Retrofitting Vessel with Solar and Wind Renewable Energy Sources as an Example of the Croatia Study-Case

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Abstract: The ship’s power system is one of the most important systems on board. It is designed for uninterrupted power supply to all ship consumers under different conditions of exploitation. When designing a ship, various optimizations are conducted to build the ship as economically and environmentally friendly as possible. The paper aims to analyze the possibility of applying renewable energy sources (RES), particularly solar and wind energy, on an existing vessel by conducting technical and economic analysis. Data for the solar hour’s number and wind distribution are gathered from the six locations in the Adriatic Sea over 32 years period. Firstly, it was investigated if data were position dependent or independent. Performing a Pearson correlation coefficient and an ANOVA analysis with F-test, it was concluded that the RES analysis is position-independent ($p > 0.05$, $p = 0.826$). Secondly, the energy system model created in Simulink was used for the analysis of the electrical network fundamental parameters. Finally, the object of the analysis is the total costs of procurement, installation, and maintenance of the system within a period of 25 years. Consequences are savings in the cost of exploitation and reduction of harmful gas emissions. The use of solar energy would result in savings of 111,556 l of diesel fuel, while the savings from wind energy would be 170,274 l of diesel fuel for 25 years.

Keywords: Renewable energy sources; solar energy; wind energy; model; power management system

1. Introduction

World trade has been closely related to maritime transport for centuries. According to the United Nations, over 80% of world trade is carried out by maritime transport [1], which makes sea transport crucial for modern world trade. Maritime transport is a substantial CO$_2$ emitter, representing 3–4% of total EU CO$_2$ emissions [2]. The monitored journeys emitted, in 2019, over 144.6 million tons of CO$_2$ into the atmosphere. These emissions originated from 12,117 ships and represented around 38% of the world’s merchant fleet above 5000 gross tonnages.

International Maritime Organization’s (IMO) short-term, mid-term, and long-term targets for reduction in the carbon intensity of ships are 20%, 30%, and 50% by 2020, 2025, and 2050, respectively [3]. Although ships pollute the environment, compared to other transport models, they generate the lowest emissions per ton of cargo per kilometer, as shown in Figure 1. Maritime transport is the most important segment in the use of ships, but fishing, tourism, and recreational use of smaller ships cannot be neglected.


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Emissions from ships’ exhausts into the atmosphere can harm human health [5], cause acid rain, and contribute to global warming [6]. To ensure that shipping is cleaner and greener, IMO is engaging in a two-pronged approach towards reducing so-called Greenhouse Gasses (GHG) emissions from international shipping. Therefore, firstly, IMO has adopted regulations to address the emission of air pollutants from ships and has adopted mandatory energy-efficiency measures to reduce emissions of GHG from international shipping under Annex VI of IMO’s pollution prevention treaty (MARPOL). Secondly, IMO [7] is engaging in global capacity-building projects to support the implementation of those regulations and encourage innovation and technology transfer.

IMO has announced two new measures in 2021: the technical requirement to reduce carbon intensity, based on a new Energy Efficiency Existing Ship Index (EEXI), and the operational carbon intensity reduction requirements, based on a new operational carbon intensity indicator (CII) [8]. The goal is to reduce carbon dioxide emissions by increasing energy efficiency and using Renewable Energy Sources (RES). According to [9] Energy Efficiency Design Index (EEDI) is defined by the expression:

\[
\text{EEDI} = \frac{\text{Main engine emissions} + \text{Auxiliary engine emissions} + \text{Shaft generators or motors emissions} + \text{Efficiency technologies}}{\text{Transport work}}
\] (1)

The core of this scientific research is in the application of technologies for improving efficiency through the application of energy generated from RES. Therefore, this paper investigates efficiency technologies which are defined by the following expression [9][9]:

\[
\text{Efficiency technologies} = \left(\sum_{i=1}^{n_{\text{eff}}} f_{\text{eff}(i)} \cdot P_{\text{eff}(i)} \cdot C_{\text{FME}} \cdot SFC_{\text{ME}}\right)
\] (2)

where:

- \(f_{\text{eff}(i)}\) - availability factor of individual energy efficiency technology,
- \(P_{\text{eff}(i)}\) - main engine power reduction due to individual technology for mechanical energy efficiency,
- \(C_{\text{FME}}\) - CO₂ emissions main engine composite fuel factor,
- \(SFC_{\text{ME}}\) - specific fuel consumption main engine (composite).

Due to the growing demands for fuel savings and reduction of negative impact on the environment, renewable energy sources are being installed in the ship’s power system. Solar, wind, and fuel cell energy are the most suitable RES on board as a platform [10]. These types of renewables are not available at the same intensity during the day, so the ship’s energy system must adapt to different production and electricity consumption conditions. The basic parameters in choosing the most suitable energy source are the type of vessel, its size, area of navigation, and legal regulations.
Hybrid systems are particularly suitable for certain vessels with inconsistent operational profiles. Furthermore, special-purpose vessels that require a large amount of electricity in a short time are appropriate for hybrid system usage. Employing the most suitable energy source at a certain moment is the main advantage of utilizing these energy systems. Many parameters influence the selection of an adequate energy source: state of charge of batteries, charging costs, and daily energy needs [11]. This type of energy supply is adoptable for ferries, passenger ships, and especially tugboats [12].

Although warships are not subject to environmental regulations [13], it is preferable to make efforts to develop vessels more economically and environmentally friendly while retaining their basic purpose. Several limitations prevent the use of RES on warships, such as increased tonnage, greater radar reflection, and easier visual detection from the air. For example, due to the high concentration of combat systems and devices in a relatively small space, it is practically impossible to place PhotoVoltaic (PV) modules or windmills in open spaces on the ship’s deck. However, there are some Navy logistic ships and public Coast Guard ships suitable for installing RES systems. Moreover, in such a way, navies will emphasize not only their protective and security role in society but the will to present care for the environment and to be engaged in a global struggle for our planet.

