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u Splitu
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FACULTY OF MARITIME STUDIES

Tomislav Peša

PARTICLE SWARM OPTIMIZATION OF THE FERRY FLEET CHARGING

DOCTORAL THESIS

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Supervisor: Maja Krčum, Ph.D.

Co-supervisor: Joško Šoda, Ph.D.

Split, 2025.

IMPRESUM

The doctoral thesis is submitted to the University of Split, Faculty of Maritime Studies in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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I declare that my doctoral thesis is the original result of my work and that it clearly states and cites the references of contributions and papers by other authors. I also declare that I have fulfilled all the conditions for initiation of the procedure of evaluation and defense of the doctoral thesis, including those related to the publishing and presentation of papers from the doctoral thesis research area.

I declare that the proposed doctoral thesis has been formatted according to the Instructions for doctoral thesis formatting.



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The Doctoral thesis defence committee for *Tomislav Peša* certifies that this is the approved version of the

PARTICLE SWARM OPTIMIZATION OF THE FERRY FLEET CHARGING

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ABSTRACT

The maritime transport sector has recently been facing increasing legal restrictions aimed at reducing its negative environmental impact. These restrictions stem from legal regulations imposed by the International Maritime Organization, the European Union, and national policies aimed at the long-term sustainability of maritime transport. Geographic areas located near urban zones are particularly important from an ecological and social perspective. This feature is characteristic of ferry transport, where ferry piers are most often located near coastal cities. The electrification of ferries helps reduce the negative impact on the environment. The doctoral thesis focuses on the research and development of solutions that include integrating renewable energy sources on ships and optimizing the charging process of electric ferries' battery storage systems, with a special emphasis on the influence of adequately selecting optimization model parameters. The scientific papers are thematically linked, forming a unified research work that connects theoretical considerations, simulations, and computer models applied in various exploitation scenarios. At the beginning of the research, the application of different types of renewable energy sources on the ship was analyzed, specifically solar energy, wind energy, and an electrical energy storage system. The ecological, economic, and most significantly, the energy impact of such a solution was observed. With confirmed economic viability and ecological benefits, the study shows that the energy generated from renewable sources on the ship can be used, for example, to power lighting, but it cannot meet the total energy needs of the ship. Given the significant energy needs of ships, it is necessary to provide adequate infrastructure for charging electric ferries. However, the already burdened shore-side power infrastructure cannot meet the needs for charging the ships' electrical energy storage if the ferry fleet is electrified. As shown in the research, the energy needs of the ferry fleet can be variable daily. By optimizing the ferry fleet charging process, a reduction in peak charging power can be achieved without the use of an additional energy storage system. In this thesis, particle swarm optimization is the proposed technique for optimizing the charging process. The presented novel optimization model presents a contribution to the field of maritime energy planning and management. Therefore, by analyzing and setting optimization parameters, it is possible to reduce the peak charging power without affecting the available shore-side infrastructure. The novelty of the proposed approach lies in its application to a specific domain that requires numerous constraints and adjustments to achieve an optimal solution. Furthermore, the proposed methodological framework integrates environmental, technical, and

economic aspects of energy transition, representing the contribution of the doctoral thesis. Applying this model and methodology fits into the broader concept of “smart ports”.

Keywords: ferry electrification; renewable energy sources; charging optimization; particle swarm optimization; power management system; decarbonization

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1. LIST OF PUBLICATIONS

This thesis is based on the works described in the following articles, each of which is referred to in the text as an “Article” followed by the corresponding Roman numeral:

- I. Peša, Tomislav; Krčum, Maja; Karin, Ivan; Bacelja, Bruna
“Optimizing the Operation of the Ship's Power Plant Using Renewable Energy”
20th International Conference on Transport Science ICTS 2022, pp. 49-55.
- II. Peša, Tomislav; Krčum, Maja; Kero, Grgo; Šoda, Joško
“A Model for Selecting the Most Suitable Renewable Source of Energy on Vessels Using Bayesian Networks” 11th International Maritime Science Conference (IMSC 2025), May 8th & 9th 2025 – Split, Croatia.
- III. Peša, Tomislav; Krčum, Maja; Zubčić, Marko; Bacalja, Bruna.
“Implementation of renewable sources of energy on Croatian coast guard logistic support vessel PT-71“, 19th International Conference on Transport Science ICTS 2020. pp. 258-262.
- IV. Peša, Tomislav*; Krčum, Maja; Kero, Grgo; Šoda, Joško
“Retrofitting Vessel with Solar and Wind Renewable Energy Sources as an Example of the Croatia Study-Case” *Journal of Marine Science and Engineering*. 2022; 10(10):1471.
- V. Peša, Tomislav*; Krčum, Maja; Kero, Grgo; Šoda, Joško
“Electric Ferry Fleet Peak Charging Power Schedule Optimization Considering the Timetable and Daily Energy Profile” *Applied Sciences*. 2025; 15(1):235.
- VI. Peša, Tomislav*; Krčum, Maja; Kero, Grgo; Šoda, Joško
“Ferry Electrification Energy Demand and Particle Swarm Optimization Charging Scheduling Model Parameters Analysis” *Applied Sciences*. 2025; 15(6):3002.

2. INTRODUCTION

Transportation in general significantly contributes to air pollution and the emission of harmful gases in the European Union (EU). According to [1], transportation is responsible for 39% of the total emissions of particulate matter PM_{2.5} (PM smaller than 2.5 µm) in Malmö, 28% in Brescia, 27% in Parma, and 26% in Angers and Verona. Maritime transport also contributes to air pollution, especially in the area of coastal cities such as Valletta, 33%; Palermo, 29%; Palma de Mallorca, 26%; Athens, 24%; and Bari, 21%. In the territory of the Republic of Croatia, as much as 95.1% of the population has been exposed to PM₁₀ (PM smaller than 10 µm) at a concentration higher than EU standards [2]. Air pollution is the main cause of premature death and disease and, as such, represents the greatest health risk related to the environment in the European Union. According to data from the European Environment Agency, observed annually, in 2019 alone, acute exposure to PM caused 307,000 premature deaths in 27 EU member states [3]. The above has significant implications for reduced life expectancy, increased health care costs, and reduced productivity. Therefore, in July 2023, the International Maritime Organization (IMO) revised its strategy to reduce greenhouse gases (GHG), compared to the ambitions set in 2018. Thus, the final goal for reducing GHG emissions in 2050, initially set at 50% compared to emissions in 2008, was reduced to 0 emissions [4]. In March 2023, the European Commission published the European Green Deal [5], which introduces a zero-emission requirement for ships at berths, mandating the use of power supplies from land or alternative emission-free technologies. The main goal of this agreement is to reduce air pollution in ports, often located near densely populated areas. The Fuel EU maritime initiative [6] is an interim agreement reached in March 2023 that promotes the systematic use of renewable energy sources and low-carbon fuels.

Maritime transport has played a key role in global trade for centuries and still stands as one of its most crucial pillars today. According to the Review of Maritime Transport by the United Nations, more than 80% of world trade takes place by sea [7], clearly indicating its indispensable importance in the modern economic system. Even though it contributes significantly to carbon dioxide emissions – accounting for 14.2% of total emissions from transport within the European Union [8] maritime transport remains the most energy-efficient form of mass transport of goods. Compared to other transport modalities, ships emit the least amount of CO₂ per ton of goods carried.

Due to the growing demand to reduce fuel consumption and the negative impact on the environment, renewable energy sources (RES) are increasingly being integrated into the power systems of ships. However, the forecast for assessing the use of a certain type of fuel in shipping is quite uncertain [9]. Among the most suitable sources for ship applications are solar and wind energy, as well as fuel cells [10]. However, the intensity of production from these sources is not constant throughout the day, requiring flexibility and adaptation of the ship's energy system to the changing conditions of electricity production and consumption. When choosing the optimal energy source, it is crucial to take into account a number of parameters such as the availability of energy, the type and size of the vessel, the area of navigation, and the current legislative framework.

The possibility of implementing a particular alternative energy source depends on a combination of economic, environmental, technical, and social factors. Among all these criteria, the availability of energy stands out as one of the most important elements when conducting a technical feasibility study. In the paper [11], a multi-criteria analysis was carried out to select a suitable type of fuel. The authors promote the use of electric propulsion, which can be obtained from RES or using energy storage system ESS.

Although a significant number of scientific papers and studies research the possibility of electrification of ships, particularly ferries, the performance of charging a ship's ESS has not been sufficiently investigated. This is especially emphasized if a group of ferries using a common port of call is observed, representing research scientific problem in this paper.

The subject of the research is the optimization of the charging process considering the time available and daily energy profile, which could be variable as shown on Figure 1. for Port of Split (Croatia) case study [12, 13, 14]. Nine ferries, each marked in a different color, operate on national lines that use the Port of Split as one of their ports. The x-axis represents the time period of one day during which ships are available for charging. The y-axis represents the required power for each ship individually, and for the entire ferry fleet cumulatively.

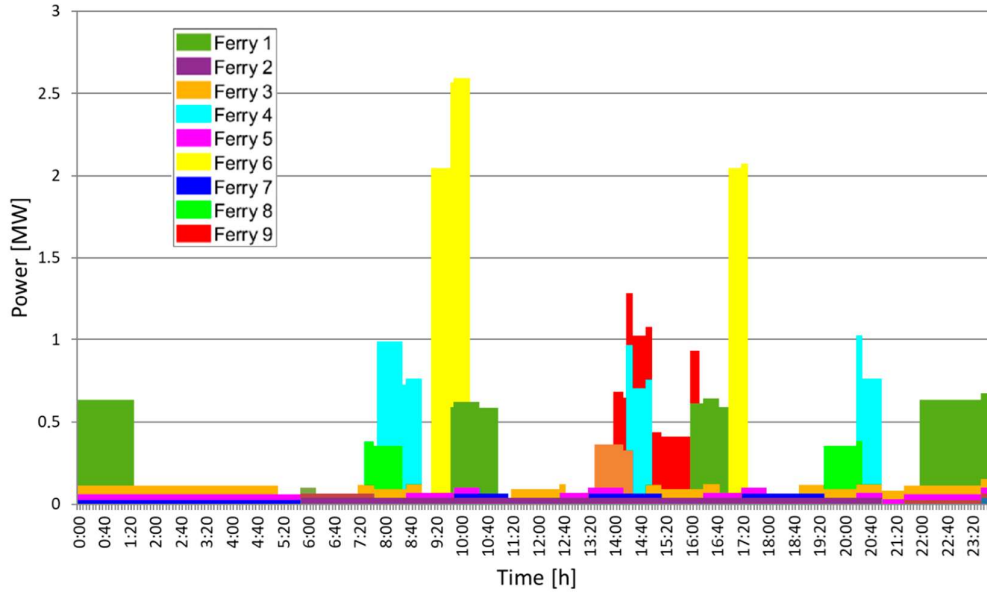


Figure 1. Display of the daily energy load diagram of the analyzed fleet for Port of Split case study

The objective function of the optimization task is to reduce the peak charging power of the groups of electrical ferries. The optimization was achieved by applying particle swarm optimization (PSO) and a greedy algorithm and by setting a priority when charging individual ships. Certain ferries shown in Figure 1. (“Ferry 6”, and “Ferry 4”) are available for a short time to replenish the battery storage. As a rule, a short time implies a high intensity of the required power. The rest of the fleet is available for charging for a longer period of the day, i.e., more time spent on the berth. Disconnecting an individual ship from a charger results in a proportional increase in charging power in the remaining time slots available. The increase in charging power is distributed equally over the entire charging interval due to the technical limitation of the maximum charging current under the nominal capacity of the ESS.

Regarding the defined problem and the subject of research, the following hypotheses could be defined:

H0: In the case of electrification of the ferry fleet, the energy needs exceed the capacities of the shore-side power infrastructure. The profile of daily energy needs is variable and, therefore, not suitable for charging from a shore-side infrastructure.

H1: Optimizing the charging process can reduce the required installed power of the shore-side connection without using additional sources and ESS.

H2: Proper model selection and parameter adjustment can additionally reduce the required installed power during the optimization process.

3. LITERATURE REVIEW

The literature review focuses on presenting and analyzing research and trends in the application of RES in the maritime sector.

The history of maritime affairs records several development phases in which significant progress has been made in increasing the efficiency of ships, which at the same time has reduced their harmful impact on the environment [15]. These phases were often triggered by economic crises that caused freight rates to fall, forcing shipowners to look for more efficient solutions to reduce operating costs, especially fuel consumption. Future rates of change in this area will largely depend on the legislative constraints of individual countries and on the interest of the shipping sector in reducing operating costs. To encourage the desired changes, implementing advanced technical solutions is necessary. Given that shipping accounts for a relatively small share of total global electricity consumption, the main objective should be to adapt existing technologies to the specific conditions of the maritime industry.

A life-cycle cost analysis of different configurations of power systems was carried out with the aim of reducing the carbon footprint in the coastal shipping sector in Croatia [16]. The authors proposed the introduction of fully electric propulsion for ships, both in the context of converting existing vessels and when building new ones. In [17], a techno-economic analysis of the implementation of RES in the short-sector maritime navigation segment was conducted. The research results showed that the most advantageous solution, in terms of environmental protection and cost efficiency, is a configuration that includes a battery system combined with photovoltaic cells on board.

According to [18], riverboats powered by batteries or hybrid systems show lower emissions and reduced operating costs. A study [19] analyzed the installation of a photovoltaic system on a ferry operating on a short route in the Sea of Marmara and found that the payback period would be approximately three years. Still, the payback time is highly dependent on regional conditions; for example, due to the low price of diesel fuel in Latin America, in the case of Jamaica, it can reach up to 19 years [20]. In recent years, an increasing number of studies have focused on optimizing the technical parameters of ships to reduce fuel consumption. While such efforts are commendable and represent a step towards greater energy efficiency, the use of fossil fuels remains inevitable in all the cases analyzed. Therefore, the integration of renewables on board and in ports is key to achieving the sustainability of maritime transport [21].

There are various technical solutions for applying different types of energy, generally involving the adaptation of existing shore-side technologies to the maritime environment. Considering that certain types of vessels have extended service lives, additional efforts are needed to align their operation with current legal requirements and environmental standards [22].

RES are nowadays used on a wide range of ships. However, taking into account the size of the vessel and the energy need that characterizes a typical ferry fleet, the contribution of the on-board self-generated electricity to the propulsion system remains negligible. Such electricity can be used for less demanding systems, such as lighting or other auxiliary consumers with low consumption. Therefore, it is necessary to ensure efficient charging of the ship's ESS from a shore-side power system. From an environmental point of view, this model of electricity supply is justified only in the case when the electricity of the shore-side power system is produced from RES. In this context, the revised Renewable Energy Directive (EU/2023/2413) further underlines the importance of the clean energy transition, setting a binding target of at least 42.5% share of RES in total energy consumption in the European Union by 2030, which represents a significant increase from the previous target of 32% [23].

In accordance with the ship's energy requirements and the capacities of the shore-side power system, different concepts of charging stations for battery systems on ships have been developed. Although charging systems can be implemented in several ways, in practice, the following configurations are most often used:

- direct charging from the shore-side grid (either AC or DC),
- charging using own diesel generators (DG) combined with a connection to the shore-side grid,
- charging via a shore ESS combined with shore-side power grid.

Each of these configurations has specific advantages and challenges, depending on the availability of infrastructure, the type of vessel, navigation patterns, and local energy policies.

Electricity infrastructure in the coastal area of the Republic of Croatia is primarily constructed to meet the needs of households and the tourism sector, while the share of industrial consumption is relatively low [24]. Consequently, excess power in the network is generally insufficient for the needs of ship charging stations, especially during the summer season when the number of tourists is increased and the load on the power grid peaks. At the same time, it is during this period that the energy consumption of the ferry fleet is most significant. In view of

the above, when designing shore-side charging stations, it is necessary to carry out a detailed analysis of the existing load on the electricity infrastructure, the energy needs of vessels, and the operational profile of ferries [25]. Such an approach enables the optimization of the charging system in accordance with the real capacities of the local network and the operational requirements of maritime transport.

Therefore, charging station schedule optimization is a necessity. When conducting energy system optimization of different transport technologies, various techniques and methods are used. However, the most commonly used are Particle Swarm Optimization (PSO), Deep Learning (DL), Genetic Algorithm (GA), Fuzzy Logic (FL), Multi Objective Optimization (MOO), Mixed Integer Linear Programming (MILP), and Petri Network (PN) [26, 27]. PSO is used to optimize the charging and discharging process of the composite ESS of a fuel cell ship under maneuvering conditions [28]. By reducing the amplitude of voltage fluctuations, the power quality of the marine power grid is improved, and the battery service life is extended. The same method is used in [29] to optimize the ESS size efficiently and enable the stable operation of the fuel cell ship. Another example is the schedule optimization of drone routes aiming to prevent collisions during charging flights [30]. The presented methodology achieves good results in optimizing the drone charging schedule. Article [31] proposes a novel energy management strategy for the solar-diesel hybrid generator system on a ship and takes the ship's efficiency into full consideration. By applying the PSO algorithm, reduced fuel consumption and greater efficiency in the operation of the ship generator were achieved. In [32], GA is utilized for the location optimization of electric vehicle charging stations. A proposed algorithm for the optimal distribution of charging stations is presented to reduce investment costs. DL based optimization scheduling method for the ship's power system, generator, and ESS is proposed [33]. The method proposed in this paper can achieve the dynamic optimization scheduling of energy management with the goal of economy. Improved FL is used to achieve the optimal output power distribution and online control [34]. The MILP model with discrete time is employed to find the optimal number of batteries, docking stations, and locations to effectively power the vessel's demand with electric energy [35]. A model based on MILP is used to minimize the total cost comprising charging cost, the construction cost of charging stations, and the fixed cost of ships [36]. Optimization was achieved using a cost-efficient and environmentally friendly service network for electric ships. Article [37] proposes a PN scheduling framework model for automated guided vehicles to optimize scheduling.

The optimal schedule for charging electric vehicles and buses is primarily aimed at minimizing the cost of charging [38, 39]. Minimizing the cost is achieved by charging the electric ESS when the price of electricity is lower during certain periods of the day. The [40] proposes using smart control of battery ESS in the harbor area. Due to the limited capacity of the shore-side power system infrastructure and the variable need for electricity, using shore-based ESS is suggested to ensure a stable and reliable supply of electricity to ships. Peak loads of the port infrastructure arise as a result of cargo handling, ship consumption, and the needs of the port itself.

By predicting the schedule of consumption at a certain time, the energy management system can be optimized [41]. In [42], an interdisciplinary scientific team proposed to transform seaports into smart energy hubs. The authors suggest the use of RES and a power management system that enables a bidirectional flow of electricity depending on current needs. However, energy optimization is presented at a conceptual level. According to [43], to reduce the carbon footprint, seaports must apply technological innovations to become more energy efficient. Extensive electrification and transformation into smart energy hubs will play a key role. The [44] proposes the use of a future smart AC harbor microgrid that controls the charging of electric ships with energy produced from RES. The research analyzed network protection parameters in the event of a short circuit in the grid-connected and island mode.

To confirm the importance and topicality of the issues presented, this paragraph discusses recent works in the field of optimizing electric ferry charging and its impact on the distribution network. First, it is important to determine the necessary capacities of the shore-side infrastructure to meet the needs of charging stations for electric vehicles. Proper planning and capacity determination are crucial for the stability and reliability of the shore-side power system [45]. Articles [46, 47] analyze the impact of coordinated charging of the electric ferry fleet on the local electricity infrastructure. The results show that the coordinated charge-discharge mode can improve the system's performance, leading to an increase in voltage and optimal load on distribution transformers. Furthermore, [48] proposes the use of electric ferry and electric vehicles electrical ESS to power the zero-emission buildings. In this way, energy sharing improves the performance and stability of the shore-side power system. All presented research and concepts emphasize the advantages and importance of energy systems management.

4. RESEARCH OBJECTIVES

This doctoral thesis aims to contribute to the long-term sustainability of maritime transportation by applying RES on board. The main purpose is to systematically investigate and determine the parameters influencing the selection of a specific RES on board and to create a simulation model for optimizing the charging schedule of a group of ferries. As a rule, this type of transport is characterized by short routes with a predetermined sailing order. Since the length of the sailing is generally short, the speed of the sailing is usually not a priority. Considering the specifics of this type of transport energy and environmental sustainability can be achieved using electrical energy.

The main aims of this doctoral thesis are:

1. With a systematic approach to exploring the application of RES in maritime transportation, it is possible to define and determine the basic parameters for the application of different types of RES and implement them into the mathematical model.
2. A defined mathematical model based on the application of the PSO, it is possible to propose optimal solutions for the charging arrangement of the group of ferries.
3. The robustness of the model analyzed under different exploitation conditions depends on various parameters and settings. By correctly selecting the parameters based on the performed analysis, it is possible to further improve the optimization results.

5. MATERIALS AND METHODS

Due to increasingly stringent legal restrictions that are initiated by the negative impact of maritime transport on the environment, it is necessary to abandon the use of fossil fuels. Using RES is the way to achieve this goal. In ferry transportation, one of the most promising options is electrification. It is important to note here that there are different approaches and methods for achieving decarbonization in the maritime sector. However, due to the specificity of the observed ferry fleet and location in the presented case study, electrification of vessels using ESS was chosen as one of the possible solutions. The methodology of scientific research in this doctoral thesis is conceptually presented in Figure 2. Generally, the process can be observed through three phases: the Restriction stage, the Problem formulation stage, and finally the Optimization stage.

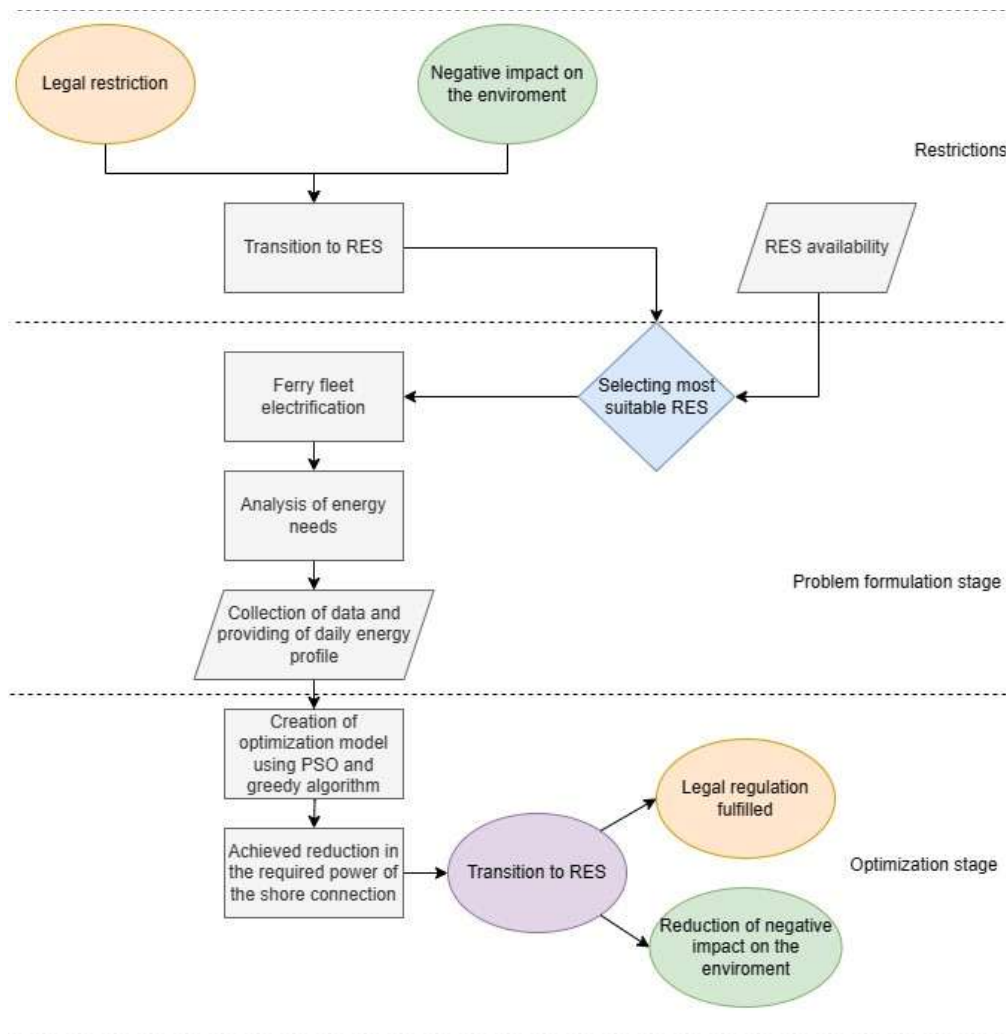


Figure 2. Proposed methodology

Following Figure 2, which shows the research methodology, Figure 3 illustrates the research process. The research process from the initial idea of optimizing a ship's power plant using RES to the selection of a specific type according to availability and the characteristic of the ship is presented. The technical, ecological, and economic aspects of implementation are shown. The response of the energy system is analyzed in Matlab Simulink. Furthermore, a model is proposed for optimizing the charging schedule of electric ferries based on the PSO and greedy algorithm. The model is tested under various operating conditions to investigate its applicability. By properly setting the model parameters, an increase in the efficiency of the optimization model is achieved.

