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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.

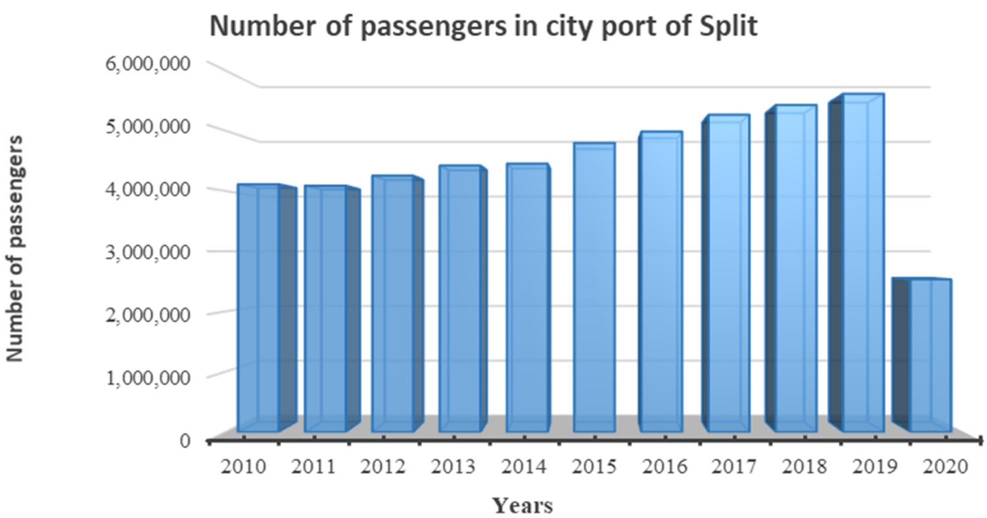

Figure 1. Number of passengers in city port of Split.

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]:

$$S = L_{OA} \times B \times N, \tag{1}$$

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.

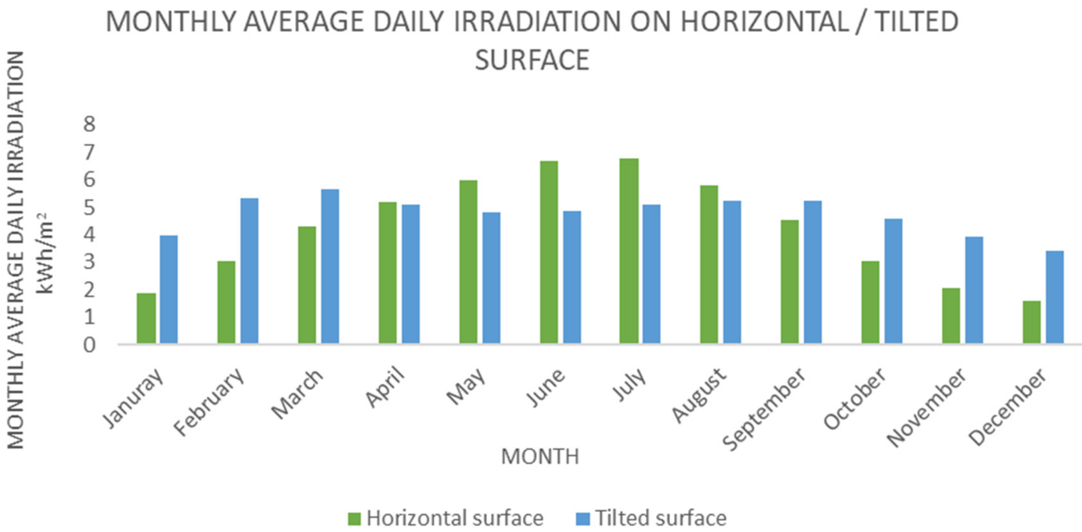

Figure 3. Split monthly average daily irradiation.

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.