While conducting optimization of the ship’s power plant, different approaches can be applied to solve optimization tasks [14]. Optimization can be approached with the aim of reducing harmful gas emissions in the atmosphere, lowering investment and maintenance costs, and fuel consumption reduction. A vessel that consumes less fuel is more environmentally friendly; therefore, these requirements are complementary [15]. Considering the investment costs for installing and maintaining RES systems for smaller vessels, the most common repayment period of the investment is approximately several years through the reduction of fuel consumption. Whether the RES system is suitable for a particular type of ship depends not only on the specifics of the ship’s exploitation but also on the environment in which it is operating [16].

This manuscript is organized as follows: first, Section 2 gives an introduction to the research with the Literature review, then Section 3, Materials and Methods, presents ship as a platform for RES. Sections 4 and 5 give us Results and Discussion for the RES implementation. Finally, Section 6 provides us with the Conclusion.

2. Literature Review

There are numerous new project solutions applying renewable energy sources when it comes to newly built ships. However, the possibility of using RES on existing vessels is relatively poorly researched. In a paper [17], life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian coastal shipping sector are conducted. The authors suggested an all-electric ship propulsion system, both in the case of retrofitting existing ships or acquiring completely new vessels. Article [18] analyzes the techno-economic assessment of RES implementation in short-sea shipping. This research indicated that the most environmentally friendly and most cost-effective solution is the one with only a battery and PV cells implemented onboard. According to research [19], battery and hybrid-powered inland ships have lower emissions and costs. A study [20] investigated solar panel system installation on a short-route ferry operating in the Marmara Sea and revealed that the payback time would be around three years. Payback time depends on various factors, for example in Latin America due to low diesel fuel price payback period can be up to 19 years for the Jamaican case [21]. In recent years, a lot of studies aim to optimize the technical parameters of the ship by lowering fuel consumption. All these strives are welcomed, however, in all cases usage of fossil fuels is inevitable. Therefore, the usage of renewables on ships and ports is essential to make maritime transport sustainable [22].

There are some technical solutions for the application of certain types of energy which generally result in an adjustment of land technologies to the maritime
environment. Special types of vessels have extended exploitation periods; hence, it is necessary to make efforts to adapt them in accordance with the latest legal restrictions and ecological standards. Addressing the research gap and novelty, the contribution of this study is a useful model for retrofitting specific types of vessels with RES in a particular geographical area.

The scientific hypothesis in this paper is:

Renewable energy sources application is possible to implement on existing vessels, and it may be shown to be effective. The possibility of implementation and the efficiency of renewable energy sources on existing vessels are observed. It is shown through the example of the Croatia study case.

In order to refer to the identified hypothesis, this article has research examples of applying solar and wind energy sources on ships. First, six locations on the Croatian side of the Adriatic Sea have been chosen (areas around Rijeka, Mali Lošinj, Zadar, Split, Hvar, and Dubrovnik) to cover the whole Adriatic Sea. Then, for each location, the data of the following variables: the number of Sun’s hours and the wind speed from 1971 to 2000 yearly were obtained. Performing the Analysis of variance (ANOVA) statistics on variables, it will be shown that there is no statistical significance (p>0.05) between the chosen variables and the position from which data were collected, which means our research on RES is valid for all Adriatic Sea. Furthermore, the logistic ship is presented as a platform for installing renewable energy sources. After systematic technical specifications collection, a comprehensive analysis of the equipment has been conducted to select the most appropriate one. The knowledge developed in this article provides a pattern for implementing solar and wind energy on board to be used in other regions around the World.

References to wind and solar energy applications are shown in Table 1. This table compares the application of wind and solar energy on vessels in real conditions. Most often, these vessels are electrically propelled and can be fully electric or hybrid. According to [23], only 31% of them are fully electric vessels, while 69% are hybrid-powered vessels. Electric vessels are usually smaller in size and can sail shorter distances due to limitations in an electrical storage system. Hybrid-powered ships are more suitable for sailing on longer voyages. Experimental tests are performed on larger vessels with installed PV modules, and the produced electricity is mainly used for the needs of the ship’s power system. Therefore, fuel-saving analysis cannot be conducted.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Ref.</th>
<th>Methodology</th>
<th>Results</th>
<th>Fuel Sav.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind-Kites</td>
<td>[24]</td>
<td>Performance test of Skysails kite is conducted on a general Cargo ship</td>
<td>Up to 2 MW of power can be generated under favorable wind conditions</td>
<td>10–15%</td>
</tr>
<tr>
<td>Wind-Kites</td>
<td>[25]</td>
<td>Analytical model for towing kite Performance evaluation</td>
<td>Tanker with 320 m² towing kite, the model showed 10% of fuel savings on a 10 m/s wind speed and up to 50% savings at a 15.6 m/s wind speed</td>
<td>10–50%</td>
</tr>
<tr>
<td>Wind-Rotor sails</td>
<td>[26]</td>
<td>Experimental tests on the Cargo ship “Enercon E-skip”</td>
<td>On the voyage between Germany and Portugal, fuel consumption was decreased by 23%</td>
<td>23%</td>
</tr>
<tr>
<td>Wind-Rotor sails</td>
<td>[27]</td>
<td>Sea trials on Ro-Ro Carrier “Estraden” retrofitted with rotor sails</td>
<td>Sea trials showed 2.6% fuel savings with only one rotor, after installing the second rotor trials showed 6.1% fuel savings</td>
<td>2.6–6.1%</td>
</tr>
<tr>
<td>Wind-Rotor sails</td>
<td>[28]</td>
<td>Experimental tests on the bulk carrier m/v Afros</td>
<td>Estimated savings evaluated by a third party organization were 12.5</td>
<td>12.5%</td>
</tr>
<tr>
<td>Wind-Rotor sails</td>
<td>[28]</td>
<td>Experimental tests on the bulk carrier m/v Axios</td>
<td>The annual savings are projected to be 12%</td>
<td>12%</td>
</tr>
<tr>
<td>Wind-Rotor sails</td>
<td>[29]</td>
<td>Model evaluation for Flettner rotor on a very large ore carrier</td>
<td>Estimated that this technology would be able to achieve an efficiency of up to 8%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Table 1. Overview of wind and solar energy applications.
The history of shipping records several phases in which significant progress has been made in increasing the efficiency of the ship and thus reducing the harmful effects on the environment [37]. The mentioned phases are related to economic crises due to which the fares have fallen, so ship-owners have been forced to find solutions to reduce the cost of operating the ship, primarily the amount of fuel consumed.