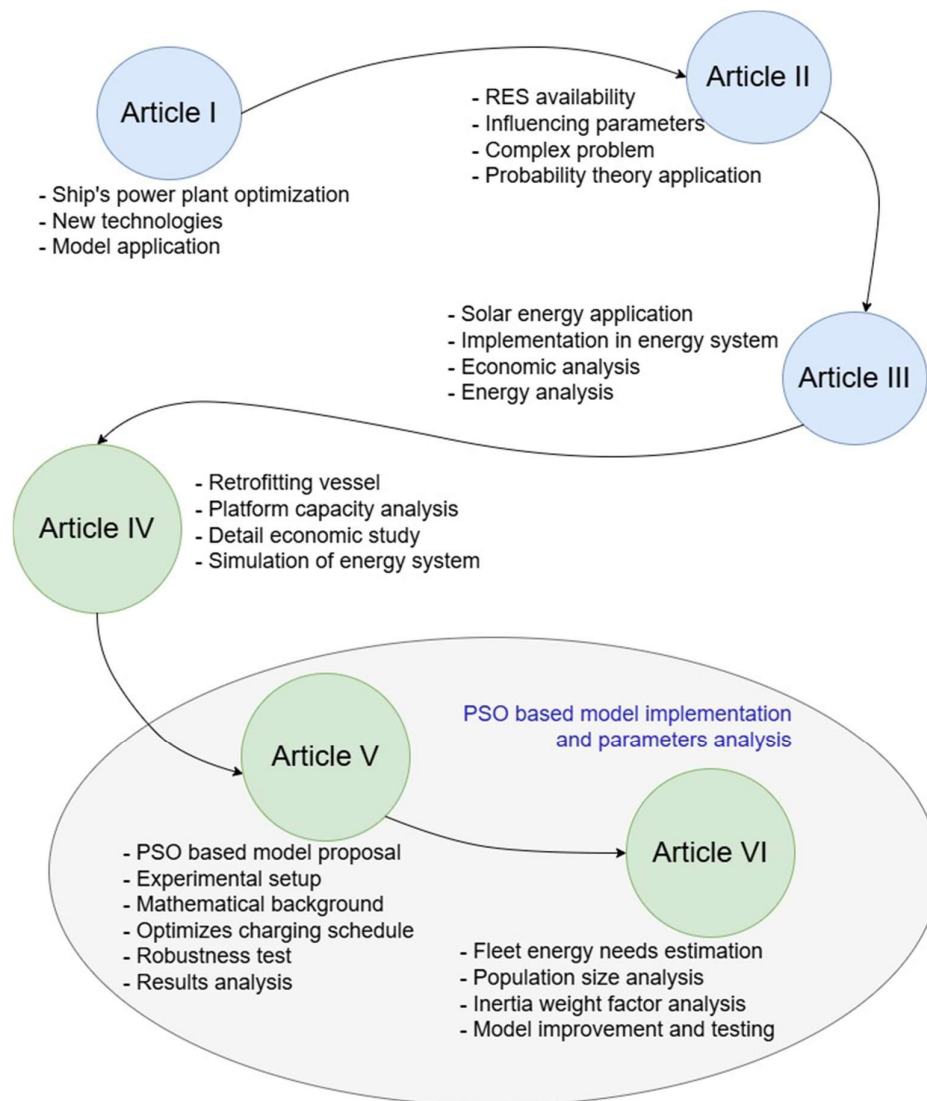


Figure 3. Overview of scientific research process and the contribution of each published article

Initially, the process of optimizing the operation of a ship's power plant using RES was considered to increase the efficiency of maritime transport (Article I). A description of the ship's power plant and technologies used in maritime transport was presented. The advantages of applying hybrid systems were detailed. The design of the ship's electric propulsion and the advantages that such a concept brings were described. Furthermore, new technologies and concepts that steer development in the maritime industry towards the application of RES were presented. In addition, the need for the use of simulation models that assist in the planning of ship energy systems was shown. The importance of conducting the validation and verification process was emphasized so that the model credibly represents the behavior of the real system. As such, it can be used for testing with a certain degree of reliability.

Building upon previous research, a model based on Bayesian networks was developed to select the most suitable RES on ships (Article II). The presented model integrates various technical, economic, and environmental criteria to assess the probability of successfully applying a particular solution to a specific type of ship at a specific location. The model, using conditional probability theory, serves as a decision-making tool in the planning and design phase of RES-powered ships, thereby reducing the risk of making incorrect decisions.

To reduce emissions of harmful gases and mitigate negative environmental consequences, it is necessary to apply an integrated approach in the design, construction, and operation phases of ships. Although there has been a significant increase in the use of RES based solutions in new shipbuilding, the possibilities of integrating them into existing ships are still insufficiently explored. Therefore, the possibility of integrating a photovoltaic system on a logistics ship was analyzed in the continuation of the research (Article III). The conducted study shows the technical and economic aspects of integrating solar energy into the electrical power system of the ship. The application of the presented solution is economically viable, and it is possible to achieve savings in emissions of harmful gases into the environment.

To determine significant parameters for the possibility of applying a certain type of RES on a ship as a platform, a scientific study (Article IV) was conducted. The research analyzes the possibility of applying RES, particularly solar, wind energy, and an ESS on a vessel by conducting technical and economic analysis. The ship's energy system was simulated in the Matlab Simulink program to analyze the flow of energy production from various RES daily. Furthermore, the simulation shows that all network parameters are stable. The observed daily period shows the different states in which the electrical energy system can operate. Although the results of the study confirm the feasibility of installing the RES system, the energy produced

in this way is not sufficient to meet all the energy needs of the ship. Consequently, it is necessary to provide infrastructure for charging the ship's ESS from a shore-side power system.

To determine the necessary capacities of the shore-side infrastructure, it is essential to analyze the energy needs of the ferry fleet on a daily basis (daily energy profile). Furthermore, a computer model based on PSO was created to reduce the peak charging power of a group of ferries under various exploitation conditions by implementing an optimal charging schedule (Article V). The model has been tested in various conditions to prove its robustness. The model was simulated on a case study for the City port of Split. This approach, using RES, has reduced the negative impact on the environment, and legal regulations have been met.

To increase the efficiency of the proposed model, the parameters that affect its operation were analyzed (Article VI). A critical schedule has been determined in which optimization is demanding, and almost no reduction in the objective function is made. On this schedule, the target parameters of the model are analyzed. It was found that with the correct selection of specified parameters, it is possible to significantly improve the optimization model itself. Crucially, the model can be applied in a discrete domain as the daily energy profile of the ferry fleet is presented in a discretized one-day interval. Finally, the model is simulated on the City Port of Split, considering the energy needs of the ferry fleet and the capacities of the energy infrastructure, using a case study as an example. Based on the case study sample, it is concluded that the model is generally applicable. The advantage of the presented methodology and model is that it can be applied to other problems that require optimization in a discrete time interval.

Although the presented model applies the existing method (PSO), it is important to emphasize the scientific contribution primarily in the methodological adaptation and integration of several specific constraints, which have not been systematically processed so far. Namely, the model includes constraints related to the sailing schedule, time spent in port, and the daily energy needs of an individual ship, achieving the minimization of peak power while simultaneously meeting operational requirements. In this way, published scientific papers not only demonstrate the application of the selected method but also provide guidelines and recommendations for the selection of parameters that can be applied in similar research.

In this thesis, several different scientific methods are used. The method of data collection, and statistical analysis was used while determining the daily energy profile, taking into account the sailing schedule associated with the fuel consumption of each ship in the statistically most intensive period of the season. The simulation method was used to simulate the ship's energy system during the energy feasibility assessment of the proposed solution for installing RES on board. The most important method used is mathematical modeling, where the PSO algorithm and the greedy algorithm were applied to optimize the charging schedule of a group of ferries. This has resulted in a reduction in the peak charging power of shipboard ESS. The method of analysis and synthesis of data sets was also used when analyzing conditions related to the number of sunny days, seasonality, energy needs, sailing schedule, etc.

5.1. Mathematical Background of PSO in General

In this doctoral dissertation, the PSO method supported by a greedy algorithm was used. Compared to other optimization methods, PSO stands out for its high accuracy, speed of convergence and ease of implementation [49], which is why it is often used in the management and optimization of energy systems. On the other hand, greedy algorithms in each iteration choose a locally optimal solution with the intention of reaching the global optimum through a series of such decisions. They aim to reduce the total number of iterations, while maintaining satisfactory coverage of the solution area.

The PSO method was proposed and developed by engineers Russell C. Eberhart and psychologist James Kennedy [50]. PSO is a random search optimization algorithm based on cluster intelligence and inspired by the behavior of birds. In this nature-based algorithm, individuals are referred to as particles and fly through the search space, seeking the global best position that optimizes a given problem [51].

All possible candidates for solving the problem are initially presented as a group of particles, with each particle defined by its position, velocity, and fitness value. The position of the particle corresponds to the potential solution to be optimized, while the velocity determines the direction and distance of its movement within the search space.

The value of the goal function for each particle is calculated based on the given goal function. During each iteration, information about the best individual solution (local optimum) and the best solution at the population level (global optimum) is updated, as well as the velocity and position of each particle. The algorithm stops when it reaches a predefined maximum number of iterations or when the position between the particles falls below a certain threshold.

All possible solutions are initialized into a group of particles characterized by position, velocity, and fitness values. The position of each particle represents a potential solution to be optimized, the particle's velocity represents the direction and distance of the particle's movement, and the fitness value of the particle can be calculated according to the objective function. The optimal value of the individual and the optimal value of the population are calculated while the velocity and position of the particle are updated. The algorithm stops when it reaches the maximum number of iterations or the particle's position is less than the given threshold value. Compared to other optimization algorithms, PSO has high accuracy and increased problem-solving speed and is easy to use [49]. Due to the abovementioned advantages, it is often used to manage and optimize energy systems.

The velocity $\vec{V}_t^i$ and the position $\vec{x}_t^i$ of each particle in the swarm is represented by a d -dimensional vector. They are defined by the individual and the collective knowledge in each iteration. Collective knowledge influences the flight trajectories of the particles over the space of possible solutions. The search stops when the optimum criteria are fulfilled. The velocity d -dimensional vectors in every iteration, t , is updated according to the following equation [52]:

$$\vec{V}_{t+1}^i = \vec{V}_t^i + \varphi_1 R_{1t}^i (\vec{p}_t^i - \vec{x}_t^i) + \varphi_2 R_{2t}^i (\vec{g}_t^i - \vec{x}_t^i) \quad (1)$$

where φ_1 and φ_2 are two real acceleration coefficients known as cognitive and social weights, respectively; $\vec{p}_t^i$ and $\vec{g}_t^i$ are the personal best of particle i at iteration t ; and R_{1t}^i and R_{2t}^i are uniformly distributed d -dimensional random vectors. The position of each particle i , at every iteration t , varies according to the following equation [53]:

$$\vec{x}_{t+1}^i = \vec{x}_t^i + \vec{V}_{t+1}^i \quad (2)$$

The global best solution is formally defined as follows:

$$\hat{y}_t \in \{\vec{p}_t^1, \vec{p}_t^2, \dots, \vec{p}_t^s, \} \mid f(\hat{y}_t) = \min(\{f(\vec{p}_t^1), f(\vec{p}_t^2), \dots, f(\vec{p}_t^s), \}) \quad (3)$$

where $\hat{y}_t$ represent the position of the best or target particle in the entire swarm in a d -dimensional space.

Furthermore, the Poisson distribution was used to form possible solutions in discrete signals because the normal distribution does not describe the phenomenon. Since such a distribution in such a complex problem can hardly find a local and global optimum for certain conditions, a higher priority is given using the greedy algorithm. The greedy algorithm is used to solve the problem to give a local optimum at each stage, intending to find the global optimum [54]. Due to their high efficiency, they are a suitable choice for implementing various optimization tasks [55]. The initial greedy algorithm prioritizes the ship whose current energy needs are the highest in amount. Thus, a greedy algorithm reduces the required number of iterations and uses particles to achieve the global optimum.

However, in the case of a problem in which the peak charging power of several ships with similar energy needs connected to the network simultaneously is optimized, the influence of the greedy algorithm is restrained. Following the above, the proposed program code can be described as a hybrid algorithm that uses PSO and a greedy algorithm.

The proposed hybrid model uses greedy particle swarm optimization (GPSO) advantages. Greedy algorithms make locally optimal solutions at each iteration, trying to reach a global optimum. GPSO combines PSO and greedy algorithms to generate test data effectively. It aims to minimize the number of iterations while maintaining good area coverage. Compared to genetic algorithms (GAs), GPSO outperforms in terms of average iterations, execution time, and coverage percentage [56]. GPSO leverages the strengths of PSO and greedy approaches, making it a promising candidate for solving complex problems.

5.2. Mathematical Background of the Proposed Model

The particle contains a large number of data, the most important of which is the “encoded particle” matrix. This matrix is made up of the analyzed ships that represent the rows of the matrix and the associated time intervals that represent the columns of the matrix. Based on the entry table of the sailing schedule, the state in which the ship can be in terms of loading is determined. When the ship is not available for charging, it is assigned a mark of “-1”. When it is available for charging and is not being charged, it is assigned a mark of “0”. When it is being charged, it is assigned a mark of “1”.

The schedule matrix “encoded particle” size $m \times n$ in which m represents number of ferries and n number of time slots is defined as follows:

$$N_m = \{1, \dots, m\}; N_n = \{1, \dots, n\}$$

$$M = \{M_{ij}, i \in \{1, \dots, m\}, j \in \{1, \dots, n\}; M_{ij} \in \{-1, 0, 1\}\} \quad (4)$$

The input matrix of the daily sailing schedule, the state in which the ship can be in terms of charging, is created by introducing the auxiliary f function with the following equation:

$$f: \{1, \dots, m\} \times \{1, \dots, n\} \rightarrow \{-1, 0, 1\} : f(i, j)$$

$$= \begin{cases} 1 & \text{if ship } i \text{ charges in interval } j \\ 0 & \text{if ship } i \text{ is in port and not charging in interval } j \\ -1 & \text{if ship } i \text{ is not in port in interval } j \end{cases}$$

$$M = \{M_{ij} : i \in N_m, j \in N_n, M_{ij} = f(ij)\} \quad (5)$$

Function f translates pairs of natural numbers in which the first value is between 1 and m and the second is between 1 and n , into a number from columns $-1, 0, 1$.

The change in matrix position is defined as follows:

$$M_{k-1}^{g*} \dots \text{the best global schedule in previous iteration } (k-1)$$

$$M_{k-1}^{l*} \dots \text{the best local schedule in previous iteration } (k-1)$$

$$M_{k-1} \dots \text{actual particle schedule in previous iteration } (k-1)$$

The difference in the global optimum (in our case, minimum) is calculated as follows:

$$\Delta M_g = M_{k-1}^{g*} - M_{k-1} \quad (6)$$

The difference in the local optimum is calculated as follows:

$$\Delta M_l = M_{k-1}^{l*} - M_{k-1} \quad (7)$$

Relative differences in power between the actual schedule and global optimum are calculated as follows:

$$\varepsilon_g = \frac{P_{k-1} - P_{k-1}^{g*}}{P_{k-1}} \quad (8)$$

Relative differences in power between the actual schedule and local optimum are calculated as follows:

$$\varepsilon_l = \frac{P_{k-1} - P_{k-1}^{l*}}{P_{k-1}} \quad (9)$$

The probability of a schedule change is calculated, i.e., displacement to global and local optimum in which $p_{d,g}$ probability of displacement toward global best and $p_{d,l}$ probability of displacement toward local best, is calculated as follows:

$$p_{d,g} = w_g \cdot \frac{P_{k-1} - P_{k-1}^{g*}}{P_{k-1}} \quad (10)$$

$$p_{d,l} = w_l \cdot \frac{P_{k-1} - P_{k-1}^{l*}}{P_{k-1}} \quad (11)$$

where w_g represents the global weight and w_l represent local weight.

The PSO algorithm's weight factors are important parameters controlling the particle's movement [57]. A higher weight factor increases the possibility of searching for a particle so that it leaves the area of the local optimum. On the other hand, a lower weight factor increases the capabilities of the particle in local search [58]. Using calculated probabilities and differences in actual position and global and local optimum, global and local velocity matrices are calculated, respectively, as follows:

$$V^g = p_{d,g} \cdot \Delta M_g \quad (12)$$

$$V^l = p_{d,l} \cdot \Delta M_l \quad (13)$$

Attribute: In the places in which the actual position matrix and matrix of global and local optimum, respectively, do not differentiate, the velocity matrix component is equal to 0.

$$V^g = w_g \cdot \frac{P_{k-1} - P_{k-1}^{g*}}{P_{k-1}} \cdot (M_{k-1}^{g*} - M_{k-1}) \quad (14)$$

$$V^l = w_l \cdot \frac{P_{k-1} - P_{k-1}^{l*}}{P_{k-1}} \cdot (M_{k-1}^{l*} - M_{k-1}) \quad (15)$$

Global and local velocity matrix are combined into a single velocity matrix:

$$V = V^g + V^l = w_g \cdot \frac{P_{k-1} - P_{k-1}^{g*}}{P_{k-1}} \cdot (M_{k-1}^{g*} - M_{k-1}) + w_l \cdot \frac{P_{k-1} - P_{k-1}^{l*}}{P_{k-1}} \cdot (M_{k-1}^{l*} - M_{k-1}) \quad (16)$$

A new location matrix dimension $m \times n$ with randomized numbers between 0 and 1 is formed based on the following rule:

$$M_k = \{M_{ij}\}: \begin{cases} M_{ij} = 0 \text{ if } s_{ij} < |V_{ij}| \text{ and } V_{ij} < 0 \\ M_{ij} = 1 \text{ if } s_{ij} < |V_{ij}| \text{ and } V_{ij} > 0 \\ M_{ij} = M_{k-1,ij} \text{ otherwise} \end{cases} \quad (17)$$

The defined constraints, settings of the proposed model, software program and computer equipment are described in detail and elaborated in Chapter 5. Experimental Setup of Article II.

6. RESULTS AND DISCUSSION

The key findings of this doctoral thesis are presented in this chapter. Published articles form the necessary framework to accomplish the previously defined research goals. The main contribution and significance are presented as follows:

1. Development of an algorithm for the selection and evaluation of a certain type of RES for electricity on board. In accordance with the parameters of RES, the creation of a model that analyzes the energy and economic effects of the installation. Based on the results obtained, it is possible to propose the most suitable type of RES that is available and applicable on the ship as a platform.
2. Development of a mathematical model that optimizes the charging schedule of a group of ferries using the common port of call. A model based on the PSO and greedy algorithm optimizes charging to reduce peak charging power.
3. Systematic analysis of the daily energy needs of the ferry fleet, considering fuel consumption and sailing schedules based on and confirmed by real data from case studies. Optimization of model parameters to increase the efficiency of the model, i.e., reducing the peak charging power.

The total contribution of this thesis is multiplied by the individual contribution of each paper. Articles that make up a complete whole can serve all stakeholders involved in the process of decarbonization of maritime affairs, especially ferry transportation, when making decisions. Namely, shipping companies, seaport operators, and electricity infrastructure operators must launch an initiative to achieve energy transformation in line with regulatory frameworks. Therefore, this research provides a guideline for achieving sustainable maritime transport goals.

When conducting the presented scientific research, limitations were defined and elaborated individually for each work. It is important to note that when analyzing the acceptability of applying a certain type of RES on a ship, limitations related to the ship's stability and construction, as well as the impact on the crew and navigation safety, were not considered. Furthermore, when optimizing the charging schedule of electric ferries, it is assumed that all ships in the fleet are electrically powered and that all docks are equipped with adequate chargers, in addition to all the above technical limitations.

6.1. Optimizing the Operation of the Ships Power Plant Using Renewable Energy

The paper entitled Optimizing the Operation of the Ships Power Plant Using Renewable Energy considers the possibilities of optimizing ship power plants using RES and hybrid drives. The advantage of the aforementioned approach is reflected in increasing energy efficiency and reducing fuel consumption, both aimed at reducing emissions of harmful gases into the environment. The use of hybrid systems provides flexibility in operating with different exploitation profiles, allowing diesel generators to function in the optimal range, which results in greater efficiency of the propulsion system. Furthermore, concepts were presented by which large maritime companies propose a direction for achieving sustainable maritime transport and reducing dependence on fossil fuels. The importance of simulation models, which have become a basic tool in various areas of research, is particularly emphasized. The ship's energy system is extremely complex, so computer modeling is inevitable. Models use various computer algorithms and databases, which allow the simulation of real processes in real time with a high level of reliability. It is crucial that the model realistically represents the simulated system with certain approximations and a defined degree of accuracy. The reliability of the model is tested for each specific application through the validation and verification process.

6.2. A Model for Selecting the Most Suitable Renewable Source of Energy on Vessels Using Bayesian Networks

Following Article I, the paper entitled A Model for Selecting the Most Suitable Renewable Source of Energy on Vessels Using Bayesian Networks proposes a model based on conditional probability theory. The ship's energy system is complex, however, when analyzing the implementation of additional RES daily variable, the situation becomes significantly more complicated. Therefore, only a computer model can carry out such an analysis considering different parameters of interest. The paper presents a model that takes into account legal restrictions for a certain area of navigation as well as the availability of energy potential of a particular type of RES. When conducting an economic analysis, the price of installing the equipment is considered in relation to the amount of energy generated in the observed period. The energy analysis is of greatest importance, as it is based on the energy needs of the ship and, in accordance with the possibilities for installing RES, proposes the optimal solution.

6.3. Implementation of Renewable Sources of Energy on Croatian Coast Guard Logistic Support Vessel PT-71

The paper entitled Implementation of renewable sources of energy on Croatian coast guard logistic support vessel PT-71 analyzes the technical capacities of the ship as a platform for installing solar panels. It is proposed to connect the photovoltaic system to the ship's existing power system using an inverter that controls the flow of energy. The direction of energy flow depends on the current state of electricity production and consumption. The surplus energy produced is stored in the ship's ESS. In accordance with the irradiation of horizontal surface, the amount of energy that the system can generate was calculated. Based on the analyzed costs of installation and exploitation of the system in relation to the price of diesel fuel, it was determined that the price of energy obtained from photovoltaic system is more than twice as low as that generated by diesel generators. However, during the implementation of the proposed renewable system, it is necessary to analyze, in addition to the economic and ecological, technical, safety, and social aspects of such an option.