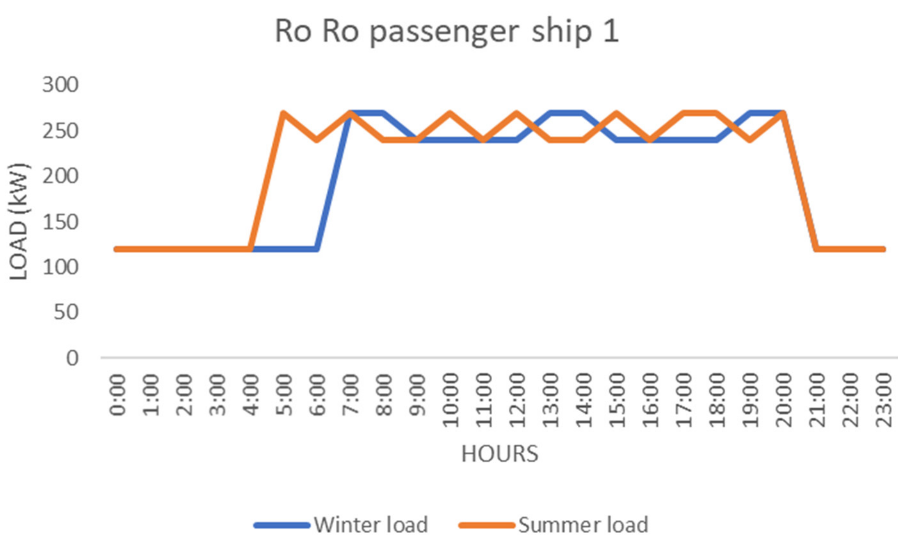

Figure 4. Ro-Ro passenger ship 1 daily load for one winter day and one summer day.

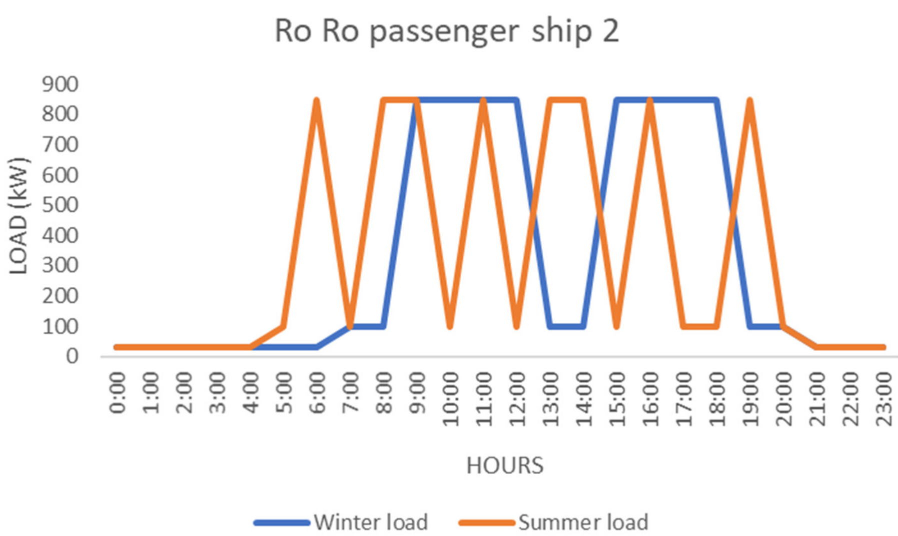

Figure 5. Ro-Ro passenger ship 2 daily load for one winter day and one summer day.

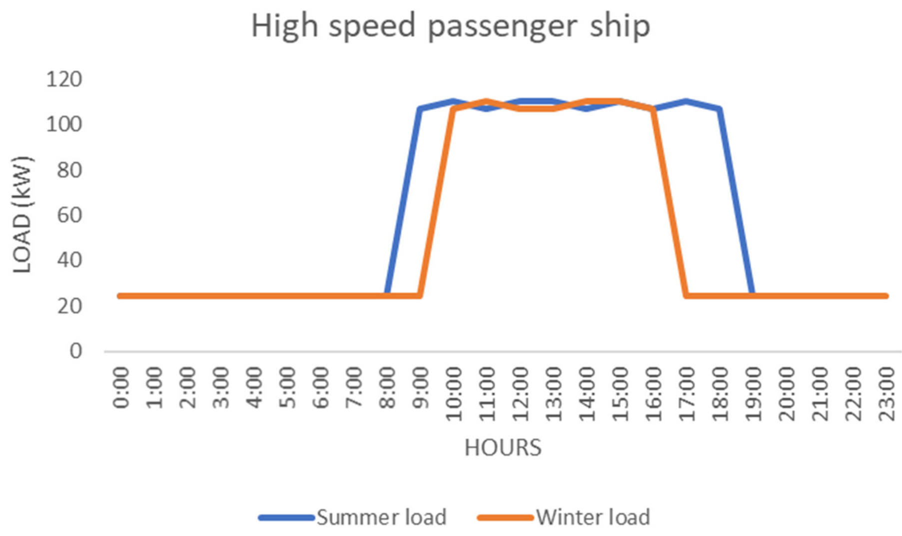

Figure 6. High-speed passenger ship daily load for one winter day and one summer day.

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.