The future change rates in this field will mostly depend on the legal restrictions imposed by individual countries and on the interest of ship-owners in reducing the cost of the ship’s exploitation. In order to achieve these changes, it is necessary to implement advanced technical solutions. As shipping is a relatively small segment of total electricity use worldwide, the goal to strive is to adapt existing technologies to the specific shipping environment.

### 3. Materials and Methods

In this paragraph, the ship is presented with its features as a platform for the installation of the RES system. The ship’s power distribution scheme and a proposed solution for the use of renewable sources are introduced. A proposal for the technical implementation of the system for the application of solar and wind energy was presented, considering the specifications of all individual elements of the system. A simulation model representing the observed system was created.

#### 3.1. Proposed RES Method

A schematic power distribution diagram for the group of 230 V consumers supplied by diesel generators or optionally by solar or wind energy (colored in green) is shown in Figure 2. Synchronous generators driven by two diesel engines supply the ship’s main bus. Consumers of 230 V voltage level are supplied by the rotary converter.

![Figure 2. Schematic diagram of power distribution to implement.](image-url)
3.2. Observed Vessel

As an example of the RES application, this paper shows the logistic cargo ship PT-71. She was launched in 1956 in the Trogir shipyard under the name Meduza and is part of a series of logistic cargo ships. She is used to delivering water to islands and isolated radar stations. Characteristics of the ship: length 43.7 m, width 8.2 m, and draft 3.5 m. She is propelled by a diesel engine B&W with a power of 684 kW. The maximum speed she can achieve is 10 knots [38]. Two diesel generators supply the main switchboard. The power of each diesel generator is 32 kW, and its voltage is 115 V. Two groups of batteries (each 2 × 180 Ah) supply the auxiliary switchboard of 24 V DC. In order to get an impression of the size of the ship’s power plant, the electricity balance is presented in Table 2.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>ME pre-lubrication pump electric motor</td>
<td>0.65 kW</td>
<td>9.</td>
<td>Electric winch motor</td>
<td>4.04 kW</td>
</tr>
<tr>
<td>2.</td>
<td>General service electric pump motor</td>
<td>10 kW</td>
<td>10.</td>
<td>Rotary converter for radio devices</td>
<td>0.9 kW</td>
</tr>
<tr>
<td>3.</td>
<td>Fuel transfer pump motor</td>
<td>3.65 kW</td>
<td>11.</td>
<td>Static converter</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>4.</td>
<td>Bilge pump electric motor</td>
<td>1.84 kW</td>
<td>12.</td>
<td>Three-phase transformer</td>
<td>25 kW</td>
</tr>
<tr>
<td>5.</td>
<td>Air compressor electric motor</td>
<td>11.2 kW</td>
<td>13.</td>
<td>Single-phase transformer</td>
<td>3 kW</td>
</tr>
<tr>
<td>6.</td>
<td>Freshwater pump electric motor</td>
<td>0.73 kW</td>
<td>14.</td>
<td>Silicon rectifier</td>
<td>1 kW</td>
</tr>
<tr>
<td>7.</td>
<td>Engine room fan motor</td>
<td>0.55 kW</td>
<td>15.</td>
<td>Electric stove</td>
<td>14.5 kW</td>
</tr>
</tbody>
</table>

In total 99.56 kW

Table 2. Electricity balance [38].

Air conditioners, refrigerators, washing machines, televisions, navigation, and radio devices are powered via a 115/230 V, 50 Hz, 10 kW rotary converter. The rotary converter is designed so that the electric motor drives the generator using a pulley. The electric motor and generator have an efficiency of 90% each. Generators used for the production of electricity have an efficiency of 90%. They are driven by a Perkins 4.4GM diesel engine [39] that consumes 0.258 l of fuel per kW/h. The following formula gives overall system efficiency:

\[ \eta_T = \eta_g \cdot \eta_{RCM} \cdot \eta_{RCC} = 0.9 \cdot 0.9 \cdot 0.9 = 0.729 = 72.9\% \]  

where \( \eta_T \)-total efficiency, \( \eta_g \)-generator efficiency, \( \eta_{RCM} \)-rotary converter motor efficiency, \( \eta_{RCC} \)-rotary converter generator efficiency. Therefore, to get 1 kW/h of electricity for a group of consumers with a voltage level of 230 V, it is necessary to consume 0.354 l of fuel. Considering marine diesel “blue” fuel price of 1.23 €/l (May 31, 2022). INA Croatian oil company [40]), 1 kW/h cost € 0.435 only for fuel, excluding the costs of lubricating oil, preventive and corrective maintenance, and amortization.

Figure 3. shows the ship as a platform for installing renewable energy sources. Accommodation of PV modules is possible on the cover of freshwater tanks. The basis of the wind turbine column could be situated on the ship’s bow.