6.4. Retrofitting Vessel with Solar and Wind RES

The article "Retrofitting Vessel with Solar and Wind Renewable Energy Sources as an Example of the Croatia Study-Case" published in the Journal of Marine Science and Engineering explores the possibility of applying renewable energy sources (RES), especially solar and wind energy through technical and economic analysis.

The study analyzed the possibility of applying solar and wind energy to an existing vessel. Data on the number of hours of sun irradiation and wind distribution were collected from six locations in the Adriatic Sea over a 32-year period. First, it was investigated whether the data was position-dependent or independent. By performing the Pearson correlation coefficient and analysis of variance (ANOVA) with the F-test, it was concluded that the RES analysis is independent of position ($p > 0.05$, $p = 0.826$). Then, the energy model of the system created in Simulink was used to analyze the fundamental parameters of the power grid. Finally, the total costs of procurement, installation, and maintenance of the system over a period of 25 years were analyzed, considering savings in operating costs and reduction of harmful gas emissions.

An analysis of the effectiveness of the application of solar panels and wind turbines on board showed significant energy and economic benefits. By using solar panels on board, over an estimated period of 25 years, it is possible to save about 111,556 liters of diesel fuel, while the additional use of wind turbines would result in even greater savings of 170,274 liters of diesel fuel. Overall savings in fuel costs can be significant, and an additional advantage is the reduction of greenhouse gas emissions, which contributes to the sustainable development goals and regulations of the International Maritime Organization (IMO).

Simulations have shown that RES are very adoptable in the Adriatic Sea, where there is a significant number of hours of sun irradiation during the year and favorable wind conditions for the application of wind turbines. Combined, solar and wind power can provide a substantial proportion of the electricity needed by a ship, thus reducing reliance on conventional energy sources. When conducting the economic analysis, the costs of procurement, installation and maintenance of the system over a period of 25 years were taken into account. Potential fuel savings as well as maintenance costs for diesel generators were also considered. The proposal shows that despite the high investment costs, the system can achieve financial profitability, especially if the application of wind energy is observed. The advantage of the proposed system compared to a classic diesel generator is in the reduction of maintenance costs.

As ferry ports are mostly located next to urban areas, the environmental impact is crucial. Namely, the use of renewable sources generated from solar and wind energy reduces CO₂ emissions. In addition, there is a reduction in sulfur oxide (SO_x) and nitrogen oxides (NO_x). This has a positive effect on air quality and the reduction of acid rain. The proposed research shows that the integration of solar and wind energy into the ship's power system represents a sustainable and economically viable option in reducing the consumption of fossil fuels in the maritime sector.

The use of RES on board can have multiple benefits, including:

- reduction of operating costs related to fuel and maintenance,
- improving energy efficiency and resilience of ships,
- increasing the environmental friendliness of the maritime sector,
- reducing harmful emissions and contributing to global CO₂ emission reduction targets.

Despite the initial financial challenges, the results show that investing in solar panels and wind turbines pays off in the long run, especially in the context of rising fuel prices and increasingly stringent environmental regulations. In addition, further development of technology and improvements in the efficiency of solar panels and wind turbines could further increase the cost-effectiveness of such solutions. This study represents a valuable contribution to the development of sustainable maritime transport in Croatia, offering concrete evidence that the modernization of existing ships with renewable energy sources can have significant benefits for ship owners, the environment and the entire maritime industry.

The research results indicate that, despite the high initial costs, installing photovoltaic system and wind turbines on ships is justified from both ecological and economic perspectives. The importance of research is particularly emphasized from the aspect of price and availability of fossil fuels, as well as increasingly stringent legislative regulations. This research contributes to the development of sustainable maritime transport by providing concrete evidence that modernizing existing ships can significantly benefit shipowners, particularly by reducing negative environmental impacts.

6.5. Electric Ferry Fleet Peak Charging Power Schedule Optimization

Building upon the findings from Article IV, which confirmed the technical and economic feasibility of integrating renewable energy systems on board ships, the research naturally progressed toward addressing the limitations of on-board generation capacity. Since the produced renewable energy could not fully satisfy the operational demands of vessels, it became essential to investigate the shore-based charging infrastructure. Therefore, the next stage of the research (Article V) focused on developing a computational optimization model based on the PSO algorithm to reduce the peak charging power of a group of electric ferries.

The article "Electric Ferry Fleet Peak Charging Power Schedule Optimization Considering the Timetable and Daily Energy Profile" explores methods to reduce the peak charging power of a fleet of electric ferries using the same port of call. In doing so, the daily energy needs of each individual ship are analyzed, considering the sailing schedule during the high season when the number of departures is statistically the highest. The functional goal of the optimization task is to reduce the peak charging power, all in order to reduce the load on the shore-side power grid. It is important to note that the optimization is done without the use

of an additional electricity storage system. By applying the proposed novel model, a reduction in peak charging power of 24% was achieved. The reduction achieved is significant in terms of the load on the shore-side power network and the infrastructure costs of increasing the power system's capacity. This research shows that adequate optimization of the charging process of a group of ferries can significantly increase the efficiency of the system. The presented approach in the application of the PSO method and the greedy algorithm in the optimization of the ferry charging schedule is a novelty in the field of sustainable maritime transportation.

By studying the daily energy profile of the fleet, it was identified that the load profile is non-periodic, i.e., the highest load occurs in the morning and afternoon hours, when most ferries dock in ports and charge their batteries. By using optimization algorithms (PSO and greedy algorithm), the system reallocated charging times, which reduced the load on the network without affecting the timetable.

First, it was found that the ferries' energy needs were significant and exceeded the capacity of the shore-side infrastructure. Secondly, by analyzing the energy consumption of a group of ferries, it was determined that the energy profile was extremely non-periodic. Peak consumption occurs in the morning and afternoon when most ferries are in port and need to charge their own ESS. By applying optimization based on the PSO method, a reduction in the peak charging power was achieved. This has been achieved by disconnecting lower-priority ships from the power grid to provide the shore-side energy system capacities to priority ships. With this allocation of charging intervals, a reduction in charging power has been achieved without affecting the sailing schedule. An additional aspect of the analysis showed that minimizing the charging power according to the actual energy consumption of the ferries can further reduce the overall peak charging power by improving system efficiency.

To confirm the model's robustness for use in varying operating conditions, a test was conducted where several ships with similar energy needs were connected to the charger simultaneously. In this case, the greedy algorithm does not influence because it cannot prioritize the most energetically significant ship. Furthermore, the model was validated on a different sailing schedule, during which one of the ships was disconnected from the charger. It was also tested in such a way that the daily energy needs of one of the ships ("Ferry 6") were varied. In that test, the relationship between the required number of iterations in relation to the reduction of peak charging power is analyzed, as shown in Figure 4.

From Figure 4., it can be observed that the number of iterations required to achieve the objective function depends on the daily energy needs of an individual ferry. When the daily energy needs of “Ferry 6” are approximately 0.5 MW, there is a situation where several ferries of similar power are connected to the charger at the same time. In that case, the optimization is complex, and the optimization effect is reduced.

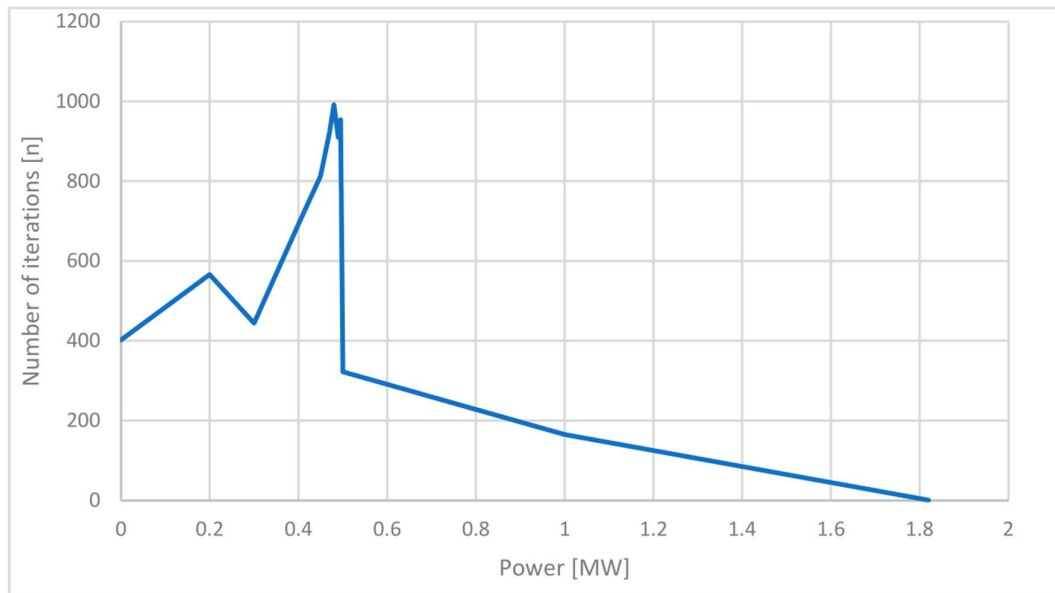


Figure 4. Dependency of the required number of iterations to achieve the minima concerning the daily energy needs of “Ferry 6”

The number of iterations required to achieve the optimal solution is correlated with the efficiency of the model, as shown in Figure 5. When the optimization results are predictable, i.e., less demanding, a significant reduction in peak power is achieved in a short time with a small number of iterations. On the other hand, when the values of the energy requirements are equalized with a large number of iterations, a relatively small reduction in the required power is achieved. For example, when the daily energy needs of “Ferry 6” are 0.48 MW, 992 iterations are needed to achieve a total peak power reduction of 0.76%. When the daily energy needs of “Ferry 6” are between 0.4 MW and 0.6 MW, a large number of iterations are required to achieve a small reduction in the charging power of the group of ships. The reason is that several consumers with similar energy needs are connected to the charger simultaneously. On the contrary, when the daily energy needs of “Ferry 6” are 1.82 MW, one iteration is required to reduce the peak power by 24%.

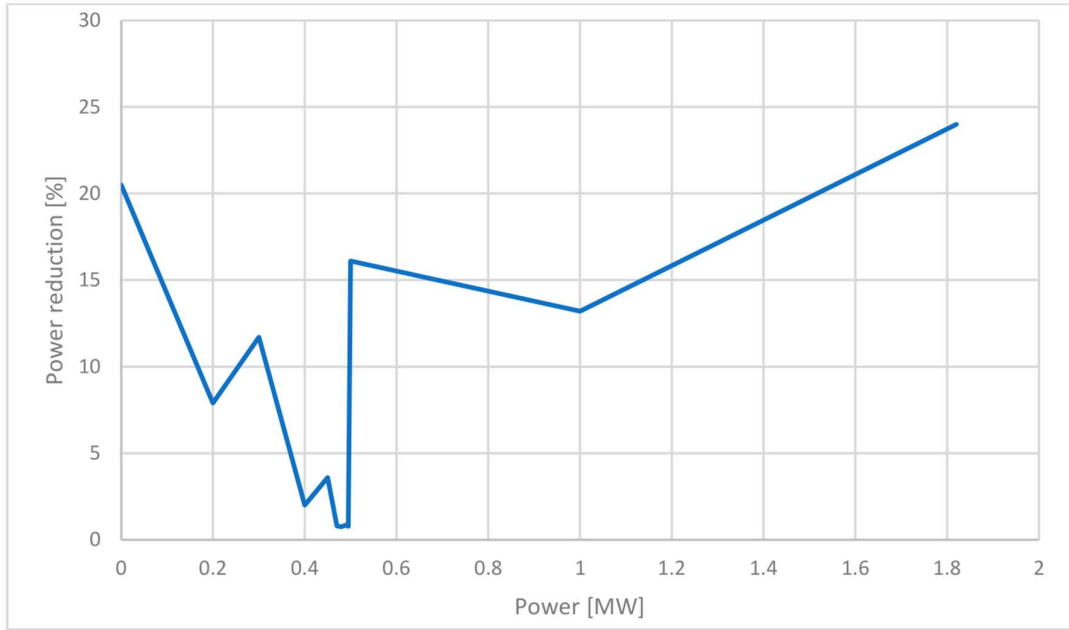


Figure 5. Dependency of power reduction in relation to the daily energy needs of “Ferry 6”

Also, testing the model in different scenarios showed that the optimization can be adjusted in cases of changes in the timetable or the number of electric ferries.

An additional advantage of this study from an ecological perspective is the reduction in the required production capacity of electricity from renewable sources during peak demand. Furthermore, optimally allocating the required peak charging power can also reduce the economic costs associated with charging electric ferries for line operators.

This research, which employed an advanced optimization method, significantly improves the efficiency of the electric ferry charging process without reducing operational performance. The key contributions of the presented optimization model are:

- reduction of the charging power of the ferry group in the amount of 24%,
- disburdening of shore-side energy infrastructure, which results in lower investment costs in shore-side infrastructure,
- consequently, lower greenhouse gas emissions and a reduction of negative impact on the environment.

In conclusion, the proposed optimization model can serve as an applicable solution for maritime operators aiming to reduce costs and increase the sustainability of their electric ferry fleets. Also, the method is scalable and can be adapted to different types of electric ships, which opens the possibility for further implementation in the maritime industry, especially in regions with developed ferry transportation.

The proposed methodology and optimization model can serve maritime decision-makers as a viable option to reduce the cost of electrifying a fleet of ships, supporting long-term maritime transportation sustainability. This concept can be applied to other ports and types of maritime transportation, which opens opportunities for future application in the maritime sector, especially in areas with developed ferry transport.

6.6. Ferry Electrification Energy Demand and Particle Swarm Optimization Charging Scheduling Model Parameters Analysis

After verifying the effectiveness of the PSO-based optimization model on a real-world case study (Article V), the next logical step was to improve its performance under varying operational conditions. Therefore, Article VI concentrated on analyzing and tuning the optimization parameters, aiming to enhance convergence speed, robustness, and overall efficiency of the model. Furthermore, this article systematically elaborates the methodology for analyzing the energy needs of a ferry fleet.

During the electrification process of the vessel, it is necessary to determine the daily energy needs. In other words, it is necessary to analyze the fuel consumption of existing ships to determine the equivalent amount of electricity that can meet the energy needs. A comprehensive analysis considered the ships that maintain ferry lines. The consumption of diesel fuel and the non-seasonality of the number of sailings during the season when the highest load was recorded were analyzed. In accordance with the timetable, the daily energy profile of the ferry group was generated, which needs to be optimized. The proposed methodological approach to analyzing the energy needs of a group of ships represents a contribution and novelty of scientific research.

Analysis and parameter setting are crucial for effective optimization. The optimal size of the particle population allowed for a better search of the search, while the moderate size of the inertia factor improved the rate of convergence of the model. In case of inadequate parameter setting, optimization is slower and less effective as shown on Figure 6. It can be seen from the figure that the greatest reduction in peak power is achieved when the number of particles is set to 256. Compared to the initial reduction of 0.76% when the number of particles was 1024, a reduction in peak power in the amount of 13.47% was achieved. The relationship of the required number of particles to achieve a certain objective function cannot be generalized

and must be analyzed and optimized for each individual problem [64]. This indicates the importance of careful adjustment of model parameters for each specific application. By applying the presented algorithm based on particle swarm optimization with properly set optimization parameters, it is possible to reduce the peak charging power of the ferry fleet by more than 20%. A detailed description of the applied method, program code and flow chart is given in section 3.3. Optimization Methods and Methodology of Article VI.

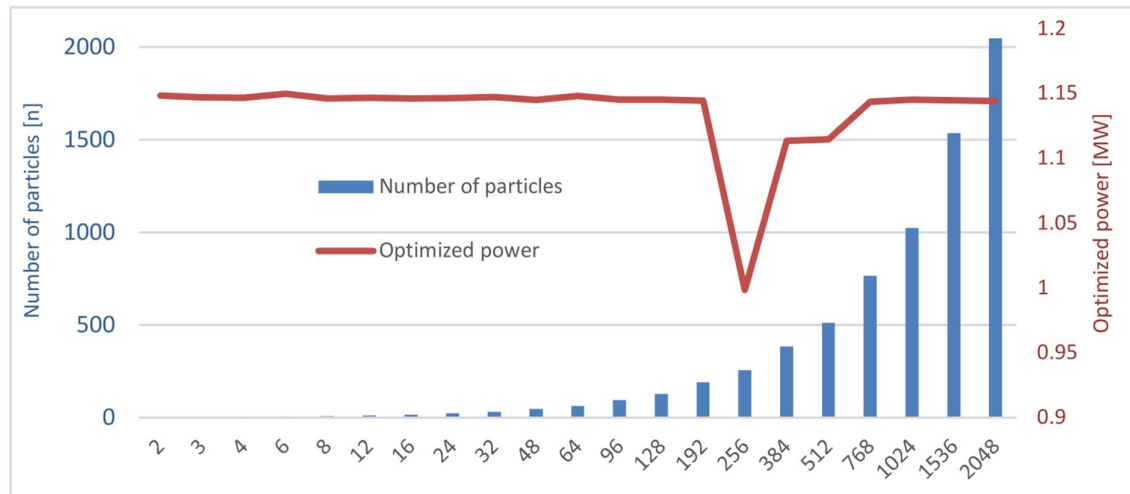


Figure 6. The influence of the selection of the number of particles on the reduction of the peak charging power

Although this research deals with the analysis of parameters and optimization of the charging schedule of a group of ferries, the greatest benefits are directed towards the shore-side infrastructure. The contribution of reducing the peak charging power is not only in reducing the required capacity of the shore-side connection, but also in the even distribution of consumption. In this way, the optimal load on the power source of the shore-side power system is achieved. Thus, the reduction in peak charging power achieved by optimizing the schedule reduces the infrastructure costs associated with the production and distribution of electricity. Furthermore, the presented model has been tested in different exploitation conditions where it has been confirmed that the correct setting of optimization parameters contributes to increased efficiency.

The advantages and contributions of scientific research in the presented optimization model are represented by:

- methodology of assessing the energy needs of the observed ferry fleet,
- reduction of peak charging power, which has achieved an even load on the shore-side power system, which has a financial effect as a result,
- analysis of optimization parameters with the aim of minimizing the goal function,
- validation and verification of models for different application conditions.

The presented model contributes to the sustainability and economic viability of the electrification of the ferry fleet, all in support of the transition to sustainable maritime transport.

7. CONCLUSION

This doctoral thesis provides a comprehensive methodological framework that includes and connects theoretical, practical and simulation aspects of the energy transition in maritime transport. The originality is not only the presented novel model, but the systematic integration of environmental, technical, and economic parameters of the proposal for decision-making. In the way shown, the gap between the application of RES on ships and the implementation in power management of the port is bridged. The presented research contributes to the uprising of a broader vision of maritime transport development, aiming to meet decarbonization strategies.

A model for optimizing the charging schedule of a group of electric ferries based on the PSO method has been presented. Although there are examples of the application of the proposed method in the optimization of energy systems, the application of the PSO method in this specific environment is novel. The originality also represents the way of application of the method itself, as it allows the adaptation of the theoretical concept to real operating conditions. In order to ensure the efficient operation of the model, various constraints have been introduced that define the boundaries of the model and the mode of operation. The aforementioned constraints guide the model to clearly define parameters to prevent unwanted deviations. The application of the PSO method and defined constraints makes the model relevant, stable and applicable in the domain of maritime transport.

The presented research objectives of the thesis were achieved in the following way:

- parameters for the implementation of a certain type of RES on a ship as a platform were determined,
- the suitability of the concept from the energy aspect of the application was confirmed by a simulation model of the energy system created in Simulink,
- an optimal schedule was proposed using a mathematical model based on PSO and a greedy algorithm, which enabled the reduction of peak charging load,
- by appropriate selection of parameters, the improvement of the optimization model in different exploitation conditions was achieved.

The results presented show a significant potential for retrofitting existing ships using RES. Furthermore, by optimizing the schedule of the charging process of a group of electric ferries, it is possible to reduce the peak charging power, which results in reduction of the load on the shore-side power infrastructure. In this way, it contributes to the long-term sustainability of maritime transport.

In addition to the presented technical improvements, the research emphasizes the broader economic and environmental context of the electrification of ships with the aim of achieving neutrality of environmental impact. By introducing RES and advanced energy management systems, it is possible to contribute to long-term financial savings, reduce dependence on fossil fuels and contribute to increasingly stringent goals related to climate policy.

The presented model effectively optimizes the peak charging power of a group of ferries. However, the model does not analyze the current parameters of the shore-side electrical infrastructure. Namely, the state of the electrical grid is dynamic, with fluctuations in energy availability, real-time prices, and the load on power transformers. It is also necessary to consider the impact on the aging of battery ESS as well as the costs associated with servicing and maintaining the installed energy systems. Furthermore, the model achieves adequate results by minimizing the objective function in certain scenarios. A systematic analysis of the results obtained confirmed the sensitivity to the proper setting of model parameters, which influences the effectiveness of the model.

In accordance with the presented field of research and the aim of the thesis, future research may be directed as outlined below:

- Additional testing of the model for other ports of interest, considering all the specifics of the ferry fleet as well as the sailing schedule.
- Analysis of the possibility of using the ESS of ships that are not a priority for sailing in such a way that the available energy is returned to the system for the purpose of regulating the parameters of the power grid.
- Integration of RES into the energy system of the port with the aim of relieving the shore-side network.
- Improvement of the optimization algorithm of the model and analysis of other influencing parameters of the model with the aim of increasing the efficiency of charging process.

Furthermore, the operational environment of the maritime sector is extremely sensitive because it is influenced by various market conditions, legislative decisions, geopolitical situation, price and availability of fuel. In addition to the above, the price of equipment is of particular interest, especially its efficiency and technical relevance. Therefore, in future work, it is possible to expand the model in a way that considers and analyzes certain parameters with the aim of expanding the model and the possibilities of its application.

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OPTIMIZING THE OPERATION OF THE SHIP'S POWER PLANT USING RENEWABLE ENERGY SOURCES

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ABSTRACT

Shipbuilding is a compromise that tries to achieve the full functionality of a vessel through optimal usage of all ship systems. The aim of shipbuilding is to reduce the size of a vessel and the costs of its implementation and exploitation while keeping initial technical requirements fulfilled. As a result of size reduction, one can minimize the costs of purchase and maintenance throughout their exploitation period. Because of that, it is necessary to conduct optimization from different points of view for each device installed on the ship. The goal is to choose a system that accomplishes all of the above-mentioned requirements without losing necessary safety and reliability level.

This article shows different approaches in optimizing ship power plant. It brings out the advantages of using hybrid systems and shows the configuration of ship's electric propulsion system. Furthermore, this paper presents renewable energy sources (RES) that are appropriate for maritime environment and are in accordance with the recent trends in applying RES in shipbuilding industry. It describes the basics of simulation model usage and highlights its validation and verification process.

Keywords: Ship power plant, renewable energy sources, optimization, model, verification and validation

1. INTRODUCTION

The ship's power system can be observed as an isolated island network [1]. Typical ship's electrical network consists of systems for the production, distribution and consumption of electricity. Exceptions are electric vessels that sail shorter distances and do not have devices for generating electricity. Due to the large oscillations in the network load, especially in the case of electrical propulsion, the ship's power plant should ensure the required quality of power supply for all devices. Production of electricity on vessels is carried out through primary movers (diesel engine, turbine, engine shaft, gas turbine). The most common source of electric power on board is an easily controlled diesel generator that adapts to the power network.