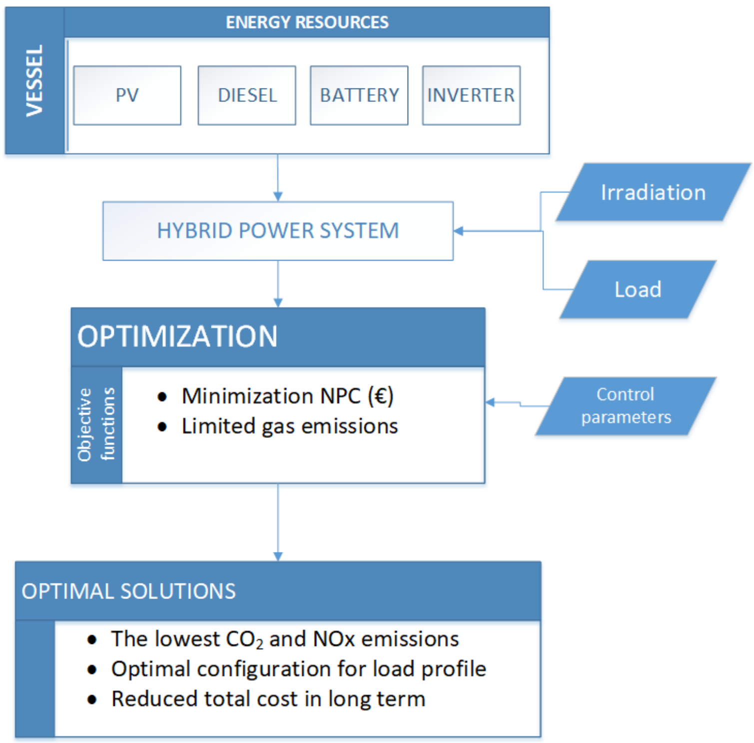

Figure 7. The flow diagram of the optimization components and outcomes.

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:

$$minF = min[TC(x), AE(x)] \tag{2}$$

$$x = \{N_{PV}, a, N_{BAT}, b, N_G, c\} \tag{3}$$

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:

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

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]:

$$AE = \sum_i E_i = \sum_i S_{jklm} \times EF_j \tag{5}$$

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

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:

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

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

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

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.