![Schematic illustration of the location of the PV modules and a wind turbine](image-url)
3.3. Solar Energy Application

While designing the system, the first limitation is the available space appropriate for accommodating PV modules on the ship’s deck. On board, there is the possibility of placing PV modules on the cover of the freshwater tanks. The dimensions of the stern tank cover are 560 cm × 635 cm, while the bow tank cover is 560 cm × 575 cm, with a total surface of 64.5 m². Due to the specific operational conditions on board, PV modules should be resistant to severe weather conditions and sea salt. This paper discusses the cost-effectiveness of installing PV modules manufactured by Nature power, model Rigid mono-crystalline with nominal power of 200 W [41]. The dimension of each panel is 147 × 66 × 3.5 cm, the weight is 11.2 kg, and the maximum output current is 9.85 A, with a maximum output voltage of 20.3 V. Considering the dimensions of the tank cover, it is possible to install a total of 56 modules with a total installed power of 11,200 W and a maximum output current of 551.6 A at a voltage of 20.3 V. When determining a suitable place for panel installation it is necessary to place them as high as possible on the ship, so the parts of the ship’s structure and superstructure do not create shade and thus reduce efficiency.

Rechargeable batteries are the most expensive system element with a limited lifespan. In order to reduce the use of rechargeable batteries as much as possible, the PV modules are connected to a group of consumers with a voltage level of 220 V and a frequency of 50 Hz via a hybrid “all in one” converter. Batteries serve as an accumulator of excess energy produced, which is consumed when PV modules stop generating enough energy to cover the needs of consumers. The minimum electricity consumption required to meet the basic needs of the ship does not fall below 4.3 kW. Therefore, the system should be able to store excess electricity with a maximum power of 6900 W.

Due to the positive references from several different independent sources [42–44], Trojan was selected for batteries with a nominal voltage of 12 V and a capacity of 225 Ah. When calculating the characteristics of the battery station, the initial limit is the maximum charging current of 13% of the rated capacity of the batteries. Since the system should be able to store 6900 W of electricity at a voltage of 48 V, the maximum charging current of rechargeable batteries should not exceed 144 A. Accordingly, batteries with a total capacity of 1125 Ah were selected. The voltage of 48 V was achieved by a series connection of four batteries, and the capacity was achieved by a parallel connection of five groups of batteries. Therefore, 20 batteries are needed to form a battery station. In the near future, a significant decline in the prices of battery systems is predicted, which will result in a cost reduction of the observed RES system [45].

Table 3 shows the costs of all elements of the solar system. The costs of procurement, installation and maintenance of the entire renewable energy system were taken into account. Individual elements of the RES system were selected without favoring a particular manufacturer. System maintenance costs are taken from the technical documentation for each element of the RES system.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Price Per Unit</th>
<th>Total Procurement Costs</th>
<th>Maintenance Costs (Period of 25 Years)</th>
<th>Total Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>PV panel Nature power Rigid 200W [41]</td>
<td>440</td>
<td>24,640</td>
<td>280</td>
<td>24,920</td>
</tr>
<tr>
<td>2.</td>
<td>Battery Trojan Spre 12,225 Ah (three sets) [46]</td>
<td>517</td>
<td>31,020</td>
<td>270</td>
<td>31,290</td>
</tr>
<tr>
<td>4.</td>
<td>Installations</td>
<td>2000</td>
<td>2000</td>
<td>400</td>
<td>2400</td>
</tr>
<tr>
<td></td>
<td>In total</td>
<td></td>
<td></td>
<td></td>
<td>63,669</td>
</tr>
</tbody>
</table>
3.4. Wind Energy Application

Throughout the history of shipping, wind energy has been used intensively until the mass usage of internal combustion engines. Nowadays, the wind is used to achieve thrust by sails or produce electricity by wind turbines. According to [48] wind assisted ship propulsion has excellent potential to make ships more energy-efficient (rotors: 0.4–50%; kites: 1–50%; rigid sails: 5–60%; soft sails: 4.2–35%; wind turbines: 1–4%). The choice of the most favorable solution depends on several parameters: the type of ship, the route of navigation, the type of operation, and legal restrictions.

The application of the Flettner rotor technology was also taken into consideration. However, as the introduced ship as a platform for the installation of RES is small in size, the installation of such RES would significantly affect the stability of the ship. Namely, the smallest rotors available from prominent manufacturers have large diameters, Anemio 21 m [49], Norsepower 18 m [50], and Eco Flettner 18 m [51].

Given that this is a specific ship that spends most of its time in the base port, a logical choice would be a wind turbine that delivers electricity even when the ship is resting in the port.

Unlike solar modules, few ready-made wind turbine solutions are suitable for installation on a ship. There are concepts of wind turbines that can descend to the deck due to bad weather conditions. The wind turbine size and features should be tailored to the ship as a platform. The impact on the stability, safety of navigation, and maritime properties of the ship should be taken into account. As the center of gravity of the wind turbine is close to the center of the rotor, the impact on the ship’s stability is quite negative, especially in strong gusts of crosswinds. In addition to the above, the rotating turbine reduces the possibility of spotting objects in front of the ship, which has a negative impact on general safety. However, the above is not the subject of this paper.

It is well-known, a wind turbine is a rotating machine that converts wind’s kinetic energy into electricity. First, wind energy is converted into mechanical energy, which is then converted by the electric generator into electrical energy. According to the German mathematician A. Betz [52], a kinetic energy approach shows that the maximum power coefficient CT cannot exceed a maximum of 59.3%.

In order to make the comparison of the application of solar energy and wind energy as similar as possible, a 10 kW wind turbine manufactured by Waltery Wind Turbine was selected [53]. The basic features of wind turbines are:

- rated power: 10 kW,
- maximum power: 12 kW,
- rated voltage: 240/380 V,
- weight: 368 kg,
- propeller diameter 6.55 m,
- number of wings: 3,
- height of column: 9 m,
- lifespan: 20 years.

No data are available on the application of this wind turbine on board, so it is difficult to reliably determine the acceptability of the installation of this device on board. Due to the unfavorable influence of sea conditions, it can be predicted that the lifespan would be shorter than the application on land and approximately 13 years. This means one aggregate replacement with an estimated service life of 25 years. In relation to the solar system, installing wind turbines is more demanding and expensive and requires the approval of the official registry. It would be anticipated that the construction of the wind turbine tower foundation and cable anchors for the fastening tower would amount to approximately 6700 €. Given the ship’s purpose and the location of the existing equipment, the only suitable place to install the wind turbine is the elevated deck of the ship’s bow, as shown in Figure 3. Table 4 shows the costs of all system elements. As for
the solar system, the costs of procurement, installation, and maintenance of the entire renewable energy system were taken into account.