The ship's electrical network is specific because it simultaneously conducts production and consumption of electrical energy. The essential difference between a

ship's network and an isolated island network is the type of the load. The changes of the load of the vessel's network are more significant, consequently requirements for the resilience of the network are more demanding. It is necessary to provide a sufficient amount of energy in a relatively short time thus energy storage system (ESS) is an excellent supplement to the ship's energy system in total. According to [2] ESS provides primary frequency support and also improves the transient stability of the network. Rechargeable batteries, super capacitors and flywheels are mainly used for the ship's ESS.

Electronic power devices that control the flow of energy on the ship play a crucial role in the optimal use of energy resources. The aim is to achieve energy and economic efficiency in the design and operation of vessels. Optimal energy management contributes to the



stability of the network in different operating conditions while reducing fuel consumption.

The ship's generator must adapt to the requirements of electrical energy consumers. In the event of a short-term overload, the ESS supplies energy to the grid. On the contrary, in the case of a long-term overload, ship's power grid needs for more energy, hence the system automatically switches on the "standby" generator. If the consumption of electricity exceeds the possibilities of its production, it is possible to disconnect less important consumers from the network. Less important consumers are those who do not significantly affect the safe management of the ship and cargo.

The characteristics of electrical power consumers largely depend on the type of the ship and the cargo being transported. The ship's power plant manages the entire flow of electrical energy onboard, thus its efficiency is fundamental to the overall efficiency of the vessel.

There are different approaches in the design of the ship's electrical network due to the features of each individual vessel. However, the most common approach is to use a low-voltage three-phase alternating current system with a voltage level of 400 V or 440 V. The advantage of this approach is the use of standard industrial equipment and worldwide available devices. This approach is not cost-effective for large ships powered by electric propulsion, hence on these ships high voltage and low voltage levels are usually combined to supply the devices as Figure 1. shows.

This figure serves as a basis for understanding the ship's power system topology and the role of its individual elements. Picture depicts sources of electrical energy: diesel generators, fuel cells, and batteries. Fuel cells are a renewable source of energy. However, the batteries and the shore connection can also be observed as RES if they are supplied from renewables.

Electric propulsion motors are supplied by high voltage, while auxiliary ship's devices such as pumps, compressors, fans, etc. are supplied by low voltage.

Alternating machines, regularly synchronous generators are used to produce electrical energy of certain frequency and voltage. Those are the basic parameters that should be maintained within defined values. Ship's generators are to the greatest extent powered by a diesel engine or gas turbine. The speed governor maintains the referent frequency, while the automatic voltage regulator (AVR) regulates the generator voltage. The speed governor design can be hydraulic-mechanical or electrical. AVR is an electronic device used to regulate the excitation current and consequently, it regulates the generator voltage.

It is simple to regulate one generator, however, when two or more generators work in parallel operation, the situation becomes more complex. Instability in operation or failure of the entire system may occur because one generator takes most of the load. Due to that, it is necessary to harmonize the operation of the generators in order to the even load distribution.

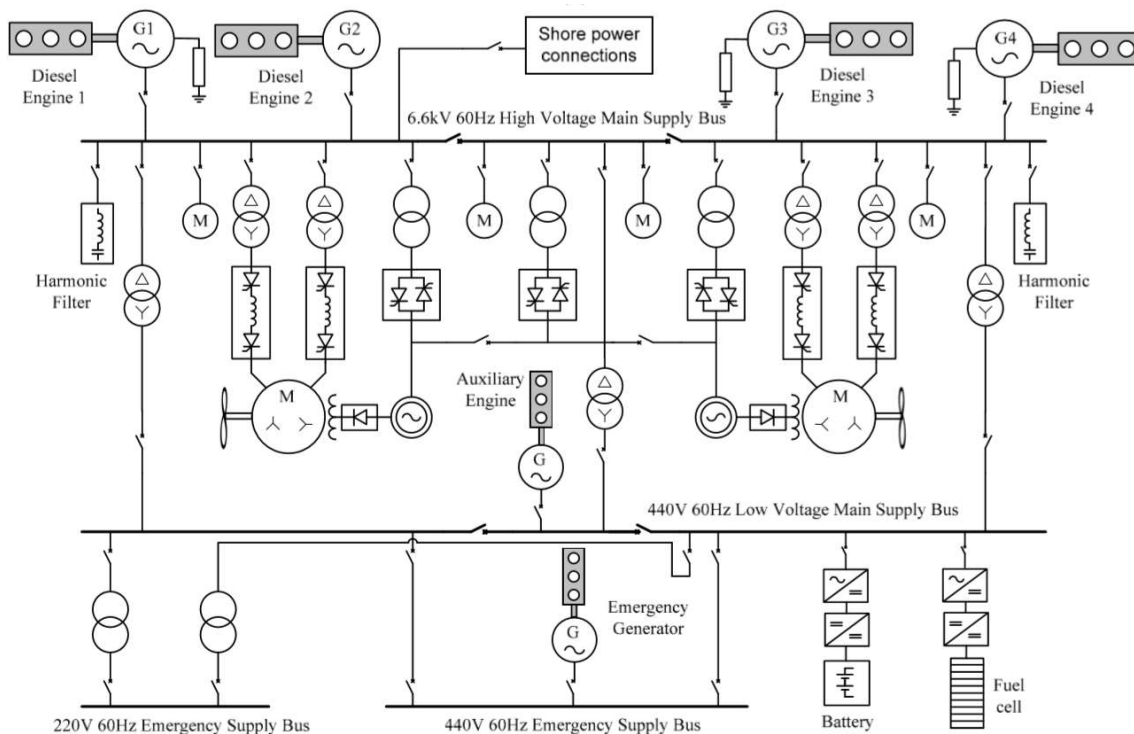


Figure 1: Cruising ship Queen Elizabeth II power plant example [1]



2. SHIP'S POWER PLANT

The goal of optimization is saving in fuel consumption, which positively affects the economical and ecological aspects of exploitation of the vessel. However, the priority is to obtain high level of reliability of the vessel power network. According to [3], reliability is achieved by installing high quality system components and redundancy of structural system components. All components installed in the energy system should be tested through various methods of verification before installation and additionally in everyday use. At the end of the testing period, components of lower quality and reliability are replaced. Unfortunately, this is an expensive way to increase the level of availability of a particular technical system. The redundancy of key systems also accomplishes the required level of reliability even though the installed equipment is of poorer quality. Therefore, when using this method, it is necessary to have a well-trained and equipped crew which is able to quickly return the defective device to operational condition.

According to [4] the redundancy of generators alone does not provide a sufficient level of reliability. Usage of energy storage units is increasing in recent times. That improves the security in terms of the quality of produced electrical energy supplied to ship's consumers. Due to the different modes of operation of energy storage systems, they have certain advantages over the addition of diesel-electric generators. The essential advantage is the energy availability in a short time. In case of the power network oscillations the response time in the electrical energy storage system is much shorter and can be measured in a few milliseconds, for example, flywheels [5].

Electrical energy storage units are frequently used in the car manufacturing industry, buses, and train production. On the other hand, maritime transport occupies a small percentage of the research and application of new technologies. Therefore, it is necessary to strive for the application of existing technologies from advanced energy developed industries. Energy storage facilities are generally used as a supplement to the existing energy system. However, there are functional examples in which only rechargeable batteries electricity is used as the only source of energy on board. The leading representatives of exclusively electric propulsion vessels are ferries operating on shorter distances [6].

The reliability of the ship's power system is achieved not only by doubling the number of the devices but also by placing the equipment in separate rooms. Because of the fire or water flooding possibility in the engine room, there is a danger of failure of the entire power supply system onboard. Therefore, key devices for the production and distribution of electrical energy must be placed in different rooms. Furthermore, diesel power units often malfunction because of fuel supply problems, so it is necessary to design a system in which the diesel engines have an independent supply of fuel from different tanks.

In the case of vessels with the required high reliability, cable routes are installed over both sides of the ship in order to avoid power outages of key devices. Automatic switches which turn the available line on are most commonly installed. Due to the growing number of installed consumers of electrical energy on newer ships, the switchboard is becoming more complex. The switchboard's investment costs, the required installation space and its mass are increasing. Therefore, the optimization of the ship's power plant is even more important in the efficiency of the ship [7]. The type of vessel, the route on which it is sailing, the available type of propulsion energy and legal restrictions for the area of navigation should be taken into account while searching the most suitable solution.

In the past period the advanced power management systems of the ship's power plant have been aimed to improve efficiency. One of the methods is that power flow control is formulated as an optimization problem where the optimal load distribution on power sources is determined through numerical methods. Each variable needs to be assigned a corresponding cost that has a direct impact on the selection of the most favorable method. However, the cost of a particular energy source is not the only parameter in decision-making [8]. For example, taking into account the price of electricity obtained from batteries, their price is higher due to multiple conversions and losses. Despite the above, energy from rechargeable batteries is in certain conditions most favorable when there is an excess of energy produced in the power system of the ship. Paper [9] presents a model of electric propulsion optimization of a merchant ship based on the exploitation profile and the energy price, which is the main optimization criterion. Economic and energy modules represent an appropriate transmission function. Output data is energy price and other factors of influence.

The cruise ship industry is at the forefront of introducing innovations in the improvement of the ship's power plant [10]. As these are large ships with a large number of passengers and crew members, the need for electricity production is extremely high, especially given the fact that electric motors are most often used to propel the ship [11]. Because of the interest of maritime companies, and even more due to the pressure of legal framework related to the emission of harmful gases, the goal is to reduce fuel consumption for supplying diesel-electric generators. According to [12], savings are possible by using alternative fuels to power ship generators. This paper demonstrates that the presented approach can support decisions for identifying the cruise ships power plants optimal solutions. That simultaneously results by reduction of the lifecycle costs and emissions whilst enhancing the system safety. In the best scenario the NOx emissions reduction can be by 71- 72% less in comparison to the baseline. Ship's draft and displacement, weather force and direction, hull and propeller roughness also affect fuel consumption [13].



2.1. Hybrid system application

According to [14] by applying advanced hybrid systems, and depending on the type of vessel and the type of route, it is possible to reduce fuel consumption by 10% to 35%. Naval ships, towing vessels, and offshore vessels are suitable for hybrid energy application because of their operational profile. In these types of ships the engine power is 20% or less at 90% of its operational time. The application of hybrid propulsion systems on overseas ships is currently questionable from an economic point of view [15]. The efficiency of the ship's power network depends on choosing the most suitable sources of electrical energy at a given time in accordance with the needs of power consumers [16, 17, 18].

In marine power plants with multiple generators, as primary energy sources, it is necessary to use the generator in the optimal mode of operation. This is done by reducing the number of generators connected to the network and increasing the load on those connected to the network. Due to the above, fuel consumption is reduced and thus there is a reduction in emissions of harmful gases. It is commonly known that the efficiency of the generator is higher at higher loads, as shown in Figure 2. Under light load conditions of diesel engine specific fuel oil consumption can go up to 400 g/kWh while at a load of 87% is 200 g/kWh. According to [19] optimal operating range of a diesel-electric generator is between 70% and 89% of its rated power. Also, the maximum load should be avoided because of diesel engine life span reduction and absence of available energy.

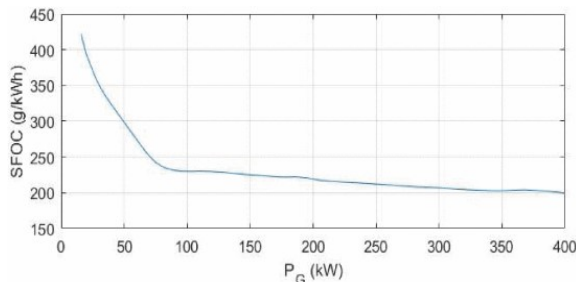


Figure 2: Specific diesel oil consumption for engine Perkins 2506C-E15TAG1 [20]

Hybrid systems are particularly suitable for certain types of vessels that require a large amount of electricity in a short period of time. Ferries and passenger ships are suitable for this type of propulsion due to restrictions on the emission of harmful gases and noise into the environment. Furthermore, tugs operate in navigation regimes that vary significantly in intensity.

Due to the different load profiles, the ship's power plant must be adaptable and able to select the most suitable energy source from several different aspects. In general, the economic aspect of the operation of the vessel is the most dominant, but when the ship is located near urban areas, the impact on the environment becomes most important. In order to achieve optimal use of the energy system, the control mechanism should take into account

the parameters of the energy storage system, the state of charge of the batteries, and daily energy needs [21].

2.2. Electric propulsion vessels

In recent times, more research and development on the application of DC network technology is conducted. The disadvantages of alternating current when compared to direct current are asymmetrically loaded phases, the appearance of harmonics, and reactive power [8]. There are many advantages of direct current application, especially in hybrid systems. On the contrary, the major weaknesses of DC systems are: limited control and switching actions, insufficient system capacity and unavailability of equipment on the worldwide market. Also, DC voltage cannot be step up or step down easily. Electrical storage systems, as most RES, are DC so no additional energy conversion is required. Furthermore, it is not necessary to synchronize the generator units, which allows the exploitation of diesel machines in the most suitable mode of operation [22, 23, 24]. Figure 3 shows the elements of the electric propulsion system.

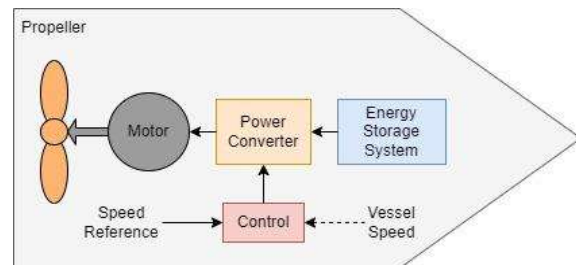


Figure 3: Electric propulsion system elements

Advances in power electronics that are becoming more accessible and energy-effective enable the efficient transmission of electricity to consumers while reducing the weight and volume of equipment required. According to [25] the remarkable advancement in semiconductor electronics is improved capacity and switching speed that leads to improved power control and efficiency. On those grounds, DC networks will soon take lead in certain areas of application. Energy storage or onshore power can be used when the ship is at berth and therefore there are no emissions of harmful gases into the environment (if they are produced from renewable sources) or noise production.

When designing a new vessel power system, various ideas and technologies can be applied in order to achieve the most efficient solution. However, there are a number of limitations to the modernization of existing ships [26]. The designer should consider the possibility of accommodating equipment, the possibility of installing an energy storage system, installation of lower-power generators, considering the investment costs and the time of return on investment.

With standard diesel-mechanical propulsion, the drive machine often operates in an unfavorable mode, especially with certain types of vessels, such as tug boats [14]. By replacing one main engine that directly



drives the shaft with several generators, it is possible to operate the diesel engine in more favorable operating modes. That results with an increase in the reliability of the energy system.

2.3. New maritime technologies applications review

This paragraph presents new trends and technologies aiming to optimize the operation of ship power plant. All these concepts are introducing renewables in order to reduce harmful emissions from ships into the atmosphere. Large global companies involved in the design and construction of ships have presented concepts that predict new ways of building ships. The introduced concepts suggest the way in which modern shipbuilding should be developed with the long-term goal of independence from fossil fuels.

NYK Super Eco Ship 2030

The concept ship has been crafted as a pure car and truck carrier (PCTC) in cooperation with MTI and Elomatic, an engineering and consulting company based in Finland. NYK said the power needed to operate the ship has been cut by 70 percent by remodeling the hull to decrease water friction, reducing the weight of the hull, introducing fuel cells for electric propulsion, and relying on other highly efficient propulsion devices. Instead of fossil fuels, the ship would be powered by solar energy and hydrogen produced from RES, all of which would lead to a reduction of CO₂ by 100 percent and thus result in a zero-emission vessel [27].

B-9 cargo ship

B9 Shipping, part of the B9 Energy group of companies, are developing the ships and have started work on a full-scale demonstration vessel validating the engineering and economic assumptions of the initial vessel design. The initial design featured a 100 metre, 3000 ton cargo carrier with three masts each rising 55 metres. Powered by soft sails and biogas from anaerobic digestion, the ships will optimize naturally available resources to provide efficient and affordable low-carbon shipping [28].

Zero-Emission Ferry Concept

Scandlines has ordered a new zero-emission freight ferry for the Puttgarden-Rødby route. The ferry will be inserted in 2024 and will launch the next generation of ferries on the route. With a crossing time of one hour, the ferry is emission free. It can also be operated as a hybrid ferry and then the crossing time is 45 minutes [29].

Viking Energy, Eidesvik Offshore

In recent years, ammonia has been frequently experimented with as an energy carrier, which is considered by many to be the marine fuel of the future. The Finnish marine technology group Wärtsilä has launched ammonia combustion tests to help the company prepare for the use of ammonia as an

environment-friendly marine fuel. The company is developing ammonia storage and supply systems as part of an ammonia fuel cell installation project on the Eidesvik Offshore supply ship, Viking Energy. The plan is to install a large 2 MW ammonia propulsion cell on the ship by 2023, which will allow it to sail on clean fuel for up to 3,000 hours a year [30].

Propulsion with ammonia as a fuel or energy carrier is easier to use than hydrogen. Ammonia has a higher energy density (energy per unit volume), so it can be more easily stored in a liquid state at a temperature closer to ambient temperature. Also, ammonia contains more hydrogen molecules per unit volume than hydrogen itself, which makes it an excellent carrier of energy [31].

Ammonia as a fuel is toxic and corrosive, so special measures are required for its handling and storage [32]. In order to enable the use of ammonia, it is necessary to build infrastructure that will ensure its storage and delivery to vessels. All safety, environmental and legal requirements (that have not yet been fully defined and should be in line with national and international standards) should be fulfilled. Although the use of ammonia as a marine fuel is a new technology, the Republic of Croatia has over 100 years of experience in the synthesis of ammonia through the company Petrokemija.

Even though decarbonization is a trend pursued by global shipping, there are technological and economical constraints that will affect the application of new technologies in shipping. Although most of the world's trade is conducted by sea, it produces only about 3% of total pollution. However, due to the use of cheaper, lower-quality fuel containing a higher proportion of sulfur, shipping industry makes 13% of total global SO₂ emissions [33].

3. MODEL APPLICATION

Simulation models have become a basic tool in various research areas when designing a particular system. Modeling of the entire system is necessary when a large group of experts is working on the project, each of whom is making a model of a smaller part of the system or subsystem. The energy system is complex and its planning is a demanding process that is constantly evolving and upgrading.

The models use different mathematical algorithms and databases, which allows them to solve the most complex problems in a relatively short time. This enabled the emergence of the so-called E³ models (energy-ecology-economy) which take into account the energy, environmental and economic aspects of the application of a particular solution [34].

The most commonly used mathematical techniques in energy models are linear, integer, and dynamic programming. Linear programming is a mathematical technique based on the principle of maximizing or minimizing a given criterion with given constraints.



Integer programming has developed as an extension of linear programming and is applied to analyzes whose results are integer. Dynamic programming is a method that divides the initial problem into several smaller problems and finds the optimal solution for each of them [35]. Models with stochastic and Fuzzy-linear programming techniques have been used more often in recent times to solve the problem of uncertainty in the values of parameters, data and decision variables (linear program solutions).

3.1. Validation and verification

Simulation models are commonly used to solve certain problems. Researchers and other users of computer models use the results obtained in the decision-making process, so it is crucial that the models and data are accurate. The model is adapted to a specific purpose or area of application and its reliability is determined for a specific area [36]. The applicability of the model should be examined for all possible conditions in which the actual system can be found in order to determine that the model credibly represents a given system. The level of model reliability is a parameter that is determined before or at the very beginning of the modeling process.

There are multiple advantages in the application of computer models in the optimization of marine power plants. However, it is crucial to determine the reliability of the model through validation and verification. Although these two concepts seem to be very similar, in practice they are quite different.

Verification provides an answer to the question of whether the applied algorithms solve the set equations in the correct way, regardless of how accurately they represent the modeled system.

Validation is a process in which the accuracy and reliability of simulation results is determined by comparison with experimental results [37]. Although validation and verification are conceptually different, they are most often performed simultaneously.

It would take too many resources to determine that the model is absolutely reliable in the entire domain of possible applications. Instead, the model is evaluated until the required level of reliability is reached, so it can be said that the model is valid for a given application. Figure 4 shows the relationship between reliability, resources required, and model value for end-user. When a high level of reliability is required, the costs of validation can be significant [35].

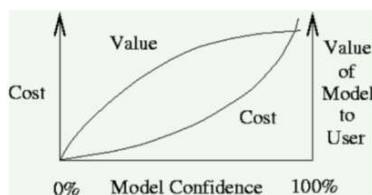


Figure 4: Model reliability

The verification and validation process needs to be carried out throughout the model development process.

The simplest approach is for the development team to make a subjective assessment of reliability based on the output data. A more advanced option would be for the model users themselves to conduct a simulation model evaluation. When it comes to larger models in the development in which a larger number of people participate, it is desirable to include impartial experts who evaluate the model. In this way, the computer model gains credibility. Regardless of the type of validation and verification approach, it is important that it is implemented during the design process to keep model costs as low as possible.

Verification and validation of the model of the existing marine power plant can be done by comparing with the actual results in different operating conditions. If the results match, it can be said that the simulation model represents the real system. Such a validated model can be used to test conditions and parameters that would be potentially harmful for installed equipment and devices in real conditions. If it is a matter of verification and validation of a system that is in the design phase, then other available methods of model validation are used. In choosing the method of validation of the simulation model, there is no unique pattern of which techniques and procedures should be used due to the specifics of each model and the area of its application. However, the most commonly used algorithm is the one that shows the process of software development, Figure 5.

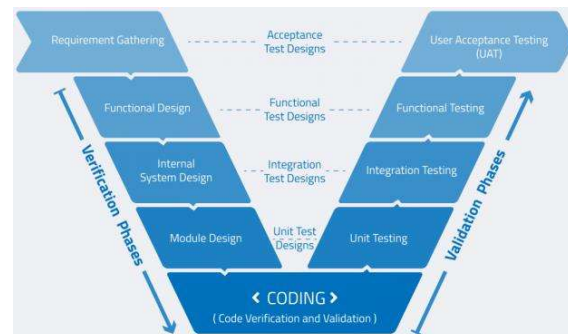


Figure 5: Model validation and verification process [38]

In the process of creating the model, an error occurs due to excessive simplification of the problem, incorrect and unrealistic assumptions, incorrect mathematical formulation, incorrect input data and incorrect commands in the algorithm and because of the selection of inappropriate numerical method. In case the considered model does not meet the conditions of verification and validation, it is necessary to make improvements of the model in order to representatively bring out the actual system. At the end of the verification and validation process, the model should represent the behavior of the real system and as such can be used to conduct tests with a certain level of reliability. If the reliability of the model is high, the model can be used for decision making.

4. CONCLUSION

Because of environmental legislations, the performance of the ship's power plant must be improved. In order to



make ship more environmental friendly while conducting optimization, a comprehensive effort needs to be done. The aim of this review article is to present different approaches to shipboard power plant optimization. It points out the benefits of using hybrid systems and describes the configuration of the power system of an electric vessel. The latest trends in the maritime industry regarding the use of RES were also presented as well as the application of the model and their validation and verification.

The conclusion of this paper is that with introducing new technologies from renewables, battery, propulsion and control system industries can improve ship electrical system and make it more efficient.

