring the thickness of steel and aluminum "OVER COLOR" with an ultrasonic device Olympus 45MG
- Inspections of hulls, machines, equipment and cargo in case of an accident
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Commendation for the success achieved during the studies (4.4)

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