**Table 4. Costs of all wind system elements are shown in €.**

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Price per unit</th>
<th>Total procurement costs</th>
<th>Maintenance costs (period of 25 years)</th>
<th>Total costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>L-10kW Generator&amp; Blade</td>
<td>3867</td>
<td>7734</td>
<td>1300</td>
<td>9034</td>
</tr>
<tr>
<td>2.</td>
<td>Controller &amp; load-dump</td>
<td>657</td>
<td>1314</td>
<td>300</td>
<td>1614</td>
</tr>
<tr>
<td>3.</td>
<td>Full Sine-wave Converter</td>
<td>1256</td>
<td>2512</td>
<td>600</td>
<td>3112</td>
</tr>
<tr>
<td>4.</td>
<td>Guy Wire Tower</td>
<td>749</td>
<td>1498</td>
<td>300</td>
<td>1798</td>
</tr>
<tr>
<td>5.</td>
<td>Production of foundations and cable trays</td>
<td>6700</td>
<td>6700</td>
<td>250</td>
<td>6950</td>
</tr>
<tr>
<td>6.</td>
<td>Battery Spre 12225Ah (three sets)</td>
<td>518</td>
<td>31,020</td>
<td>270</td>
<td>31,290</td>
</tr>
<tr>
<td>7.</td>
<td>Installations</td>
<td>1300</td>
<td>1300</td>
<td>400</td>
<td>1700</td>
</tr>
<tr>
<td></td>
<td>In total</td>
<td></td>
<td>52,078</td>
<td>3420</td>
<td>55,498</td>
</tr>
</tbody>
</table>

3.5. **Schematic Diagram of the Proposed Power System**

Figure 4a shows the schematic diagram of the existing ship’s power system and the implementation of RES, namely, solar energy in Figure 4b, and wind energy in Figure 4c. Diesel fuel is used in the ship’s existing power system to power an internal combustion engine that drives a synchronous generator. The automatic voltage regulator (AVR) regulates the network voltage while the speed governor regulates the fuel supply to maintain the engine speed and therefore obtain network frequency. The generator supplies the power network main bus through which the rotary converter adjusts the voltage and frequency for consumers with a voltage level of 220 V 50 Hz. In the case of RES, electricity is supplied directly to consumers, as shown. Figure 4b shows the source of solar energy. Solar energy is converted into electricity by the PV module. Electricity is supplied to the controller, which maintains the set parameters of the network by managing the flow of energy in accordance with the needs of the system at the given moment. It can be seen as an integrated control system that selects the most appropriate source at a given time [54]. In the event that the electricity generated from the PV modules is less than the consumer’s needs, the controller takes additional energy from the energy storage system (ESS). Conversely, in the case of excess electricity produced, it is stored in the ESS. Figure 4c shows a renewable source of electricity powered by wind energy. Analogous to the description of Figure 4b, all elements of the system function in the same way, while the only difference is in the primary energy source.
3.6. Experimental Setup

The ship’s power system is complex because the elements of electricity production, distribution, and consumption are all in one place. The system’s complexity is especially pronounced when it comes to applying high-voltage technologies and renewable energy sources. In order to choose the most suitable system configuration, it is necessary to create a model for a specific type of vessel. Applying various optimization solutions and models leads to the optimal selection of system elements. Different operating conditions in which the ship’s energy system may function should be taken into account when designing a model. Simulating models are commonly used to check the operation of existing systems and evaluate new design solutions and optimization [55].

As both proposed solutions are conceptual, there is no reference vessel on which it is possible to conduct tests in real conditions. Therefore, a simulation model has been developed based on which appropriate conclusions can be drawn. An example of the application of the RES system is simulated in the Simulink programming language and Matlab software package, as shown in Figure 5. The simulation does not show a hybrid all-in-one converter, but all system elements (diesel generator, batteries, PV modules, permanent load, and variable cargo) are modeled as separate systems that have interoperability functions. For simplicity of simulation, the rotary converter is not shown as an electric motor and generator but as a transformer having a transforming ratio corresponding to the rotary converter. Part of the program blocks of the model is taken from the MATLAB and adapted to the observed system’s values. The simulation was carried out on a Lenovo Ideapad 330 notebook (Intel Core i3, 7th generation processor, 6 GB RAM, NVidia GeForce graphics).
Figure 5. A simulation model created in the Simulink with the blocks’ input/output connections.

4. Results

4.1. Solar Energy Potential

The Croatia case study has been chosen to show the RES application. For solar and wind applications, variables, the number of sun hours, and the wind speed data from 1971 to 2000 have been taken. Figure 6 shows six locations on the Croatian side, namely, areas around Rijeka, Mali Lošinj, Zadar, Split, Hvar, and Dubrovnik on the Adriatic Sea have been chosen that cover the whole Adriatic Sea. From [56], the variable number of sun hours is defined as the total hours of sunshine a month has typically.

Figure 6. Six investigated locations on the Croatian side of the Adriatic Sea [57].
From Figure 6, it can be seen that numbers from one to six are denoted areas, number one denotes Rijeka’s area and number two denotes Mali Lošinj’s area. Moreover, with the number three, Zadar’s area has been denoted, and with numbers four and five, Split’s and Hvar’s areas were denoted, respectively. Further, the Dubrovnik area has been assigned the number six. Finally, the figure shows that the whole Adriatic Sea from the Croatia side has been covered.