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Selection of Renewable Energy Sources on Ships Using Conditional Probability Theory

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Maritime transport has a negative impact on the environment. Therefore, the International Maritime Organization and the European Union have adopted legislation that limits the emission of harmful outputs from ships. The basic way to reduce the negative impact is the application of renewable energy sources. However, renewables are not evenly available everywhere. In addition to the above, not all types of ships are equally suitable for the application of different types of energy. As this is a complex problem, a model based on the theory of conditional probability, i.e. Bayesian networks, was made. The proposed model analyzes the availability of a certain type of energy, the energy needs of the ship and the possibility of the ship as a platform for the installation of the renewable energy system. After conducting an energy and economic analysis, the optimal solution is proposed. As such, it can serve in the decision-making process on the choice of renewable energy source.

KEYWORDS: *renewable energy sources; electrification; model; Bayesian network; decision algorithm*

1. INTRODUCTION

The amount of energy consumed by the shipping industry is increasing rapidly. Consequently, the negative impact on the environment is also increasing. A generally accepted trend is the introduction of renewables. According to (Issa, M., et al., 2022), RES can be used to produce green fuels or directly for propulsion. Furthermore, RES can be applied as part of the modernization of existing vessels or when designing new vessels. Regardless of the type of energy transition method chosen, it should be technically feasible and economically acceptable. By conducting a technical-economic analysis of the implementation of carbon-neutral fuel, it is assumed that it will generate 2-6 times higher costs compared to the conventional drive (Stolz, B., et al., 2022). As the aforementioned analysis is extremely complex, the use of computer simulation models is almost inevitable. The simulation model should be able to analyze various parameters in order to obtain a comprehensive answer on the selection of the most suitable energy source.

In this paper, the use of Bayesian networks BN is proposed. The general structure of BN is extremely flexible, which is why it is often applied in different areas (Marcot B., et al., 2019). Due to their modular architecture, BNs are increasingly used in environmental applications (Serena H., et al., 2012).

In this paragraph, recent examples of the application of BN in the maritime sector are listed. The most important area of application of Bayesian networks is risk analysis related to maritime accidents (Fan S., et al., 2020, Huanhuan L., et al., 2023, Meizhi J., et al., 2020, Yu Q., et al., 2021). In the aforementioned works, risk factors affecting the safety of the crew, ship, cargo and the environment were taken into account. Observing the incidence of adverse events throughout history, significant risks were identified. Furthermore, using BN-based models reliably and accurately predicts the possibility of an incident. The information obtained is used by ship captains with the aim of increasing the level of safety. In the paper (Bayazit O., Kaptan M., 2023), using BN, the probability of the occurrence of an event that can cause environmental pollution was investigated. A model based on Bayesian networks was applied to analyze safety in the transport of electric vehicles by Ro Pax ships.

2. BAYESIAN NETWORK

Thomas Bayes, a British statistician and philosopher, was the first to present a theorem on conditional probability. In his honor, this theorem is called Bayes' theorem. The theorem justifies a way of thinking in which it is stated that truthfulness theories are confirmed by new evidence. This is conditional probability, the probability that one assumption is true provided that the other assumption is true. The main goal of Bayes' theorem is to formalize information about how one event can help in understanding another. The aim is to find the probability of an earlier event, provided that it has occurred later event (Barnett et al., 2006).

The Bayesian network is a graphical model based on probability theory and represents a group of random variables and their conditional dependence using a Direct Acyclic Graph DAG (Neapolitan, R. E., 1989). A DAG consists of a group of nodes that represent variables, while ends represent a probabilistic random dependence between these variables. Accidental dependence between individual variables is expressed with the help of a structure nodes, which provides and supplies the qualitative part of random reasoning in Bayesian Network (BN).

BN consists of three different types of nodes:

- coincidence node – variable nodes that have ends directed towards the nodes called "children" nodes, a nodes that have links starting from them are called "parents" nodes,
- decision/solution node,
- utility/resource node.

Mathematically, Bayes' theorem can be expressed by the following equation (Stuart, A.; Ord, K., 1994):

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad (1)$$

where A and B are events and $P(B) \neq 0$.

$P(A|B)$ is a conditional probability: the probability of event A occurring given that B is true. It is also called the posterior probability of A given B .

$P(B|A)$ is also a conditional probability: the probability of event B occurring given that A is true. It can also be interpreted as the likelihood of A given a fixed B because $P(B|A)=L(A|B)$.

$P(A)$ and $P(B)$ are the probabilities of observing A and B respectively without any given conditions; they are known as the prior probability and marginal probability.

3. PROPOSED MODEL

To select the most suitable RES, a flowchart is proposed that considers various parameters that influence the decision. The decision-making process is shown in Figure 1.

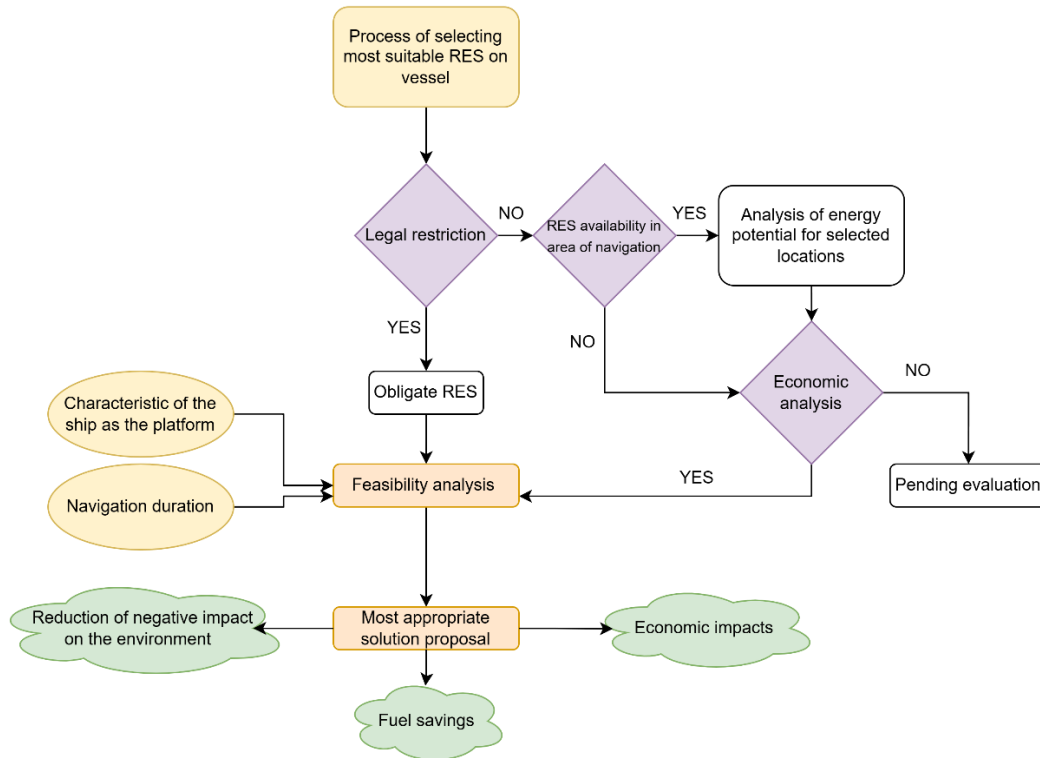


Figure 1. Flowchart diagram of the process of selecting the most suitable RES (Source: Authors)

The legal constraints are the starting point in the flowchart of the proposed model. Namely, there are navigation areas where carbon free zones are imposed, which can only be achieved through the use of renewables. This applies to special environmental areas, for example national parks, special protected areas, and city ports. In this case, an economic analysis is carried out, and regardless of the economic effect, the vessel must make the transition to renewables.

Furthermore, it is necessary to determine the importance of choosing a location that is defined by the energy potential for a specific energy source. Depending on the area of exploitation of the ship, the availability of a certain type of energy can differ significantly. For instance, solar and wind energy are not available at the same intensity in different geographical areas. The availability of electricity charging stations on land is relatively small, and the application is only at local level. Therefore, it is necessary to perform an analysis of the availability of each energy source in relation to the planned operational area of the ship.

When conducting an economic analysis, it is necessary to take into account for each type of RES the total price of the equipment per unit of installed power. However, the price of the equipment is not the only parameter that needs to be considered. The total amount of energy generated by the installed equipment depends on the energy potential hence in certain circumstances more expensive equipment will be more acceptable. There are areas of application where the return on investment in RES is 9 years for photovoltaic modules (Nugraha, I. et al., 2022). Due to the characteristics of the ship and the navigation area, the economic profitability may not be accomplished, thus it is suggested to carry out a re-analysis in the foreseeable future.

This makes a lot of sense due to the continuous increase in the efficiency of the equipment while reducing the price. In addition to the above, due to the price and questionable availability of fossil fuels, the transformation to renewable sources is becoming more and more acceptable.

The most important part of the model is the block for energy analysis, which considers all the parameters that influence the selection of the most suitable RES. Each ship as a platform for the installation of RES has its own specifics and is more or less suitable for the installation of a certain type of RES. For example, a ship with smaller dimensions is not suitable because it has less available space for installing photovoltaic modules, hence the installed system would not be able to generate a significant level of energy. On the other hand, the application of large wind turbines is not suitable on tourist ships.

The energy needs of the ship depend on its size, operational profile and sailing length. Based on the above, the size and type of source and storage of electricity should be adapted to the operating conditions of the ship. After the energy analysis, the model assigns a coefficient (or percentage) of suitability for application to different types of RES. In the case of choosing a specific RES, it is possible to observe the effects of implementation.

Different objective functions can also be defined. Most often, the legal restriction to reduce harmful effects on the environment is the driver for the application of RES. However, with the advancement of technology, certain solutions are economically more profitable compared to the use of fossil fuels, which results in a reduction in fuel consumption.

A model for selecting the most suitable RES based on BN is proposed. There are various software solutions that use BN. Part of the software is based on the Java programming language, for example JavaBayes, jBNC, UnBBayes, Banjo. BNFinder is written purely in Python while bnlearn is part of the R package. In this particular case, the Netica program is used. Netica is a powerful, easy-to-use, complete program for working with belief networks and influence diagrams. It has an intuitive and smooth user interface for drawing the networks, and the relationships between variables may be entered as individual probabilities, in the form of equations, or learned from data files (Norsys - Netica Application).

Proposed model shown on Figure 2. enables the setting of initial conditions specific to a certain geographical area. It is also possible to define the capacities of the ship as a platform for RES accommodation. The energy needs of the ship should be taken into account in order to choose a suitable energy source. In accordance with the mentioned feature, the model selects the most suitable energy source. In Figure 2, the initial conditions do not indicate the characteristics of individual types of RES.

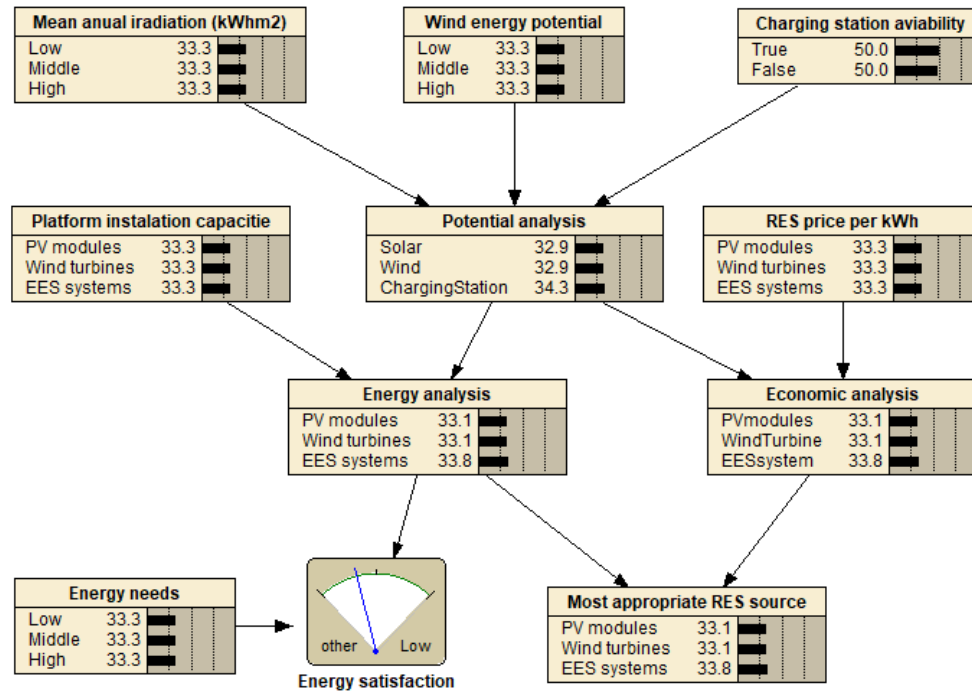


Figure 2. Bayesian network model created in Netica software (Source: Authors)

In accordance with aforementioned, Figure 2 actually presents a Netica model based on BN in which it is possible to discern any outcome, suitable or not. For example, if there is a large wind energy potential, the model will ultimately favor wind energy as RES, as shown in Figure 3.

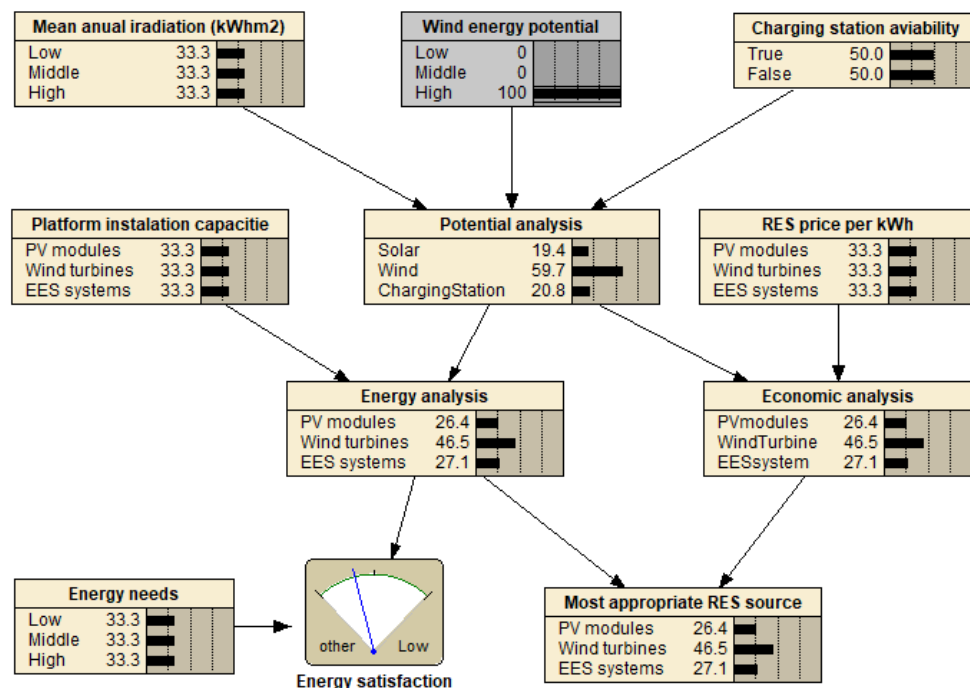


Figure 3. BN model with simulated high wind potential (Source: Authors)

Input parameters of the observed model are Mean annual irradiation, Wind energy potential, Charging station availability, Platform installation capacities, Energy needs, and RES price per kWh. In order for the model to generate accurate and credible output data, it is necessary to quantify and categorize the values that describe certain input parameters. In this process, attention should be taken to ensure that the input parameters are correctly determined so that the model does not favor a certain type of RES. After conducting a potential analysis, energy and economic analysis, the suitability for use in defined conditions is determined for a certain RES. A significant advantage of using BN is that the model can be used in the reverse direction as well. For instance, if we choose the EES system for the outcome, the model will match the input parameters with the selection as shown in Figure 4.

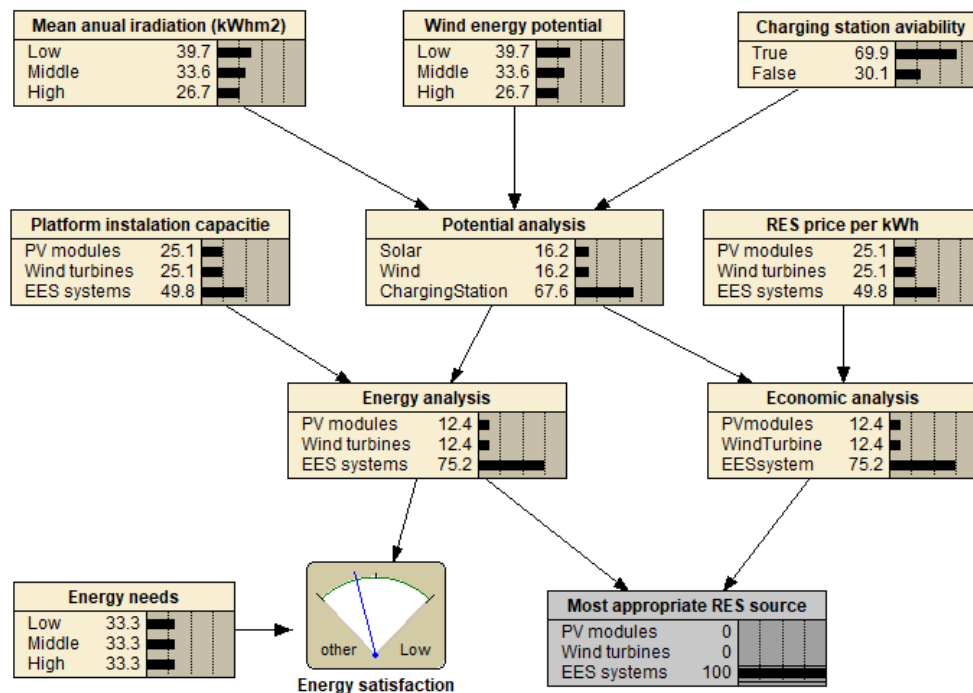


Figure 4. Bayesian Network application in reverse direction – regression (Source: Authors)

4. CONCLUSION

The advantage of using the proposed model is that it considers various parameters that influence the selection of the most suitable renewable energy source. To be functional, the model needs to be adjusted in accordance with the specifics of the energy potential in relation to the geographical position and the navigation area. Moreover, it is necessary to analyze the possibility of accommodating a certain type of energy in accordance with the energy needs of the ship. In future research, the model could be expanded and significantly improved in such a way as to include the flow of the larger geographical area. The limitation of the presented model is that it does not consider the variable input parameters that depend on weather conditions and the time of day, especially related to the availability of solar and wind energy. However, in this case, it is necessary to create a dynamic model that uses an appropriate method to change the input parameters in time and assign new initial values of the Bayesian network. Furthermore, ecological and economic justification can be used as an output variable of the model. The aforementioned variables took into account all aspects of the proposed model with the aim of obtaining an output as to whether the model is ecologically and economically viable.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

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IMPLEMENTATION OF RENEWABLE SOURCES OF ENERGY ON CROATIAN COAST GUARD LOGISTIC SUPPORT VESSEL PT-71

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ABSTRACT

Usage of renewable energy sources is something that modern shipping tends to, therefore naval shipbuilding shouldn't be excluded from it's implementation. This paper shows an example of possible implementation of „green energy“ on logistic support vessel PT-71, that is a part of Coast Guard of Republic of Croatia. It presents the possibility of installation of renewable energy sources and its economic and ecological effectiveness. The system is made of photovoltaic panels, batteries, solar „all in one “inverter and wiring. Considering the possibilities of positioning the photovoltaic panels on ship's outer free surfaces, it is estimated to install 56 panels of total nominal power 9240 W. The features of all other system elements are fitted to photovoltaic panels. The paper specifies costs of acquiring all system elements, and it also considers the costs of installation and maintenance of the entire renewable energy source. Conclusion shows the advantages of applying this kind of renewable energy system on vessels.

Keywords:

renewable energy sources, photovoltaic panel, power network optimization

1. Introduction

The Republic of Croatia has signed The Kyoto Protocol in 1997 and by doing that has obligated to reduce the emissions of greenhouse gases. According to the EU's climate and energy strategy, the reduction of domestic greenhouse gas emissions should be at least 40% below 1990 levels by 2030.

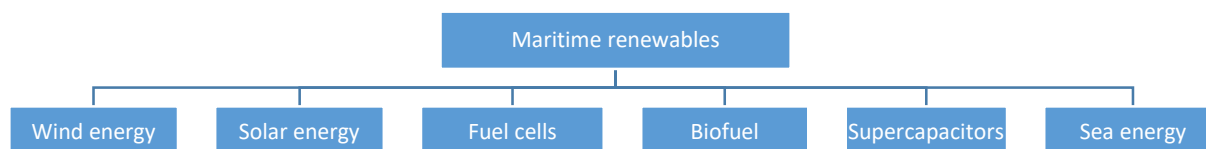
Although the expectations about the reduction of emissions of greenhouse gases globally are encouraging, it is expected that there will be significant increase of pollution in maritime traffic. It is mainly because of two reasons: first one is sort of fuel used and second reason is anticipated increase of maritime transport. Considering the global emissions, pollution from ships takes part about 3% in overall air pollution [1].

2. Sorts of renewable energy sources

Usage of renewable energy sources is something that modern shipping tends to. It is a paradox that two centuries ago wind energy has propelled overseas sailing ships and they have sailed by speed higher than 16 knots without using fossil fuels. Therefore, it is necessary to make the most of existing knowledge to apply renewable energy sources by using currently available modern technologies.

Improvements in the efficiency of naval systems and pollution response solutions should be applied not only to the construction of new ships but also as improvements to existing ships.

Available renewables in maritime are: wind energy, solar energy, fuel cells, biofuel, super capacitors charged by renewables and marine power, as shown on Picture 1 [2].



Picture 1. Available renewables in maritime

Wind energy is in fact a form of solar energy. Wind is a horizontal flow of air that is created by the difference in air pressure on earth. Two main characteristics of wind are its speed and direction. The sun radiates a large amount of energy to the earth every hour, and about 1% - 2% of this energy is converted into wind energy. The sun heats different parts of the earth unevenly, which leads to different air pressure. As a result, wind is created because it tends to balance out.

The amount of wind energy transferred on the wind turbine rotor directly depends on air density, rotor's surface and wind speed [3]. Considering the relatively small dimensions of the ship as a platform for installing wind turbines, possibilities for wind turbine accommodation are limited to smaller wind turbines with smaller nominal power. Pictures 2. and 3. show the concepts of wind energy usage on a ship.



Picture 2. Two ways of wind energy usage; Wallenius Wilhelmsen's E/S Orcelle



Picture 3. Flettner Freighter by C-Job Naval Architects

The sun is the main source of the electromagnetic radiation that penetrates the atmosphere and it is naturally inexhaustible. It gives energy that sustains life, directs the atmosphere and, through various movements, shapes the weather and climate. Since solar energy is a highly acceptable renewable energy source, it could become the most important vehicle for environmentally sustainable energy development in the very near future. For this reason, experts are intensively searching for new ways and methods to convert solar energy into electrical, heating or cooling energy [4]. Pictures 4 and 5 show concepts of solar energy use on ships.



Picture 4. Example of solar energy application on ships; Electric Vehicles Research



Picture 5. Example of solar energy application on ships; MS túranor planetsolar

Fuel cells use hydrogen as fuel, and this process has no negative impact on the atmosphere because the only by-product is pure water. By reacting hydrogen from the fuel cell tank with atmospheric oxygen, chemical energy is converted into electrical energy. There are many examples of the use of fuel cell technology, with the greatest advances being made in the automotive industry. On the other hand, the implementation of this technology in the maritime sector has many difficulties. On the one hand, there is no offshore infrastructure for hydrogen supply. Also the lack of ship space and strong vibrations lead to malfunctions in this type of ship propulsion systems [5]. The advantages of using fuel cells are undisputed, but the future of their application depends mainly on the price of the technology and the availability and price of hydrogen.