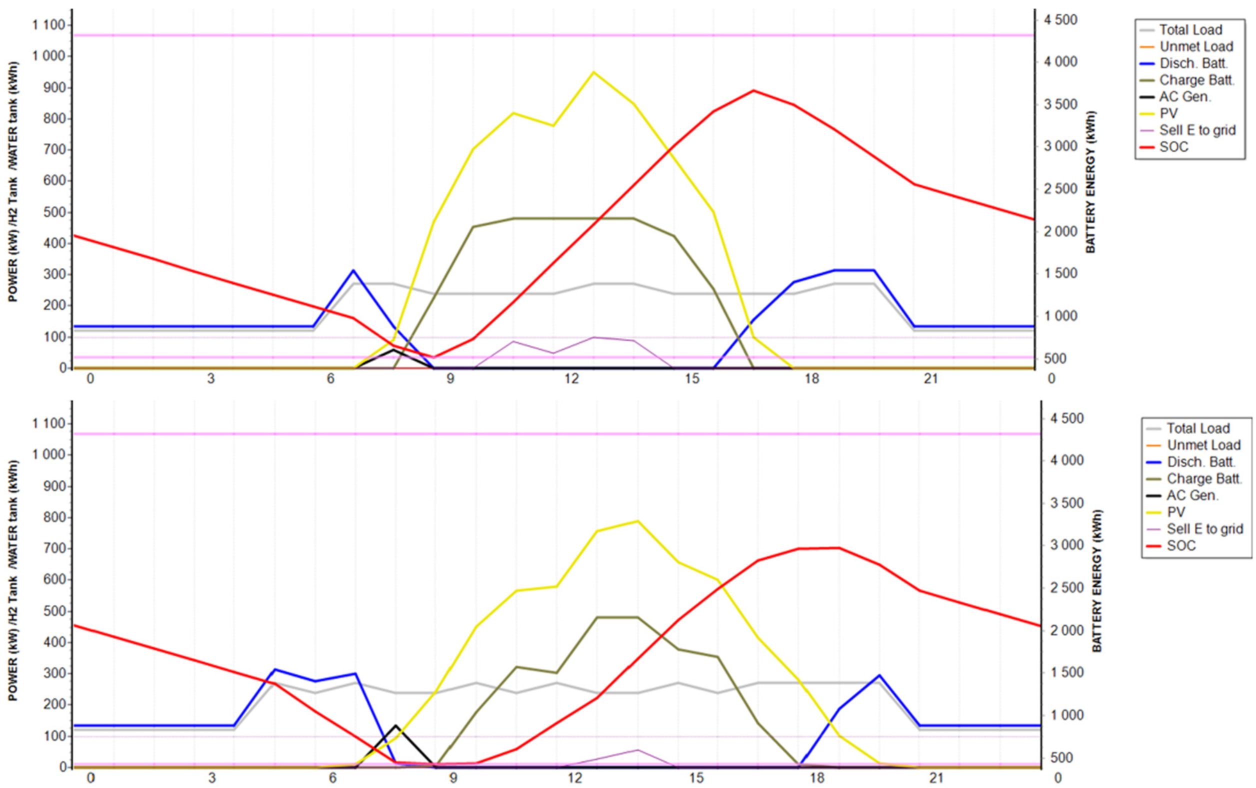

Figure 8. Hourly simulation for 17 January and 8 August 2022.

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.

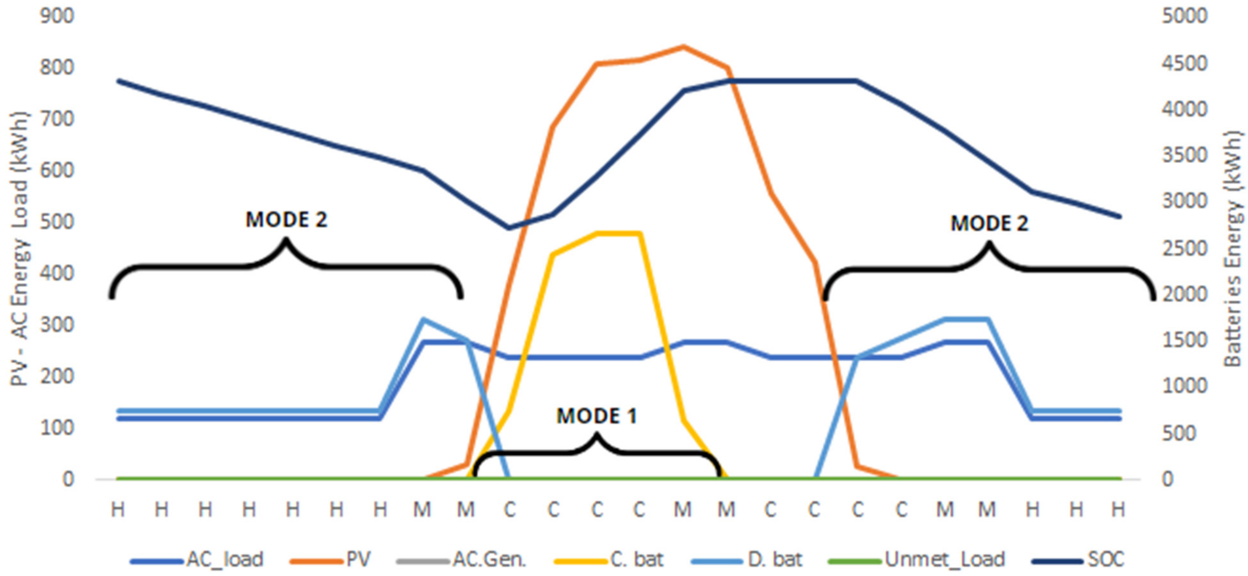

Figure 9. Solar application on Ro-Ro passenger ship 1 in different ship phases for one day.