Figure 7 shows that the highest number of Sun’s hours is in July. For example, for the island Hvar, the minimum number of Sun’s hours is in December, and the maximum number of Sun’s hours falls in July. Annually, the island of Hvar has 2733 sun hours with a standard deviation of 85 sun hours (2733 ± 85 sun hours). Contrary, the area of Rijeka has the minimum number of sun hours in December and the maximum sun hours in July. Annually, the Rijeka area has, on average, 2205 sun hours with a standard deviation of 68 sun hours (2205 ± 68 sun hours). If areas of Hvar and Rijeka were compared, it could be seen that, annually, the island of Hvar has 528 sun hours more than areas around Rijeka. Table 5 shows the basic statistical measures for six locations for a variable number of Sun’s hours.

![Graphical presentation of sun hours](image)

**Figure 7.** Graphical presentations of a variable number of sun hours for six locations at the Adriatic Sea.

**Table 5.** Annual statistical measures of the number of sun hours for six locations.

<table>
<thead>
<tr>
<th>Month</th>
<th>Annual</th>
<th>MIN</th>
<th>MAX</th>
<th>AVERAGE</th>
<th>MEDIAN</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sun hours</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rijeka</td>
<td>2205</td>
<td>99</td>
<td>298</td>
<td>184</td>
<td>166</td>
<td>68</td>
</tr>
<tr>
<td>Mali Lošinj</td>
<td>2574</td>
<td>99</td>
<td>357</td>
<td>215</td>
<td>200</td>
<td>30</td>
</tr>
<tr>
<td>Zadar</td>
<td>2567</td>
<td>109</td>
<td>350</td>
<td>214</td>
<td>197</td>
<td>84</td>
</tr>
<tr>
<td>Split</td>
<td>2630</td>
<td>130</td>
<td>347</td>
<td>219</td>
<td>201</td>
<td>78</td>
</tr>
<tr>
<td>Hvar</td>
<td>2733</td>
<td>124</td>
<td>366</td>
<td>228</td>
<td>210</td>
<td>85</td>
</tr>
<tr>
<td>Dubrovnik</td>
<td>2670</td>
<td>124</td>
<td>347</td>
<td>223</td>
<td>198</td>
<td>85</td>
</tr>
<tr>
<td>MIN</td>
<td>2205</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>2733</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVG</td>
<td>2563</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STD</td>
<td>186</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.2. Wind Energy Potential

In order to carry out the analysis of the wind energy potential at the six defined positions, it is necessary to know the characteristics and distribution of the wind. Croatian Wind atlas shows an average wind speed (m/s) and mean wind power density (W/m²) at 10 m above ground [58]. Wind speed and wind power density atmospheric numerical model shows an average value in a grid cell of 2 km × 2 km. Site-specific wind speed or wind power density values can be more or less than the average grid cell value.
Since the relief at the six coastal locations is extremely complex, the reading of the atlas results can vary greatly, which can affect the result. Therefore, this method is scientifically unreliable and as such will not be used.

Consequently, for the comparison of the wind energy potential, it is suggested to use the basic wind speed map with the measured values at the given locations \([59,60]\). Basic wind speed is defined as the maximum 10-min wind speed at 10 m above flat ground of roughness category II that can be expected to be exceeded once in 50 years. Based on the basic wind speed map, Table 6 was created for the observed coastal towns.

Table 6. Measured basic wind speed for six locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Basic wind speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rijeka</td>
<td>25.8</td>
</tr>
<tr>
<td>Mali Lošinj</td>
<td>25.6</td>
</tr>
<tr>
<td>Zadar</td>
<td>22.9</td>
</tr>
<tr>
<td>Split</td>
<td>25.4</td>
</tr>
<tr>
<td>Hvar</td>
<td>25.7</td>
</tr>
<tr>
<td>Dubrovnik</td>
<td>25.2</td>
</tr>
</tbody>
</table>

5. Discussion

This section shows the analysis of the influence of basing the ship in different ports of the Adriatic Sea. The energy potential of cities located along the coast of the Adriatic Sea was taken into account. It was found that the port of basing does not significantly affect the amount of energy generated. The response of the ship’s electric network fundamental parameters for different exploitation conditions is performed. Furthermore, a systematic comparison between solar and wind energy application is conducted.

5.1. Croatia Case-Study Area

The following subsection will present an analysis of solar and wind sources. The case study is the Adriatic Sea. Six (6) places (Rijeka, Mali Lošinj, Zadar, Split, Hvar, Vis, and Dubrovnik) have been chosen from the North to the South. The main idea behind this is to cover the whole Adriatic Sea. First, we will analyze solar energy potential, followed by wind energy potential. Then we will analyze solar and wind data together to check out for correlations and statistical measures. For correlation, a Pearson correlation \([61]\) will be taken, and an ANOVA statistical test \([62]\) will be performed to check the significance of obtained results. Finally, appropriate conclusions will be drawn.

From Table 5, it can be observed that Croatia annually has, on average, 2563 sun hours with a standard deviation of 186 sun hours \((2562 \pm 186\) sun hours). Additionally, the minimum number of sun hours in the observed period for Croatia is 2205, and the maximum is 2733.

The first question that needs to be addressed before the proposed system is analyzed is: Will the number of sun hours in a particular region impact the proposed system’s performance? Two statistical metrics have been performed to find the answer: a correlation coefficient and an analysis of variance (ANOVA) test. The relationship between the data from six locations will be determined with the correlation coefficients. Further, an ANOVA test will determine the significance level \((p)\) between the data. If data comes from the same source, a significance level will be greater than 0.05 \((p > 0.05)\). Otherwise, it will be less than 0.05 \((p < 0.05)\). If \(p < 0.05\), that means the proposed system is position-dependent, else, it is not. Performing a Pearson correlation \([45]\), the dependence between the number of sun hours in six locations is shown in Table 7.
Table 7. Correlation coefficients of the number of Sun’s hours between locations in the Adriatic Sea.