Biofuel is a type of energy that was used in internal combustion engines before the invention of cheaper fossil fuels, which replaced ethanol and other plant-based energy sources at the beginning of the twentieth century. Biofuel is made from biomass - organic matter, in most cases plant material, but it can also be of animal origin. Biomass is used to produce biogas, biodiesel, ethanol and dry matter that can be burned in ovens to produce heat or electricity. Biofuel produced from unused waste biomass is an acceptable form of energy, but if biomass is used only for energy production needs, it would certainly have a negative impact on the environment.

Supercapacitors work on the same principles as regular capacitors, but the technology of the production is based on nanomaterials which allows greater surface area of electrodes and smaller distance between them. Supercapacitors have up to 1000 times greater capacity compared to regular capacitors and their power density is much larger than in conventional batteries. Except from small mass, they have other advantages like a large number of charge and discharge cycles and very quick recharge. Given the extraordinary progress made in a relatively short period of time, supercapacitors will certainly play an important role in renewable energy systems.

The energy of the sea includes the energy of the waves, tidal energy, sea current energy, thermal energy and the energy produced by salinity difference [6].

3. Possibilities of applying renewables on ship

International Maritime Organization (IMO) in London have adopted an initial strategy on the reduction of greenhouse gas emissions from ships, setting out a vision to reduce green-house gasses (GHG) emissions from international shipping and phase them out, as soon as possible in this century. More specifically, under the identified “levels of ambition”, the initial strategy envisages for the first time a reduction in total GHG emissions from international shipping which, it says, should peak as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out entirely [7].

The lack of comprehensive information makes it rather difficult to identify precisely the possible advantages of one approach over another.

Although the renewable energy systems are installed mostly on large overseas ships, their appliance is more suitable for smaller ships that operate on shorter relations. There are examples of smaller ships that are already completely independent from using fossil fuels.

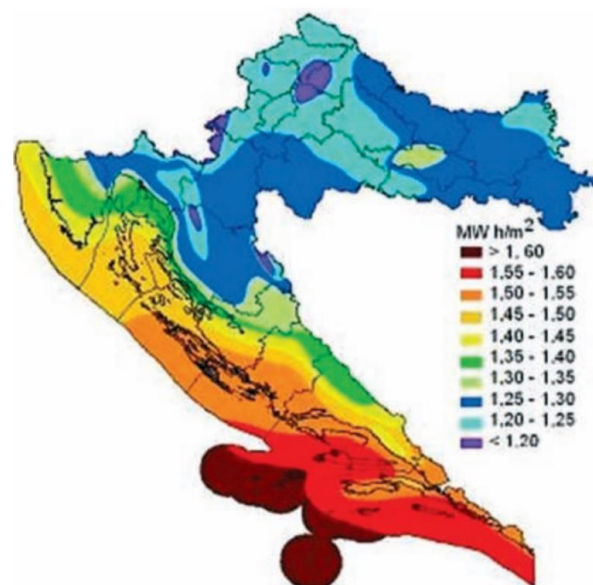
In this paper is presented the possibility of installation of photovoltaic panels on logistic ship PT-71 shown on picture 6. Overall length of this ship is 43,7 m, her width is 8,2 m and her draft is 3,5 m. She is propelled by diesel engine with 684 kW power that allows maximum speed of 10 knots.

The vessel PT-71 is a part of Croatian Cost Guard. The main purpose of this ship is fresh water supply to remote consumer on mainland and on remoted islands. This vessel is chosen because is relatively big horizontal surface suitable for installation of photovoltaic panels.



Picture 6.. Republic of Croatia Coast Guard vessel, PT-71¹

In order to approach the projecting of photovoltaic system it is necessary to know the irradiation of the locality on which the system would be installed. Picture 7 shows the average annual irradiation of horizontal surface (Ljubomir Majdandžić, Fotonaponski sustavi, priručnik).



Picture 7. Average annual irradiation for the Republic of Croatia area

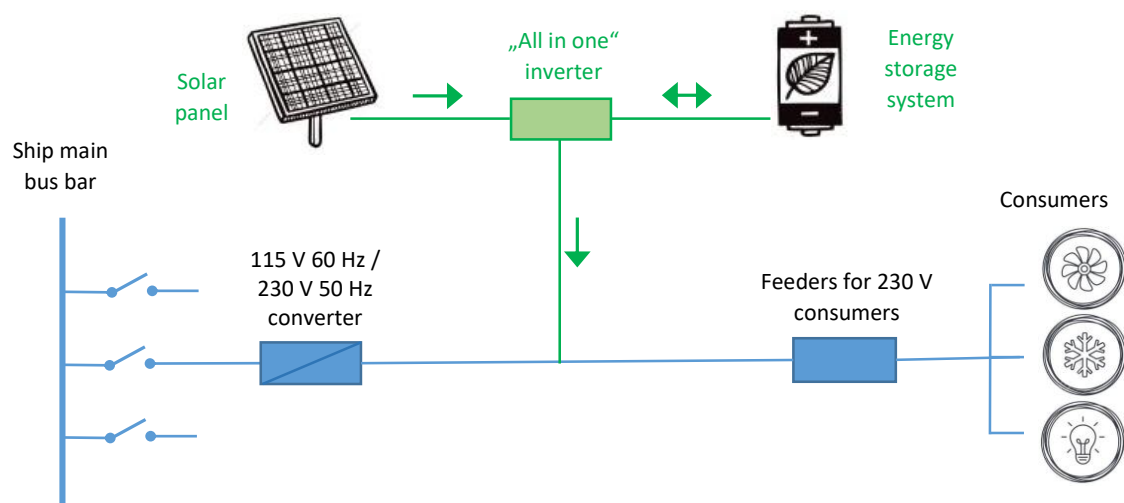
Diesel electric generators are the sources of electric energy on ship that supply all consumers via main control panel. Renewable energy system consists of photovoltaic module, batteries and hybrid “all-in-one” inverter that regulates the electric energy flow. Picture 8 shows the schematic energy flow of renewable energy systems from the source towards the consumers.

The consumers of electrical energy that are supplied from the renewable systems are heating, ventilation and air condition, radio devices, navigational devices and household appliances (refrigerators, irons, TV sets etc.).

Based on network parameters, “all-in-one” inverter regulates the current flow. In periods when there is no sunshine irradiation, consumers of 230 voltage level are supplied by diesel electric generator. When photovoltaic modules produce electric energy they use inverter to supply the consumers. When the production of electrical energy on PV modules exceeds the consumption of consumers, this excess energy is stored in batteries. Energy stored in batteries is used when PV modules stop producing electrical energy.

During the planning of this renewable energy system, losses of all system elements are taken into consideration.

¹ Source: <https://hr.wikipedia.org/wiki/PT-71>



Picture 8. Electrical energy scheme

Table 1. shows the expenses of all parts of the system. Costs of the purchase, implementation and maintenance of the whole system of the renewable energy sources have been taken into consideration. Certain elements of the system are chosen based on independent reviews without favoring certain manufacturer.

Total expenses of the purchase, implementation and maintenance of the system during the period of 25 years of exploitation is 61 204 €. Considering the annual production of 10 700 kWh, this system should generate 267 500 kWh in the period of 25 years. The price of the kWh generated from the renewable energy system in the observed period is 0,2288 €/kWh. The cost of the electric energy produced by the photovoltaic panels is less than half the price of the energy produced by a diesel electric generator. The price of certain elements of the system is available on the official websites of the manufacturers, while the cost of maintenance is based on estimated costs, taking into account the experience gained in the maintenance of marine electrical systems.

Table 1. Expenses of all parts of the system in €.

No.	Item	Total expenses of purchase	Maintenance expenses (25 years period)	Total expenses
1.	PV panel Rigid 165W	24 610	2 100	26 710
2.	Battery Trojan Spre 12225Ah (three sets)	18 136	2 000	20 136
3.	Inverter IMEON 9.12	4 358	5 000	9 358
4.	Installation	2 000	3 000	5 000
	TOTAL	49104	12 100	61 204

CONCLUSION

Although the economic and environmental aspects of naval shipbuilding are not a priority, much more effort should be made to design new ships and also to modernize existing ships to make them more environmentally friendly. The use of renewable energy sources is suitable for use on logistics vessels and on Coast Guard ships. This paper shows the example of possible implementation of photovoltaic panels on Croatian Coast Guard logistic ship. The cost of the electric energy produced from the photovoltaic panels is more than two times cheaper compared to the price of the energy produced by diesel electric generator. Implementation of the presented system encourages all companies that participate in the production, installation and maintenance of renewables. This way of renewable sources application can be adapted on any other vessel considering its specific characteristics and limitations.

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Article

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

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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 CO₂ emitter, representing 3–4% of total EU CO₂ emissions [2]. The monitored journeys emitted, in 2019, over 144.6 million tons of CO₂ 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.

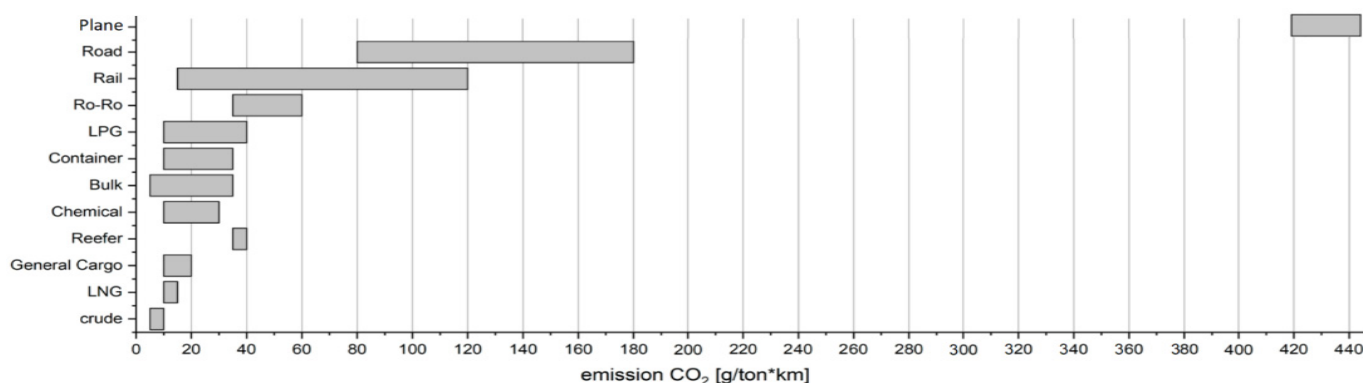


Figure 1. Illustration of CO₂ emission in the environment depending on the means of transport (adjusted from [4]).

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:

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

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]:

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

where:

$f_{eff(i)}$ -availability factor of individual energy efficiency technology,

$P_{eff(i)}$ -main engine power reduction due to individual technology for mechanical energy efficiency,

C_{FME} -CO₂ emissions main engine composite fuel factor,

SFC_{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 1. Overview of wind and solar energy applications.

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

Wind-Rotor sails	[30]	Evaluations from the long-term test on board of MV Fehn Pollux	Savings in the range of 10–25% can be expected, depending on the speed of the ship and main engine performance	10–25%
Wind-Rotor sails	[31]	Performance test is conducted on a Maersk Pelican tanker	On certain routes, during the trial, the vessel achieved fuel savings way beyond the average of 8.2% even with average wind conditions.	8.2%
PV modules	[32]	Experimental tests on the Car carrier Auriga Leader	The solar power system produced 1% of its electrical usage	<1%
PV modules	[33]	Experimental tests on the Car carrier Berge K2	About 100 kW of electrical energy is fed into the main electrical grid	-
PV modules	[34]	Performance test is conducted on a passenger ferry Blue Star Delos	PV technology and energy storage provide a continuous stable supply of a DC load	-
PV modules	[35]	Performance test Kawasaki Drive Green Highway	About 150 kW of electrical energy generated from PV modules contributes to other measures to reduce 25% or more of CO ₂ emissions	-
PV modules	[36]	Experimental test on vehicle carrier COSCO Tengfei	540 PV cells are installed on a ship with a maximum output power of 143.1 kW under standard conditions	-

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.

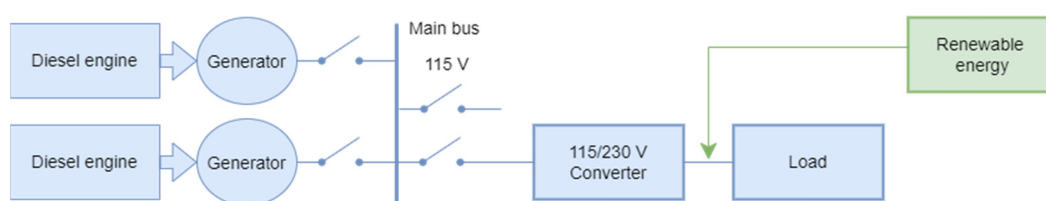


Figure 2. Schematic diagram of power distribution to implement.

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 2. Electricity balance [38].

No.	Consumer	Power	No.	Consumer	Power
1.	ME pre-lubrication pump electric motor	0.65 kW	9.	Electric winch motor	4.04 kW
2.	General service electric pump motor	10 kW	10.	Rotary converter for radio devices	0.9 kW
3.	Fuel transfer pump motor	3.65 kW	11.	Static converter	1.5 kW
4.	Bilge pump electric motor	1.84 kW	12.	Three-phase transformer	25 kW
5.	Air compressor electric motor	11.2 kW	13.	Single-phase transformer	3 kW
6.	Freshwater pump electric motor	0.73 kW	14.	Silicon rectifier	1 kW
7.	Engine room fan motor	0.55 kW	15.	Electric stove	14.5 kW
8.	Electric windlass motor	11 kW	16.	Rotary converter 220 V	10 kW
In total					99.56 kW

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:

$$\eta_T = \eta_G \cdot \eta_{RCM} \cdot \eta_{RCG} = 0.9 \cdot 0.9 \cdot 0.9 = 0.729 = 72.9\% \quad (3)$$

where η_T -total efficiency, η_G -generator efficiency, η_{RCM} -rotary converter motor efficiency, η_{RCG} -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.

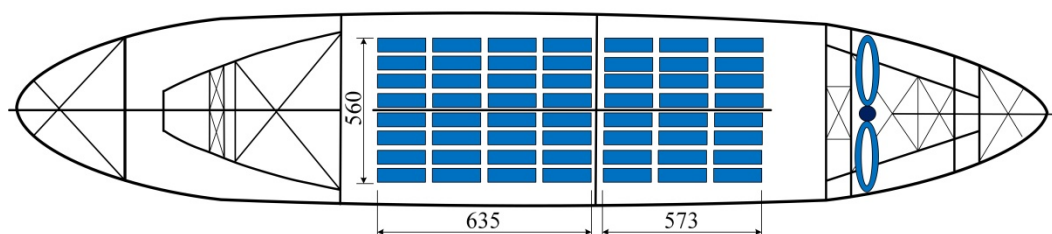


Figure 3. Schematic illustration of the location of the PV modules and a wind turbine (the stated dimensions are in cm).

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 3. Costs of all solar system elements are shown in €.

No.	Name	Price Per Unit	Total Procurement Costs	Maintenance Costs (Period of 25 Years)	Total Costs
1.	PV panel Nature power Rigid 200W [41]	440	24,640	280	24,920
2.	Battery Trojan Spre 12,225 Ah (three sets) [46]	517	31,020	270	31,290
3.	Converter IMEON 9.12 [47]	4359	4359	700	5059
4.	Installations	2000	2000	400	2400
	In total		62,019	1650	63,669

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, Anemoi 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 €.

No.	Name	Price per unit	Total procurement costs	Maintenance costs (period of 25 years)	Total costs
1.	L-10kW Generator& Blade	3867	7734	1300	9034
2.	Controller & load-dump	657	1314	300	1614
3.	Full Sine-wave Converter	1256	2512	600	3112
4.	Guy Wire Tower	749	1498	300	1798
5.	Production of foundations and cable trays	6700	6700	250	6950
6.	Battery Spre 12225Ah (three sets) [46]	518	31,020	270	31,290
7.	Installations	1300	1300	400	1700
In total			52,078	3420	55,498

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.

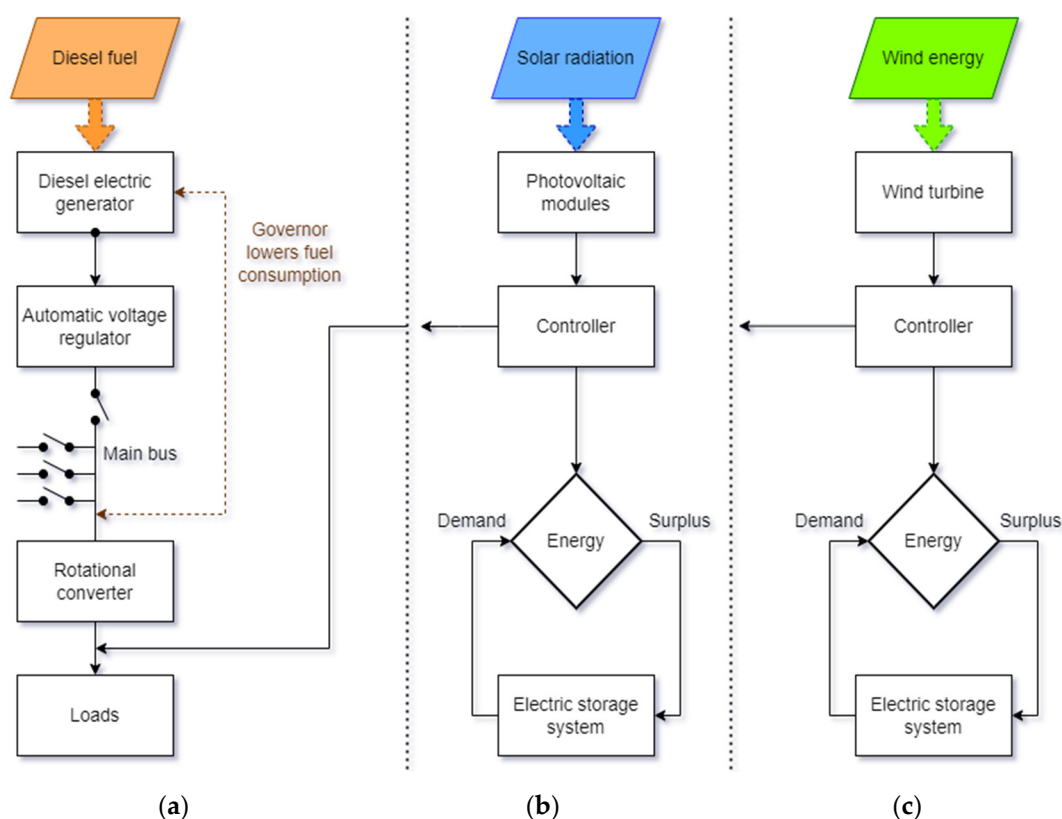


Figure 4. Hybrid energy system scheme; (a) schematic diagram of the existing ship's power system, (b) implementation of solar energy, and (c) implementation of wind energy.

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).

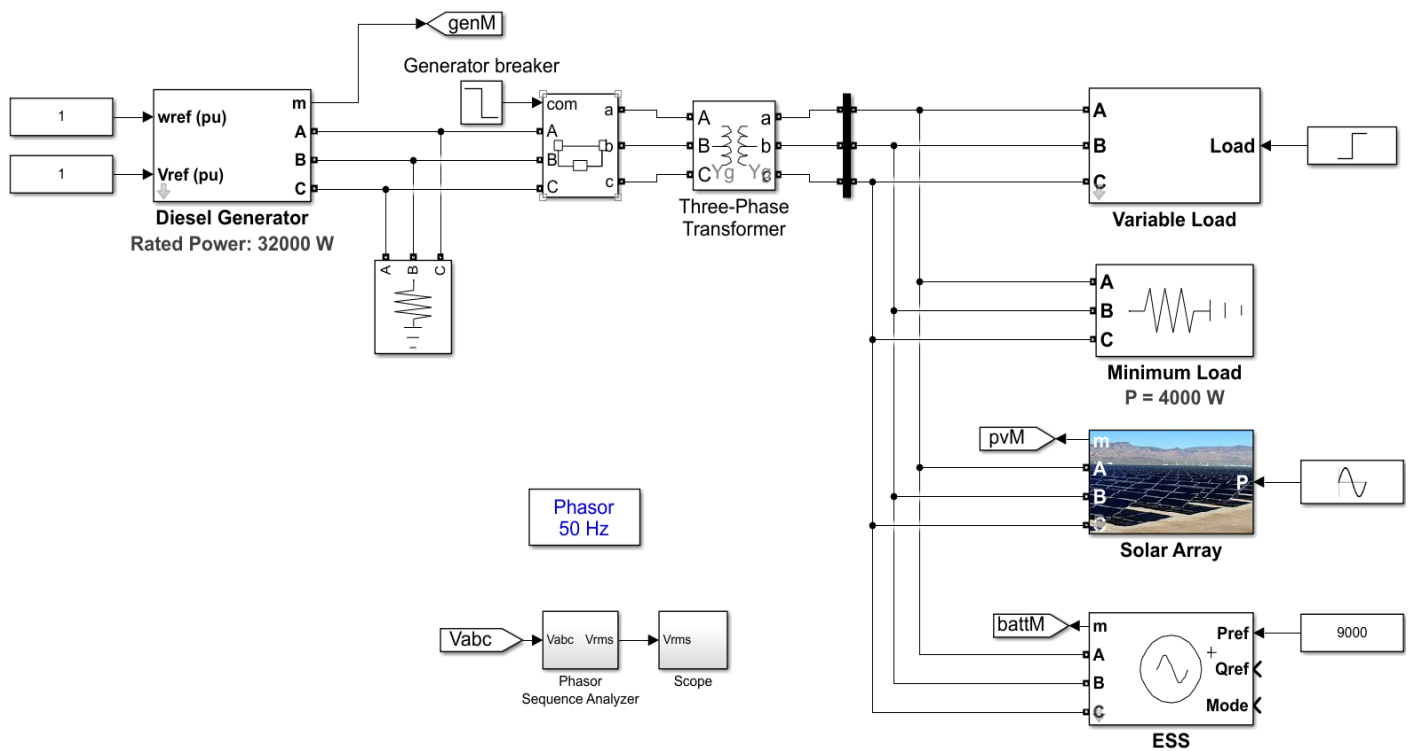


Figure 5. A simulation model created in the Simulink with the blocks' input/output connections.

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.

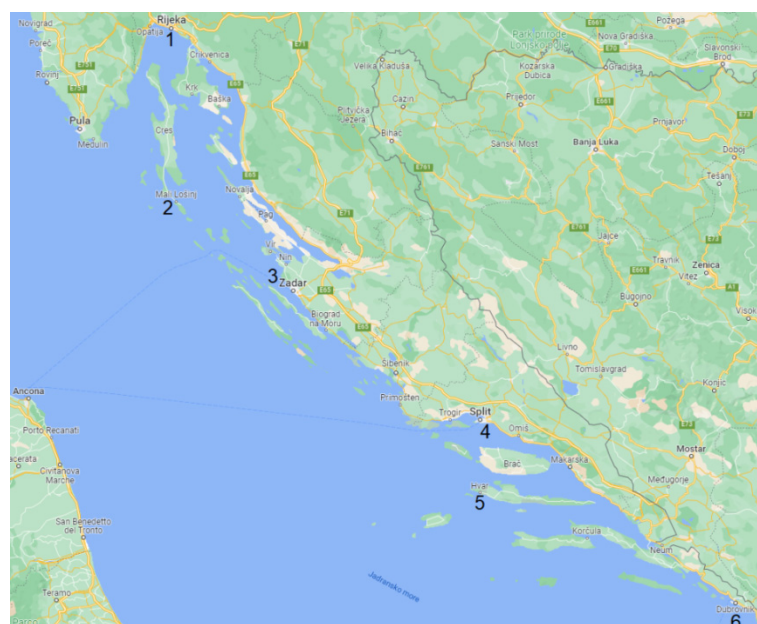


Figure 6. Six investigated locations on the Croatian side of the Adriatic Sea [57].