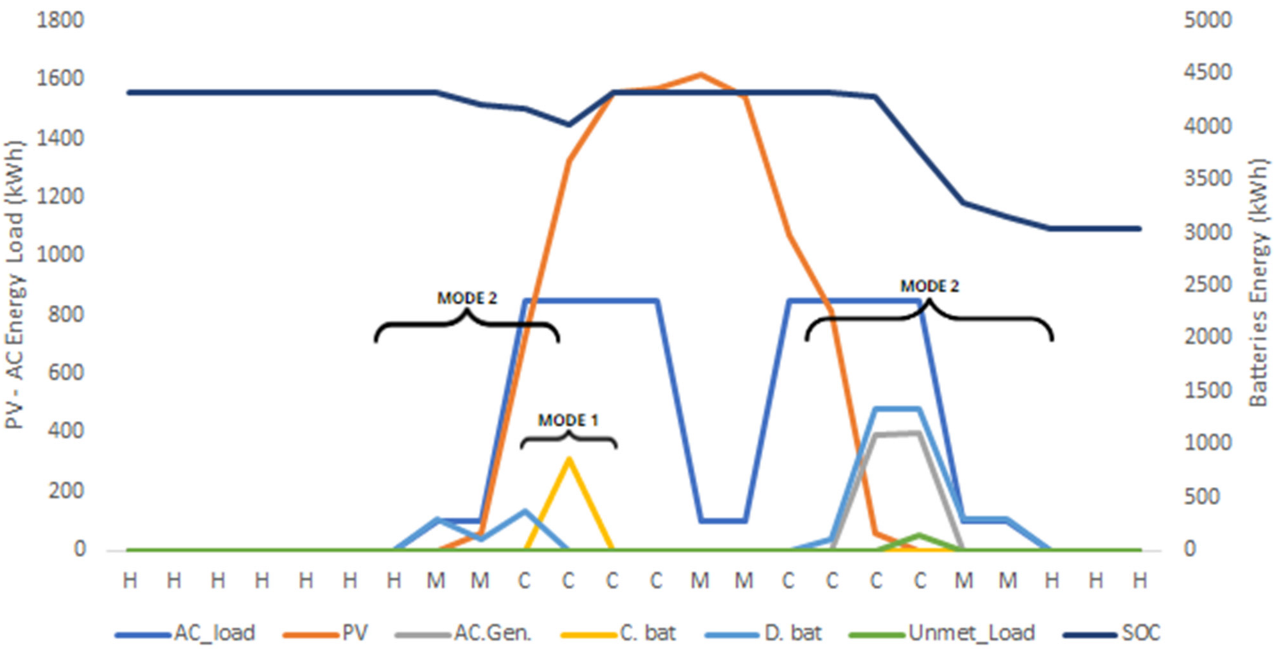

Figure 10. Solar application on Ro-Ro passenger ship 2 in different ship phases for one day.

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.

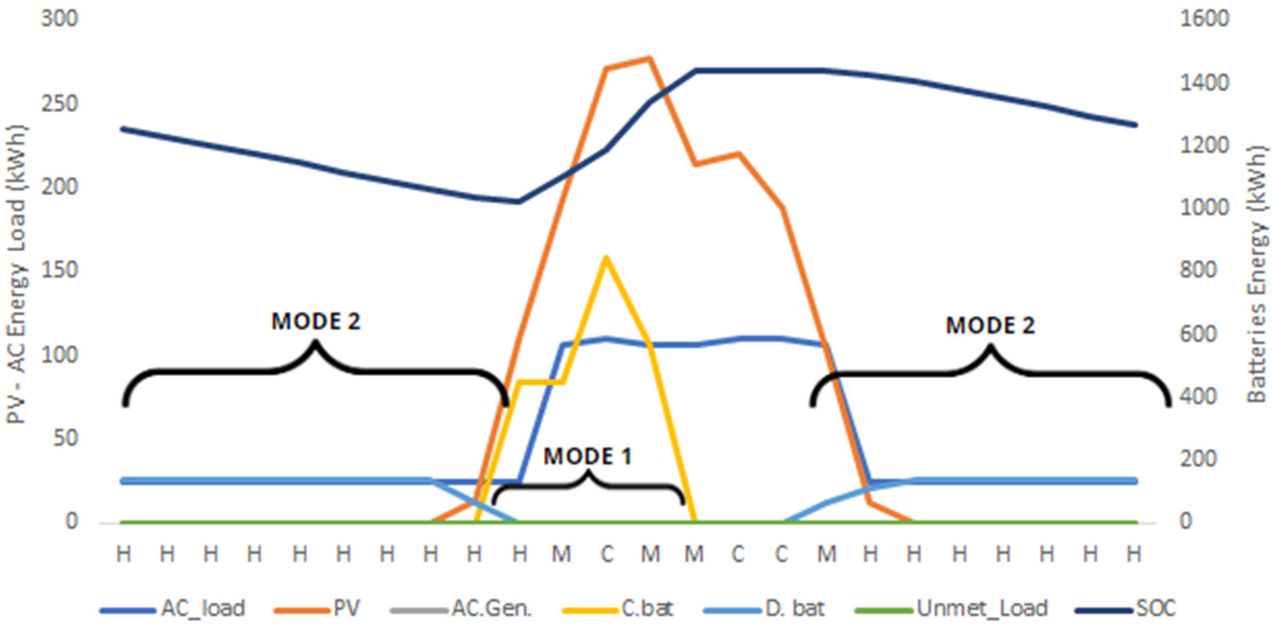

Figure 11. Solar application on high speed passenger ship in different ship phases during one day.

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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