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficients</th>
<th>Rijeka</th>
<th>Mali Lošinj</th>
<th>Zadar</th>
<th>Hvar</th>
<th>Split</th>
<th>Dubrovnik</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rijeka</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mali Lošinj</td>
<td>0.994</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zadar</td>
<td>0.996</td>
<td>0.999</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hvar</td>
<td>0.995</td>
<td>0.999</td>
<td>0.999</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Split</td>
<td>0.996</td>
<td>0.997</td>
<td>0.998</td>
<td>1000</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Dubrovnik</td>
<td>0.964</td>
<td>0.971</td>
<td>0.975</td>
<td>0.975</td>
<td>0.975</td>
<td>1</td>
</tr>
</tbody>
</table>

From Table 7, it can be observed that the data collected from all six locations experience high correlation coefficients. Furthermore, if the ANOVA test is performed, the scores are $F = 0.429$, $F_{crit} = 2.353$, and $p = 0.826$. Since $p > 0.05$ by large value (0.8268), it can be concluded that the number of sun hours is position independent, and the proposed system analysis that will be performed works for the whole Adriatic Sea.

From Table 6 and observing the Mean annual power density atlas on the Adriatic Sea, it is evident that this area is pretty homogenous. The mean wind speed value for all six observed places is 25.77 m/s with a standard deviation of 0.60 m/s (i.e., 25.77 ± 0.60 m/s).

Furthermore, if data from the sun’s hours and wind speed are analyzed together, in that case, it can be seen that the Pearson correlation coefficient is -0.2466, which indicates no correlation between the corresponding data. Additionally, performing an ANOVA analysis, the scores are $F = 878.98$, $F_{crit} = 4.964$, and $p = 4.45E(-11)$. Since $p < 0.05$ by large value, it can be concluded that the number of sun hours and wind speed data comes from different sources and should be analyzed independently. Taking into account the fact that wind speeds exceed velocities of 55.6 m/s, it could present a challenge to implement wind turbines.

5.2. Simulation Results

The real-time simulation model response of the system is shown in Figure 8. The first graph shows the network frequency due to changes based on the production and consumer side of the network. The second graph shows the sources of electricity: diesel generators marked with a red line, PV modules marked with a green line, and rechargeable batteries colored with a blue line. The third graph shows the state of charge of the batteries. Finally, the fourth graph shows the electrical voltage depending on the different states of the network.
Figure 8. Real-time system response.

The simulation lasts 45 s and represents the sunny part of the day. The term “sunny part of the day” represents a part of the day in which PV modules are exposed to natural light. The simulation is divided into three phases describing the different operating conditions of the ships’ electrical network and flow of electricity. Therefore, it is necessary to observe a graph in time for three different phases:

Phase 0-15 s:
Initially, a minimum load of 4 kW is engaged on the consumer side. The diesel generator supplies the network with a power of 4 kW, while PV modules with positive sine amplitude begin to supply electricity to the system. Due to the surplus electricity produced, the batteries are charged.

Phase 15-30 s:
At t = 15 s, the diesel generator is disconnected from the power network. Due to the increase in power generated by PV modules, the electricity produced is still higher than the consumption, and excess energy is stored in rechargeable batteries.

Phase 30-45 s:
At t = 30 s, the variable load is connected to the mains. Since the amount of energy produced by PV modules is declining, and due to the increase in electricity consumption, the batteries are being discharged to stabilize the network’s voltage and frequency.
Observing the voltage and frequency of the electrical network, it can be concluded that the energy system is stable, especially if it is considered an isolated network.

5.3. Solar and Wind Energy Comparison

Using the publicly available Photo Voltaic Geographical Information System (PVGIS) service, it can be estimated the electricity produced by a PV system based on actual data obtained from meteorological stations for a particular location [63]. Additionally, the optimal angle of inclination of the panel can be calculated. However, the ship as a platform is not static; hence, the modules are placed directly on the water tank lids in a horizontal position without using additional brackets. All characteristics of the PV modules have been entered into PVGIS online service in accordance with technical documentation provided by the manufacturer. Although according to [64] rolling of the ship influences the amount of generated electricity, this article does not discuss impact analysis since the observed ship is stationed in the port most of the time. Considering that the modules are placed at an angle of $0^\circ$ and azimuth of $0^\circ$, with total system losses of 15%, we get an estimate for average daily production of 36.6 kWh, which is 13.36 MWh annually estimate.

In the observed period of 25 years, the solar system should generate 334 MWh. The price of electricity produced by the solar system is 0.191 €/kWh. Although no significant improvements in the efficiency of PV modules and rechargeable batteries are expected in the near future, their cost might vary in a short period (crises, etc.). However, in the long term, prices should decrease when excluding external economic factors such as inflation. With the expected price reduction and the projected increase in the price of electricity, this system should have even greater economic viability in the future.

In order to determine the economic performance of wind turbines, it is necessary to know the average wind speed. In accordance with the Wind atlas of the Croatian Meteorological and Hydrological Service [58], the mean wind speed of 3.5–4 m/s at a height of 10 m was determined for the base location. Wind speed at this height is relevant for calculation due to the height of the turbine column of 9 m and the height of the ship’s superstructure. Using an online calculator [65], and taking into account the rotor diameter, mean wind speed of 3.75 m/s, cut-in speed of 3 m/s, turbine efficiency of 40%, and Weibull shape parameter 2 is projected to have an average electricity production of 2928 kWh. Electricity losses are up to 25% if the efficiency of the system elements is taken into account, namely, wind turbine controller 90%, full sine wave inverter 85%, wiring 98%. Consequently, the average electricity production in the amount of 2196 kWh would be delivered to the system. At the annual level, this amounts to 19 MWh or 481 MWh in the planned period of exploitation of 25 years. The price of electricity obtained from wind turbines is 0.115 €/kWh.

In order to decide which type of RES is more suitable for use on this type of ship, a comparative presentation of the application of solar and wind energy was performed as shown in Table 8.