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.

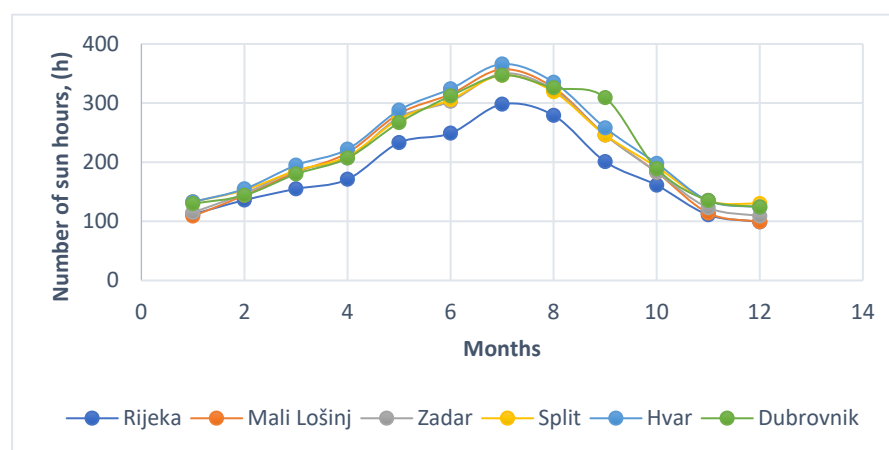


Figure 7. Graphical presentations of a variable number of sun hours for six locations at the Adriatic Sea.

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

	Months	Annual	MIN	MAX	AVERAGE	MEDIAN	STD
Number of sun hours	Rijeka	2205	99	298	184	166	68
	Mali Lošinj	2574	99	357	215	200	90
	Zadar	2567	109	350	214	197	84
	Split	2630	130	347	219	201	78
	Hvar	2733	124	366	228	210	85
	Dubrovnik	2670	124	347	223	198	85
	Min	2205					
	Max	2733					
	AVG	2563					
	STD	186					

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/m^2) at 10 m above ground [58]. Wind speed and wind power density atmospheric numerical model shows an average value in a grid cell of $2\text{ km} \times 2\text{ km}$. 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.

	Location	(m/s)
Basic wind speed	Rijeka	25.8
	Mali Lošinj	25.6
	Zadar	22.9
	Split	25.4
	Hvar	25.7
	Dubrovnik	25.2

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 ± 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.

Pearson Correlation Coefficients	Rijeka	Mali Lošinj	Zadar	Hvar	Split	Dubrovnik
Rijeka	1					
Mali Lošinj	0.994	1				
Zadar	0.996	0.999	1			
Hvar	0.995	0.999	0.999	1		
Split	0.996	0.997	0.998	1.000	1	
Dubrovnik	0.964	0.971	0.975	0.975	0.975	1

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.

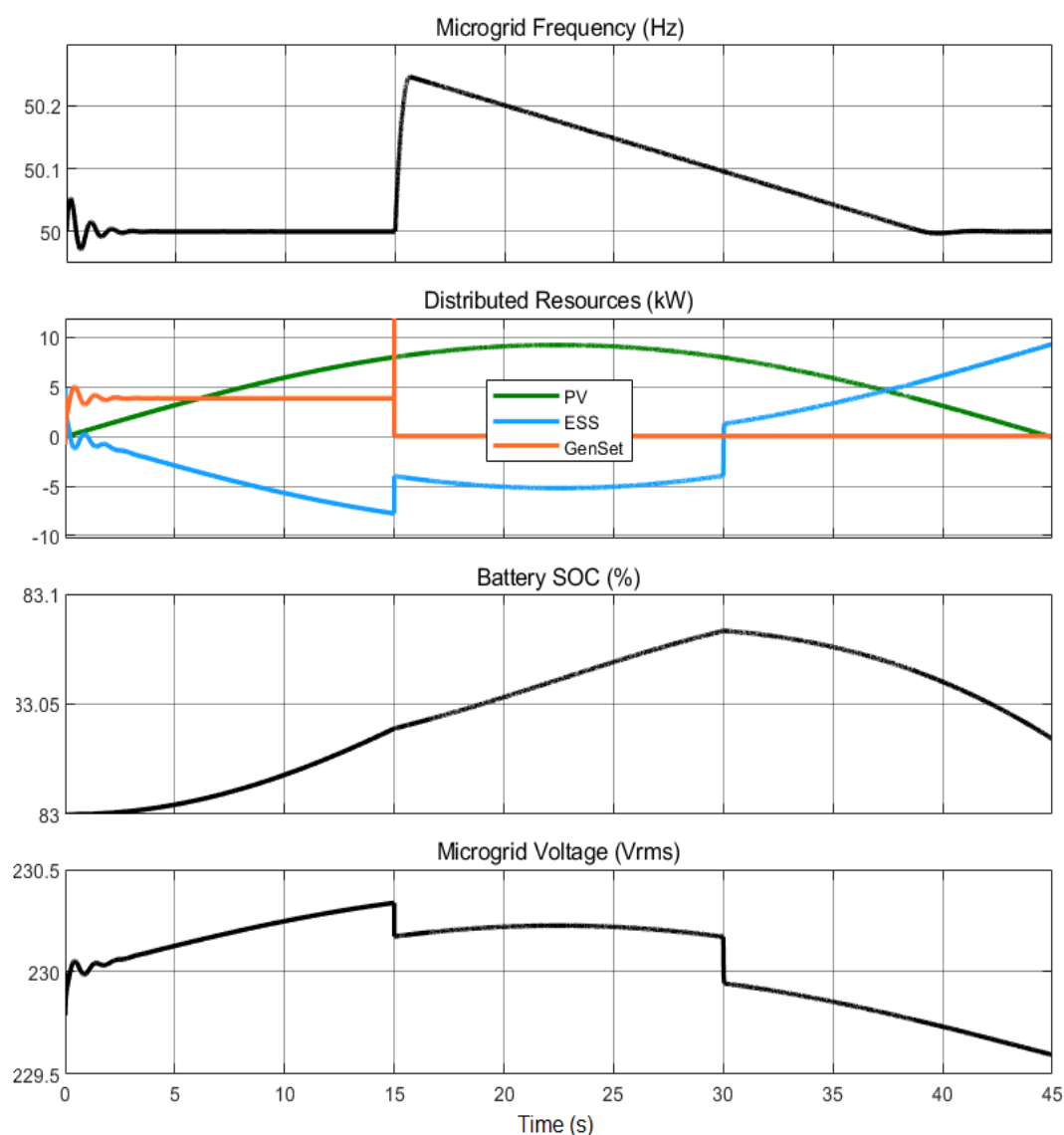


Figure 8. Real-time system response.

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° and azimuth of 0° , 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 8. Comparative presentation of the application of solar and wind energy.

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

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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Article

Electric Ferry Fleet Peak Charging Power Schedule Optimization Considering the Timetable and Daily Energy Profile

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Abstract: Decarbonization of shipping is a legal obligation imposed by the International Maritime Organization (IMO). The ferry port and daily operations located near or in urban zones negatively impact the nearby environment. The electrification of ferries contributes to reducing the negative environmental impact. The available electrical infrastructure in ports often does not meet daily needs. The ferry fleet's sailing schedule creates a non-periodic daily energy profile to determine the energy needs of the shore connection. The proposed research aims to optimize the daily electric ferry fleet peak charging power schedule process using particle swarm optimization and a greedy algorithm. A four-stage model has been proposed, consisting of the initialization of the ferry fleet's daily energy profile, initial population generation with input constraints, optimization, and the creation of the modified daily energy load diagram. Robustness and validation of the proposed model were investigated and proven for energy profiles with and without optimization. For the proposed charging schedule, the study results show a reduction in peak power of 24%. By optimizing the charging process, peak charging power has been reduced without needing an additional energy storage system.

Keywords: charging optimization; ferry electrification; particle swarm optimization; renewable energy sources



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1. Introduction

Fossil fuels represent an unfavorable energy source for a ship's propulsion and have an environmental impact. Also, due to the increase in the price of marine fuel and the questionable possibility of obtaining it, this method of operation is becoming less and less competitive from an economic point of view. Although the awareness of the public and interest groups on this issue is at a high level, the current contribution of the world's ship-ping green fleet is negligible. According to [1], only 6.52% of global ships' fleet can be powered by alternative fuel.

The possibility of applying a certain type of alternative energy depends on various parameters. It is necessary to consider the economic, ecological, technical, and social aspects of the application of each individual type of energy. Energy availability is one of the most important factors when conducting a technical feasibility study. In the paper [2], a multi-criteria analysis was conducted to select a suitable fuel type. All stakeholders involved in the research assessed the sustainability of maritime transport. The work strongly promotes the use of electric propulsion. Electric propulsion requires a large amount of electricity, which can be obtained from renewable energy sources (RESs) or battery storage.

Renewable sources of electricity are used in a whole range of ships. However, considering the size of the vessel and the energy needs of a typical ferry fleet, the contribution of the self-produced electrical energy to power the ship's propulsion system is practically negligible [3]. The electricity produced could be used, for instance, for lighting or other low-consuming needs of the ship's power system. Therefore, it is necessary to ensure adequate charging of the ship's electrical energy storage system (ESS) to power its propulsion from the shore. From an ecological point of view, such a model is justified only if the electricity of the terrestrial power system is produced from RESs. The revised Renewable Energy Directive EU/2023/2413 raises the EU's binding renewable target for 2030 to a minimum of 42.5%, compared to the previous 32% target [4]. Although a significant number of scientific papers and studies research the possibility of electrification of ships, particularly ferries, the performance of the charging ships' electrical ESSs has not been sufficiently investigated. This is especially pronounced if a group of ships using a common port of call is observed. This research aims to optimize the ferry fleet's peak power charging process, considering the time available and daily energy profile.

The main scientific contribution of this paper is the creation of the applicable model based on particle swarm optimization (PSO) and greedy algorithm methods that optimize the peak charging power of the ferry fleet, considering the timetable and daily energy profile without using additional sources and electricity storage.

The remainder of the paper is organized into the following sections. The related work is described in Section 2. In Section 3, the proposed research and the methodology are presented. The Section 4, describes the PSO in general and the mathematical background of the applied algorithm. The Section 5, presents the experimental set-up of the proposed model. The Section 6, presents the obtained results. Furthermore, the proposed model has been tested for robustness and validated. Finally, the Section 7, presents conclusions of the proposed research and its future perspectives.

2. Related Work

Various techniques and methods are used to optimize the energy system of different transport technologies. However, the most commonly used are particle swarm optimization (PSO), deep learning (DL), genetic algorithm (GA), fuzzy logic (FL), multi-objective optimization (MOO), mixed integer linear programming (MILP), and petri network (PN) [5,6].

In paper [7], the PSO is used to optimize the charging and discharging process of the composite ESS of a fuel cell ship under maneuvering conditions. The amplitude of the voltage fluctuation is reduced, the power quality of the marine power grid is improved, and the battery service life is extended. The same method is used in research [8] to optimize the ESS size efficiently and enable the stable operation of the fuel cell ship. Another example is the schedule optimization of drone routes to prevent collisions during charging flights [9]. The presented methodology achieves good results in optimizing the drone charging schedule. Further, the paper [10] proposes a novel energy management strategy for a ship's solar–diesel hybrid generator system and fully considers the ship's efficiency. By applying the PSO algorithm, reduced fuel consumption and greater efficiency were achieved in the operation of the ship generator. Paper [11] proposed a multi-objective random black-hoe PSO algorithm for an optimal peak load shaving strategy aiming to achieve the best peak load shaving effect with the minimum electricity cost for the charging schedule of EVs and battery ESSs. The PSO method was used in paper [12] with the aim of minimizing operational costs considering capital costs, maintenance costs, as well as the performance and system size of a hybrid freight train. A modified multi-objective PSO was used in paper [13] to optimize the size of renewable energy systems. The function goal was to minimize losses and energy prices.

In paper [14], the GA is utilized for location optimization of electric vehicle charging stations. A proposed algorithm for the optimal distribution of charging stations is presented to reduce investment costs. A DL-based optimization scheduling method is proposed for the ship power system, generator, and ESS [15]. The cost function correlates the dynamic optimization scheduling decision of energy with the goal of economy. The paper [16] uses an improved FL to achieve an optimal output power distribution and online control. The object of optimization is the hybrid power system with multiple power sources on a tourist ship. The MILP model with discrete time is employed to find the optimal number of batteries, docking stations, and locations to make the vessel's demand effectively powered by electric energy [17]. A model based on MILP is used to minimize the total cost, which includes charging costs, the construction cost of charging stations, and the fixed cost of ships [18]. Optimization was achieved using a cost-efficient and environmentally friendly service network for electric ships. Paper [19] proposes a PN scheduling framework model of the automated guided vehicle to optimize vehicle scheduling.

The optimal schedule of charging samples of electric vehicles and buses is mainly carried out to minimize charging costs [20,21]. The cost is minimized so that the electric ESS is charged when the price of electricity is lower at a certain period of the day. The paper [22] proposes using smart control of the battery ESS in the harbor area. Due to the limited capacity of the shore connection and the non-periodic need for electricity, the use of a land-based ESS is suggested, which ensures a stable and reliable supply of electricity to ships. Peak loads of the port infrastructure arise due to cargo handling, ship consumption, and the needs of the port itself. The energy management system can be optimized by predicting the consumption schedule at a particular time [23].

By studying the presented literature, it can be concluded that optimizing the charging process in the port of call of the ferry fleet is technically justified and necessary. Such optimization can reduce the peak power load on the energy infrastructure of the shore connection.

3. The Proposed Research

In this chapter, the proposed research will be presented. First, an optimization task will be presented. Then, it will be followed with methodology.

3.1. Optimization Task

The objective function of this optimization task is to reduce the amount of peak charging power while not dealing directly with other time slots. The amount of peak power is an important parameter when designing energy infrastructure. In the proposed research, the optimization was carried out on the ferry fleet that uses the port of Split as one of the ports of call [24]. Observing a four-year period, two days with maximum peak power demand were extracted and analyzed [25].

3.2. Methodology

Figure 1 shows the flow chart for creating the model. The proposed model is divided into four stages. Stage 1 represents the initialization of the model in which input data are collected and processed. The input parameters primarily represent the sailing schedule and each ferry's calculated daily energy needs. In stage 2, the procedure of creating the initial population and the particle was carried out, considering the defined constraints. In stage 3, the optimization was performed, and the particle's movement was achieved. In the last stage of the model, stage 4, a modified daily energy load diagram is displayed. A modified diagram determines the savings in reducing the required peak power.

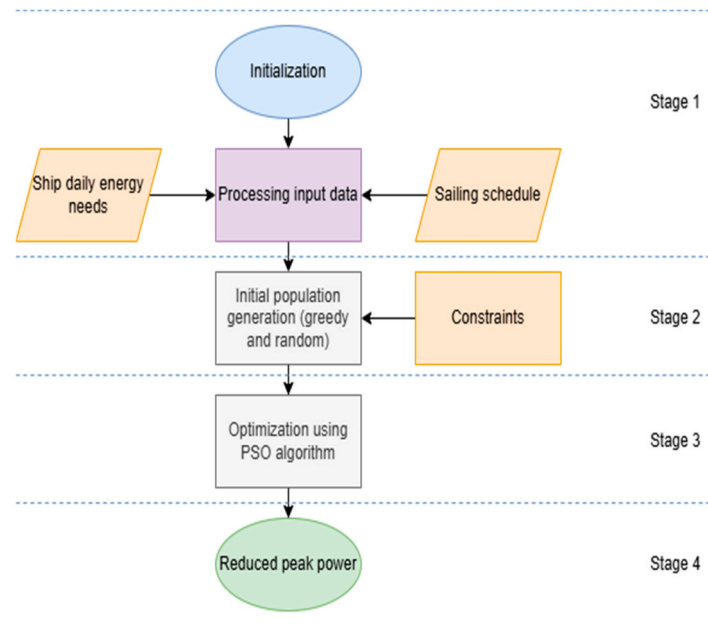


Figure 1. Flow chart of the proposed model.

3.3. The Second Stage—Initialization

Figure 2a shows the flow diagram of the initialization procedure of the initial population (Stage 2). Furthermore, Figure 2b shows the last phase of the initialization process. The mentioned particles are combined to create the initial population.

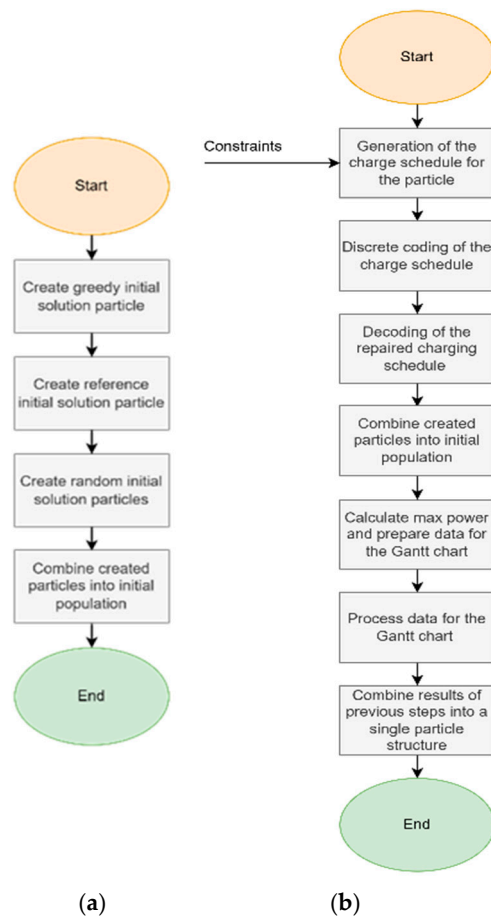


Figure 2. Diagram flow of the initialization stage: (a) Population initialization, (b) Creation of a particle.

The pseudo-code of the initialization procedure of the initial population is shown in Algorithm 1.

Algorithm 1 Initialization of the population

```

population = []
best_particle = NIL
for i = 1..n do
    if (i == n-1)
        particle = create_special_particle()
    else if (i == n)
        particle = create_greedy_particle()
    else
        particle = create_particle()
    end if
    population[i] = particle
    if (particle[i].power > best_particle.power)
        best_particle = particle
    end if
end for

```

3.4. The Third Stage

Figure 3a shows Stage 3 and illustrates the process of optimization and movement of the particle as described in the presented flowchart. The third stage represents the most complex part of the model. The specific steps in the flow chart of the optimization process include the following:

- Particle swarm movement is done in every iteration.
- After every change, local and global minima are updated.
- If a set number of iterations has not been reached, the process is repeated, or the algorithm ends.

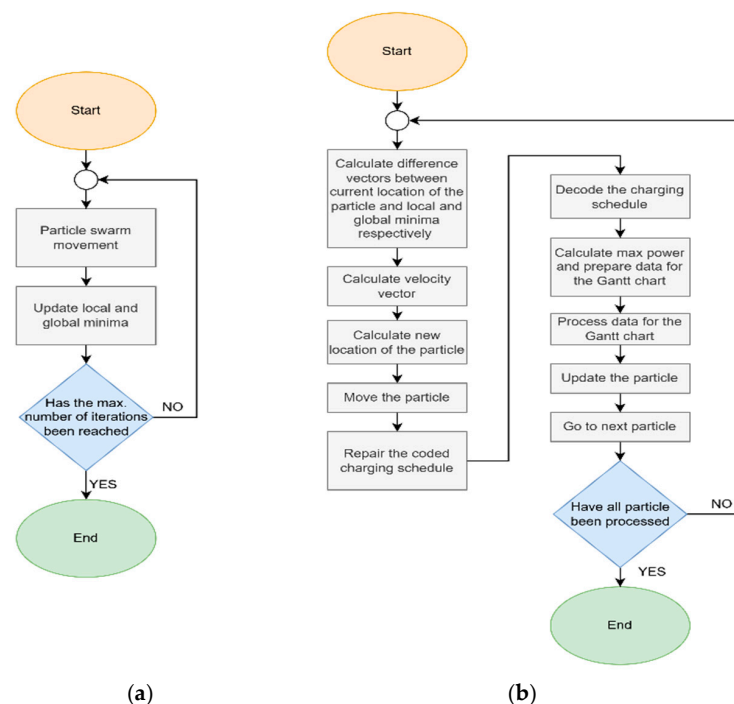


Figure 3. Diagram flow of third stage: (a) Optimization, (b) Particle swarm movement.

The specific steps in the flow chart of particle swarm movement are shown in Figure 3b. The pseudo-code of the optimization stage is shown in Algorithm 2.

Algorithm 2 Optimization

Input: max_iter, population, pop_size, best_particle

Output: population, best_particle, max_power

for i = 1..max_iter do

 population = move_particle(population, best_particle, pop_size, parameters)

 for j = 1..pop_size to

 population[j].min = update_local_minimum(population[j])

 if(population[j].min < best_particle.min)

 best_particle = population[j]

 end if

 end for

end for

max_power = best_particle.power

4. Materials and Methods

4.1. Mathematical Background of PSO in General

PSO is a technique proposed and developed by engineer Russell C. Eberhart and psychologist James Kennedy [26]. PSO is a random search optimization algorithm based on cluster intelligence and inspired by the behavior of flocks of birds. In this nature-based algorithm, individuals are referred to as particles and fly through the search space, seeking the best global position that optimizes a given problem [27].

All possible solutions are initialized into a group of particles characterized by position, velocity, and fitness values. The position of each particle represents a potential solution to be optimized, the particle's velocity represents the direction and distance of the particle's movement, and the fitness value of the particle can be calculated according to the objective function. The optimal value of the individual and the optimal value of the population are calculated while the velocity and position of the particle are updated. The algorithm stops when it reaches the maximum number of iterations or the particle's position is less than the given threshold value. Compared to other optimization algorithms, PSO has high accuracy and increased problem-solving speed and is easy to use [28]. Due to the abovementioned advantages, it is often used to manage and optimize energy systems.

The velocity $\vec{V}_t$ and the position $\vec{x}_t$ of each particle in the swarm is represented by d -dimensional vectors. They are defined by the individual and the collective knowledge in each iteration. Collective knowledge influences the flight trajectories of the particles over the space of possible solutions. The search stops when optimum criteria are fulfilled. The velocity d -dimensional vectors in every iteration, t , is updated according to the following equation [29]:

$$\vec{V}_{t+1} = \vec{V}_t + \varphi_1 R_{1t}^i \left(\vec{p}_t - \vec{x}_t \right) + \varphi_2 R_{2t}^i \left(\vec{g}_t - \vec{x}_t \right) \quad (1)$$

where φ_1 and φ_2 are two real acceleration coefficients known as cognitive and social weights, respectively; $\vec{p}_t$ and $\vec{g}_t$ are the personal best of particle i at iteration t ; and R_{1t}^i and R_{2t}^i are uniformly distributed d -dimensional random vectors. The position of each particle i , at every iteration t , varies according to the following equation [30]:

$$\vec{x}_{t+1} = \vec{x}_t + \vec{V}_{t+1} \quad (2)$$

The global best solution is formally defined as follows:

$$\hat{y}_t \in \left\{ \overset{\rightarrow}{\rho}_t^1, \overset{\rightarrow}{\rho}_t^2, \dots, \overset{\rightarrow}{\rho}_t^s \right\} \mid f(\hat{y}_t) = \min \left(\left\{ f\left(\overset{\rightarrow}{\rho}_t^1\right), f\left(\overset{\rightarrow}{\rho}_t^2\right), \dots, f\left(\overset{\rightarrow}{\rho}_t^s\right) \right\} \right) \quad (3)$$

where $\hat{y}$ represent the position of the best or target particle in the entire swarm in a d -dimensional space.