<table>
<thead>
<tr>
<th>Parameter/Type of Energy</th>
<th>Solar Energy</th>
<th>Wind Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total investment (€)</td>
<td>63,669</td>
<td>55,498</td>
</tr>
<tr>
<td>Price of energy produced, (€/kWh)</td>
<td>0.191</td>
<td>0.115</td>
</tr>
<tr>
<td>Installation</td>
<td>Moderately demanding</td>
<td>Complicated</td>
</tr>
<tr>
<td>Impact on ship stability and maritime features</td>
<td>Minimal</td>
<td>Unfavorable, especially with strong side wind gusts</td>
</tr>
<tr>
<td>Impact on living and working conditions on board</td>
<td>Almost negligible</td>
<td>Extremely unfavorable</td>
</tr>
<tr>
<td>Savings in diesel fuel consumption over a period of 25 years, (l)</td>
<td>111,556</td>
<td>170,274</td>
</tr>
</tbody>
</table>

When using PV modules, the total cost of installing and maintaining the system is higher than the use of wind energy. Nature power Rigid 200W PV modules are suitable
for installation on board and therefore are more expensive. Due to the demanding operating conditions, the life of the wind turbine and possible problems in its maintenance are in question.

Considering the total investment costs and the amount of electricity produced in a period of 25 years on both observed systems, it is concluded that the use of wind energy is far more economically acceptable. Namely, the price of kWh obtained by using wind energy is almost twice lower than that of solar energy, so the payback time of the investment is much shorter.

The installation of PV modules on the cover of the freshwater tank is relatively simple and does not require intervention on the hull. On the other hand, to construct the wind turbine tower foundation, it is necessary to prepare a project that will be harmonized with the official register.

The impact on the stability and maritime features of the ship when installing PV modules is minimal. In contrast, the wind turbine is located at a high altitude, thus, it has an extremely unfavorable effect on the ship’s stability. This is especially pronounced in strong side wind gusts and the ship’s rolling. The strongest gust of wind in Croatia is 248 km/h measured at Maslenica Bridge [66]. In addition, rotating propellers have a hindering effect on the officer who navigates the ship because they obstruct part of the field of view. The disadvantage of installing solar modules could be the possible reflection of sunlight at certain angles, which can adversely affect the navigator.

The impact on living and working conditions during the installation of PV modules is almost negligible. When applying wind energy, it is extremely unfavorable due to the high noise level and the proximity of the rotating wind turbine. This was expressed during the berthing and ship maintenance. However, there are other aspects of installing equipment on board that need to be taken into account which have not been considered in this article. Moreover, the wind turbine may generate drag resistance, depending on the wind direction [67]. However, due to the specific operational profile of the proposed ship, this influence is ignored, hence, most of the time this vessel is stationed in the port of basing. Namely, this ship sails under the case of emergency and crew training.

The use of solar energy would result in savings of 111,556 l of diesel fuel, while the savings from wind energy would be 170,274 l of diesel fuel. Fuel savings are significantly higher through the use of wind energy, which results in a reduction in emissions of harmful gases into the environment. Economic analysis is conducted considering actual fuel prices. Considering the predicted long-term rise of diesel fuel prices and uncertain availability on the market repayment period for the RES system will be shorter. Comparing the recyclability of all elements of both systems would be interesting from an environmental point of view.

When considering the ecological aspect of the application of RES, it is necessary not only to observe the impact on the environment during operation but also to consider the broader picture of using a particular technical solution. Recent research indicates that a large amount of energy is required to produce and recycle lithium batteries, which are often used in RES systems [68,69]. For ships sailing in urban areas, the environmental aspect of exploitation is becoming increasingly important, so the use of RES is inevitable. In the past few years, many scientific institutions and interest organizations in this field have been intensively researching the application of RES in shipping, but the current contribution at the global level is practically negligible.

The results of his scientific research prove the hypothesis of the study and are in accordance with previous research and results.

6. Conclusions

This paper presents the possibility of implementing PV modules and wind turbines on a logistic ship. The total costs of procurement, installation, and maintenance of the system for a period of 25 years were analyzed, and the projected electricity production during that period was taken into account. The cost-effectiveness of installing the RES is
indisputable because the price of energy obtained from PV modules is more than half the price of energy produced using a diesel-electric power unit. In addition to the presented cost-effectiveness and embracing ecological benefits of installing such a system, a significant advantage is the toughness of the electric power system of the ship, especially in case of an outage of the basic power source.

The simulation in the Simulink software tool has proven that the electrical network is stable and sustainable. Since the electricity sources in both examples are of similar power and equally non-periodic, it was not necessary to perform two separate simulations.

Researching solar and wind energy sources for retrofitting the vessels shows that solar panels are suitable for retrofitting and contribute to energy efficiency. Additionally, it has to be pointed out that for the research area (Adriatic Sea), the amount of generated solar energy (or wind energy) is invariant with the ship’s position, which is proven with ANOVA analysis and correlation analysis. Further, wind turbines also can be used on vessels, but it is not possible to introduce them on current ships due to a considerable impact on the ship’s stability and vessel safety.

Namely, technical requirements for solar panels are not demanding in regards to installation on existing vessels, which is the not case with a wind turbine. Installation of wind turbines requires significant budgets and investments that contribute to the stability of the vessel, considering wind gusts and construction.

Therefore, this represents a limitation of the proposed study because solar and wind energy sources are not analyzed as an integrated system that takes all parameters for analysis.

Another limitation of the proposed research lies in the fact that current regulations do not include the possibility of all stakeholders, especially regarding safety (crew, passengers, cargo, and environment). With the advancement of renewables technology and decreasing the price, the main challenge will become the safety of the application. This is especially pronounced in the lithium-ion battery technology regarding fire issues. Therefore, additional research and improvements in technology are needed.

Additionally, in this research, a three-blade horizontal axis wind turbine as a wind energy converter is presented. For future research, an interesting idea would be to introduce the Flettner rotor as an energy source with its features and benefits.

However, the proposed model is a helpful tool that can be easily adapted to other types and designs of renewable energy sources and different types of vessels or isolated networks.


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