Furthermore, the Poisson distribution was used to form possible solutions in discrete signals because the normal distribution does not describe the phenomenon. Since such a distribution in such a complex problem can hardly find a local and global optimum for certain conditions, a higher priority is given using the greedy algorithm. The greedy algorithm is used to solve the problem to give a local optimum at each stage, intending to find the global optimum [31].

Due to their high efficiency, they are a suitable choice for implementing various optimization tasks [32]. The initial greedy algorithm prioritizes the ship whose current energy needs are the highest in amount. Thus, a greedy algorithm reduces the required number of iterations and uses particles to achieve the global optimum.

However, in the case of a problem in which the peak charging power of several ships with similar energy needs connected to the network simultaneously is optimized, the influence of the greedy algorithm is restrained. Following the above, the proposed program code can be described as a hybrid algorithm that uses PSO and a greedy algorithm.

The proposed hybrid model uses greedy particle swarm optimization (GPSO) advantages. Greedy algorithms make locally optimal solutions at each iteration, trying to reach a global optimum. GPSO combines PSO and greedy algorithms to generate test data effectively. It aims to minimize the number of iterations while maintaining good area coverage. Compared to genetic algorithms (GAs), GPSO outperforms in terms of average iterations, execution time, and coverage percentage [33]. GPSO leverages the strengths of PSO and greedy approaches, making it a promising candidate for solving complex problems.

4.2. Mathematical Background of the Proposed Model

Step 1. The particle contains a large number of data, the most important of which is the “encoded particle” matrix. This matrix is made up of the analyzed ships that represent the rows of the matrix and the associated time intervals that represent the columns of the matrix. Based on the entry table of the sailing schedule, the state in which the ship can be in terms of loading is determined. When the ship is not available for charging, it is assigned a mark of “−1”. When it is available for charging and is not being charged, it is assigned a mark of “0”. When it is being charged, it is assigned a mark of “1”.

The schedule matrix “encoded particle” size $m \times n$ in which m represents number of ferries and n number of time slots is defined as follows:

$$N_m = \{1, \dots, m\}; N_n = \{1, \dots, n\}$$

$$M = \{M_{ij}, i \in \{1, \dots, m\}, j \in \{1, \dots, n\} : M_{ij} \in \{-1, 0, 1\}\} \quad (4)$$

The input matrix of the daily sailing schedule, the state in which the ship can be in terms of charging, is created by introducing the auxiliary f function with the following equation:

$$f : \{1, \dots, m\} \times \{1, \dots, n\} \rightarrow \{-1, 0, 1\} : f(i, j) = \begin{cases} 1 & \text{if ship } i \text{ charges in interval } j \\ 0 & \text{if ship } i \text{ is in port and not charging in interval } j \\ -1 & \text{if ship } i \text{ is not in port in interval } j \end{cases}$$

$$M = \{M_{ij} : i \in N_m, j \in N_n, M_{ij} = f(ij)\} \quad (5)$$

Step 2. Function f translates pairs of natural numbers in which the first value is between 1 and m and the second is between 1 and n , into a number from columns $-1, 0, 1$. The change in matrix position is defined as follows:

$M_{k-1}^{g*} \dots$ the best global schedule in previous iteration ($k - 1$)

$M_{k-1}^{l*} \dots$ the best local schedule in previous iteration ($k - 1$)

$M_{k-1} \dots$ actual particle schedule in previous iteration ($k - 1$)

Step 3. The difference in the global optimum (in our case, minimum) is calculated as follows:

$$\Delta M_g = M_{k-1}^{g*} - M_{k-1} \quad (6)$$

The difference in the local optimum is calculated as follows:

$$\Delta M_l = M_{k-1}^{l*} - M_{k-1} \quad (7)$$

Step 4. Relative differences in power between the actual schedule and global optimum are calculated as follows:

$$\varepsilon_g = \frac{P_{k-1} - P_{k-1}^{g*}}{P_{k-1}} \quad (8)$$

Step 5. Relative differences in power between the actual schedule and local optimum are calculated as follows:

$$\varepsilon_l = \frac{P_{k-1} - P_{k-1}^{l*}}{P_{k-1}} \quad (9)$$

Step 6. The probability of a schedule change is calculated, i.e., displacement to global and local optimum in which $p_{d,g}$ probability of displacement toward global best and $p_{d,l}$ probability of displacement toward local best, is calculated as follows:

$$p_{d,g} = w_g \cdot \frac{P_{k-1} - P_{k-1}^{g*}}{P_{k-1}} \quad (10)$$

$$p_{d,l} = w_l \cdot \frac{P_{k-1} - P_{k-1}^{l*}}{P_{k-1}} \quad (11)$$

where w_g represents the global weight and w_l represent local weight.

Step 7. The PSO algorithm's weight factors are important parameters controlling the particle's movement [34]. A higher weight factor increases the possibility of searching for a particle so that it leaves the area of the local optimum. On the other hand, a lower weight factor increases the capabilities of the particle in local search [35]. Using calculated probabilities and differences in actual position and global and local optimum, global and local velocity matrices are calculated, respectively, as follows:

$$V^g = p_{d,g} \cdot \Delta M_g \quad (12)$$

$$V^l = p_{d,l} \cdot \Delta M_l \quad (13)$$

Step 8. Attribute: In the places in which the actual position matrix and matrix of global and local optimum, respectively, do not differentiate, the velocity matrix component is equal to 0.

$$V^g = w_g \cdot \frac{P_{k-1} - P_{k-1}^{g*}}{P_{k-1}} \cdot (M_{k-1}^{g*} - M_{k-1}) \quad (14)$$

$$V^l = w_l \cdot \frac{P_{k-1} - P_{k-1}^{l*}}{P_{k-1}} \cdot (M_{k-1}^{l*} - M_{k-1}) \quad (15)$$

Step 9. Global and local velocity matrix are combined into a single velocity matrix:

$$V = V^g + V^l = w_g \cdot \frac{P_{k-1} - P_{k-1}^{g*}}{P_{k-1}} \cdot (M_{k-1}^{g*} - M_{k-1}) + w_l \cdot \frac{P_{k-1} - P_{k-1}^{l*}}{P_{k-1}} \cdot (M_{k-1}^{l*} - M_{k-1}) \quad (16)$$

Step 10. A new location matrix dimension $m \times n$ with randomized numbers between 0 and 1 is formed based on the following rule:

$$M_k = \{M_{ij}\} : \begin{cases} M_{ij} = 0 & \text{if } s_{ij} < |V_{ij}| \text{ and } V_{ij} < 0 \\ M_{ij} = 1 & \text{if } s_{ij} < |V_{ij}| \text{ and } V_{ij} > 0 \\ M_{ij} = M_{k-1,ij} & \text{otherwise} \end{cases} \quad (17)$$

5. Experimental Setup

As stated in the optimization task, considering the available daily timetable, the goal is to optimize peak charging power due to terrestrial power network limitations. In this case, we consider the example of the largest Croatian city on the coast of the Adriatic Sea. Namely, the majority of consumers in the area of the city of Split are supplied via the “Dobri” and “Sućidar” transformer stations (TS) with an installed capacity of 2×40 MVA each. Furthermore, the maximum measured peak load of the “TS Dobri”, to which the City Port of Split gravitates, is 102% [36]. Within the City Port of Split is “TS Trajektna luka” with an installed power of 0.63 MVA and “TS Jadran ribolov” with an installed power of 0.5 MVA. Even if the losses and needs of all other consumers of the City Port of Split are ignored, the existing connection does not meet the peak energy needs of the ferry fleet.

Nine ferries take part in the national lines that dock at the City Port of Split and are operated by Jadrolinija. The daily energy load diagram of the analyzed ferry fleet is presented in Figure 4. The daily energy load diagram is derived from [24,25,37,38]. The y -axis represents the required power in MW. The figure shows nine ferries with the required daily energy diagrams. The x -axis represents the time period of a day in which ships are available for charging. It has to be noted that the continuous time interval was sampled into discrete signals as 5-minute intervals within 24 h, representing one day. The 5-minute time slots were implemented as the maximum possible interval to present the sailing schedule concerning departure and arrival times. Also, maximum intervals of 5 min were chosen to reduce the number of possible combinations. Observing the daily energy needs load diagram, it is evident that it is non-periodic.

Further, as noted in the figure, “Ferry 6” (marked yellow) has the highest daily energy needs, and it docks shortly at the berth twice daily (from 9:15 to 10:15 and 17:00 to 17:30). However, the other ships, like “Ferry 5” (marked red), are available four times at the Split port docks, are easier to charge, and have the lowest charging priority. Furthermore, for instance, at $t = 10:00$, the current load is 2.594 MW, almost 5.5 times higher than the average daily load (0.477 MW). At the observed moment, the peak load is the sum of the power required to charge the ship’s ESS for six berthed ships that are available to charge.

In the process of creating a model, the following limitations are applied:

- The ship docking schedule is shown in Figure 4 and represents the examined case, i.e., it is given;
- The availability for recharging a ferry that spends the night on the ship’s mooring in the port of call is a limitation. If the ship spends the night, it is treated as one charge within the same day because the reference period is 24 h. This limitation of the algorithm can be explained by the example of “Ferry 4” (marked orange) in Figure 4.

Namely, the ship docks at the port the previous day at 22:00 and remains on the dock until 01:30 in the morning. The algorithm model treats this charging as one;

- Each ship is charged with constant power at all intervals during charging. This setting is important not to exceed the batteries' maximum charging current. Fast charging accelerates the battery's aging process and can ultimately lead to permanent damage [25];
- The charging interval is five minutes;
- If two or more ships are available for charging, at least one ship must be connected to the charger to reduce the number of variations;
- Each ship's daily energy needs must be met during charging;
- It is assumed that all docks are equipped with an adequate charger.

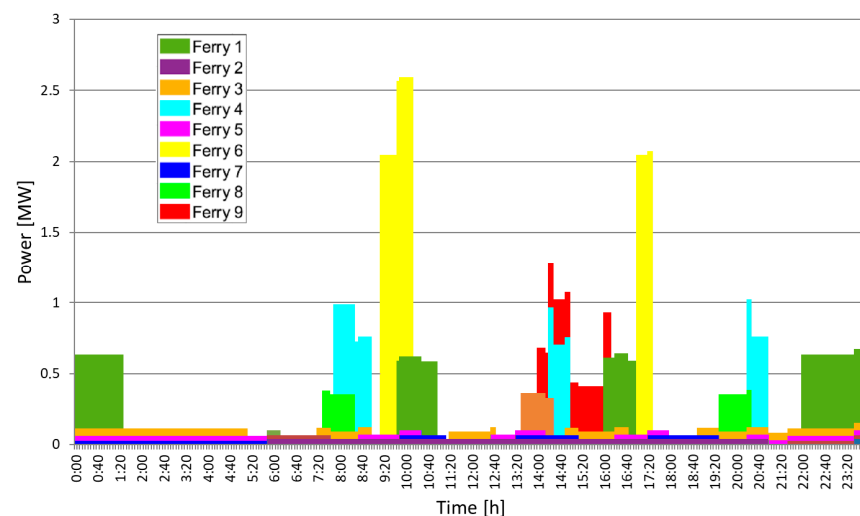


Figure 4. Display of the daily analyzed fleet energy load diagram.

The model was developed using MATLAB R2023b. A Dell OptiPlex 5080 computer with a built-in Intel® Core™ i5-10500 CPU 3.10 GHz, 8 GB RAM, 64-bit operating system, and Windows 11 Pro was used. The basic simulation settings are shown in Table 1.

Table 1. The basic simulation settings.

Parameter	Value
Number of particles	1024
Max number of iterations	1000
Global weight w_g	0.4
Global weight w_l	0.3

6. Discussion

During the experiment, two different scenarios were analyzed. In Test 1, the charging schedule is optimized to match the condition of the actual sailing schedule in the high season (during the summer). Test 2 was conducted to investigate the robustness of the model. In this case, the charging schedule was optimized when “Ferry 6” is excluded from the daily energy profile.

6.1. Test 1—Real Sailing Schedule

Optimization can be achieved by setting a priority when charging individual ships. Certain ferries (“Ferry 6”, “Ferry 2”, and “Ferry 4”) shown in Figure 4 are available for a short time to replenish the battery storage. As a rule, a short time implies a high intensity

of the required power. The rest of the fleet is available for charging for a longer period of the day, i.e., more time spent on the berth.

An optimized charging schedule (Figure 5) was created using the proposed hybrid model on the sailing schedule, considering the daily energy needs. The time intervals during which the ship is charged are marked with a different color for each ship. Furthermore, the timeline is marked in black when the outbound ship is available for charging and disconnected from the land connection. For instance, “Ferry 5” (interval marked red) is available for charging from 5:30 to 20:15 and 22:50 to 23:20. Since “Ferry 6” has the charging priority, between T1 and T2, “Ferry 5” and all other ferries are disconnected from the charging station (interval marked black). In Figure 5, the time intervals T1 and T2 correspond to the peak loads of the daily energy profile shown in Figure 4. Disconnecting an individual ship from a charger results in a proportional increase in charging power in the remaining lots available. The increase in charging power is distributed over the entire charging interval equally due to the technical limitation related to the maximum amount of charging current under the nominal capacity of the ESS.

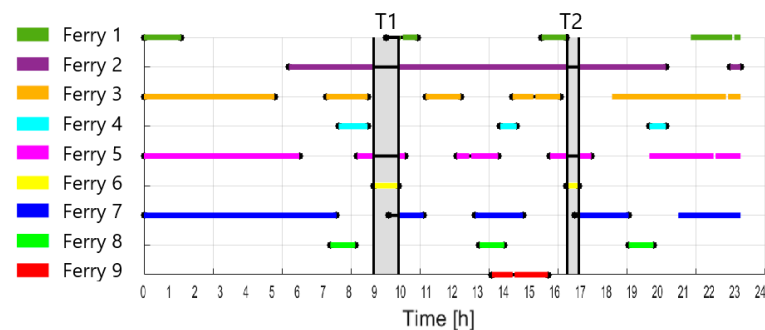


Figure 5. The optimized ship’s charging schedule.

After applying the proposed method, Figure 6 shows the new optimized daily profile of electric energy consumption required to charge all ships’ ESS following the generated new ship charging schedule. It has to be pointed out that the maximum charging power of the fleet of ships at the moment $t = 10:00$ was 2594 MW without the optimization algorithm. The peak charging current was reduced to 1974 MW using the PSO and greedy algorithm. The original amount of power is 31.4% higher than the newly created optimized power. Such a reduction relieves the energy infrastructure. Further, the transition to RES greatly reduces the economic costs associated with constructing the power network system [39].

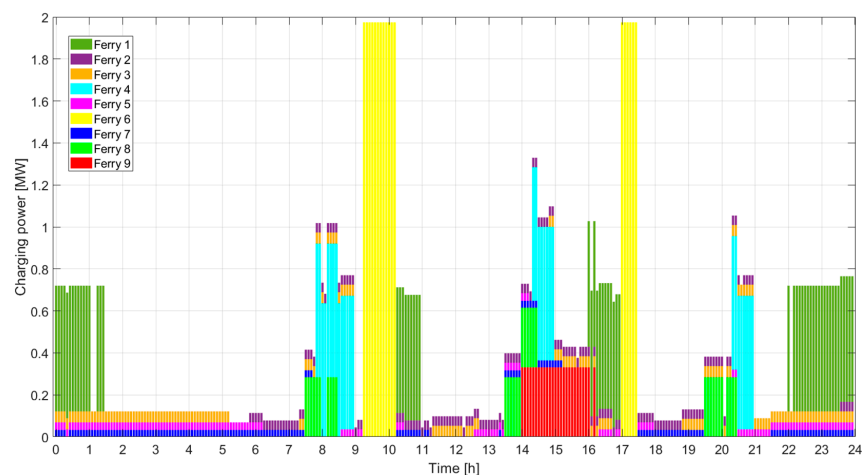


Figure 6. Modified daily energy load diagram (Test 1).

The optimization results in the previous optimization task were predictable because one ship (Ferry 6) significantly contributes to the consumption profile. Therefore, a reduction in the required peak power is achieved by giving priority to such a consumer and simultaneously disconnecting others from the network. At the end of the interval in which each ship is available for charging, the ship's energy needs are fulfilled so each ship can operate the sailing line according to the proposed schedule.

6.2. Test 2—Robustness Test

However, to investigate the robustness and the possibility of application in different exploitation conditions, the model was tested in conditions where several identical consumers are connected to the power network at the same time. This was achieved by setting the energy needs of the most important consumer, “Ferry 6”, to zero.

A number of iterations has been used as a metric to quantify the robustness. It is observed that in the newly created charging powers diagram, a relatively large number of iterations are used to achieve a local and, ultimately, a global minimum.

If in the process of optimizing the daily power diagram (eq., interval T1), when charging the priority ferry, the charging of disconnected ferries is transferred to other intervals of ferries availability. If no new optimization problem arises after optimization, it is referred to as a global minimum or an optimal solution. Otherwise, it is called a local minimum or sub-optimal solution.

The optimized daily energy profile is shown in Figure 7. From the figure, the proposed model reduced peak power from the initial 1.08 MW to the optimized 0.86 MW, i.e., a 20% reduction in the required charging power. Further, the global minimum was reached in iteration number 402. In this particular test, the greedy algorithm does not participate in optimization since more consumers of similar characteristics are connected to the network at the same time.

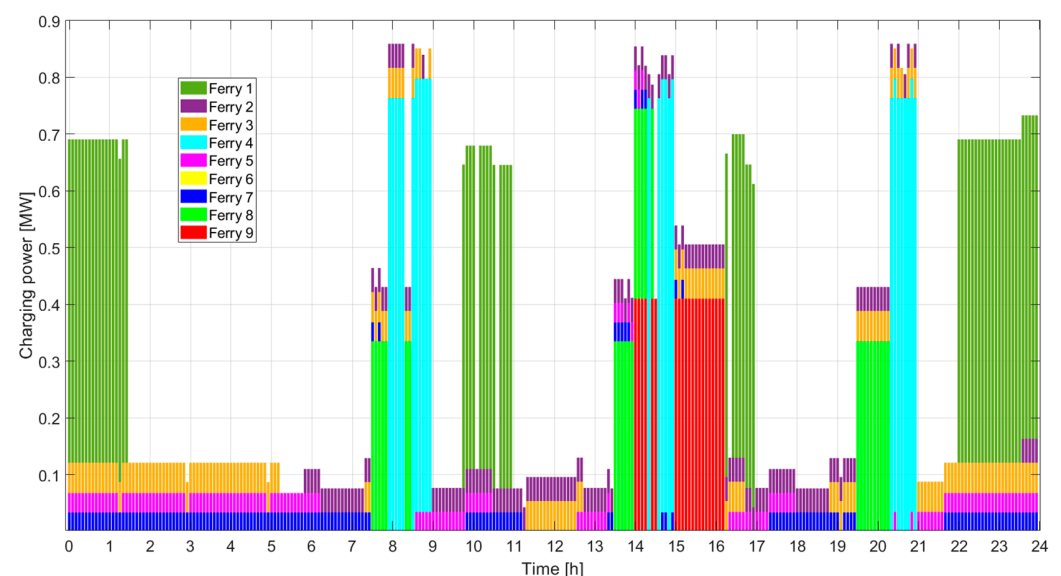


Figure 7. Modified daily energy load diagram without “Ferry 6” (Test 2).

It is important to note that the optimization results remain unchanged when running several consecutive simulations with unchanged settings.

6.3. Optimization Analysis

The required number of iterations was compared with the achieved reduction of the required peak charging power. Investigating this relationship shows the complexity of the optimization as well as the performance of its implementation. The obtained results can be

compared according to different criteria. For most objectives, the global optimum solution increases with the number of particles since more particles can explore the same space in more detail compared to a smaller number of particles. Therefore, the function can find an optimum before the initially set number of iterations is achieved. However, the increased number of particles implies that each iteration is more complex.

Furthermore, the situation becomes even more complex for dynamic environments where each possible solution interacts with each other and influences the searched space. Namely, the dynamic environment changes the searched space in each iteration. Theoretically, the global optimum can also change in each iteration. The newly created solution may be less favorable than the previously established global optimum. Therefore, a larger number of iterations are required to achieve the function's objective when using dynamic functions. As the environment constantly changes, the space is searched in more detail by increasing the number of particles. Consequently, the process itself takes longer. For instance, when the number of iterations is set to 1000, the data processing time takes 6 min compared to 104 min when the number of iterations is set to 20,000.

A special emphasis was placed on determining the relationship between the required number of iterations and the savings in the required charging power. The aforementioned optimization task is described in Figure 8, which shows the relationship between the required number of iterations to converge in the global minimum as a function of the daily energy needs of "Ferry 6."

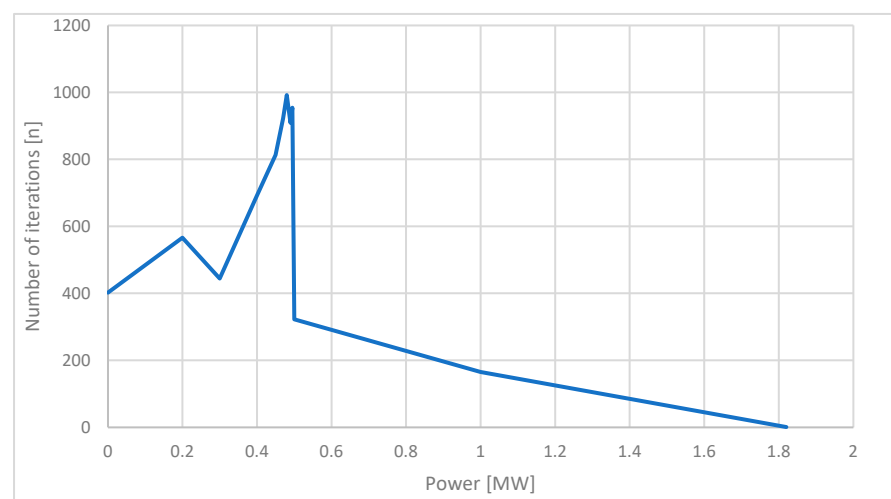


Figure 8. Dependency of the required number of iterations to achieve the minima concerning the daily energy needs of "Ferry 6".

From the figure, it can be observed that the number of iterations required to achieve the objective function depends on the daily energy needs of an individual ferry. When the daily energy needs of "Ferry 6" are approximately 0.5 MW, there is a situation where several ferries of similar power are connected to the charger at the same time. In that case, the optimization is complex, and the optimization effect is reduced. When analyzing the proposed optimization model, three different energy states of "Ferry 6" were considered when energy needs are set to 0 MW, 0.48 MW, and 1.82 MW, separately.

One parameter was observed as a variable, namely the daily energy needs of "Ferry 6", with all other constant parameters. The graph shown in Figure 9 depicts the state where the needs of "Ferry 6" are equal to 0. In this case, the algorithm optimizes the energy needs of the other eight ships connected to the charger and thus reduces the required peak charging power by 20%. The largest peak power reduction was achieved at the very beginning of the optimization, and the global minimum was achieved in iteration number 402.

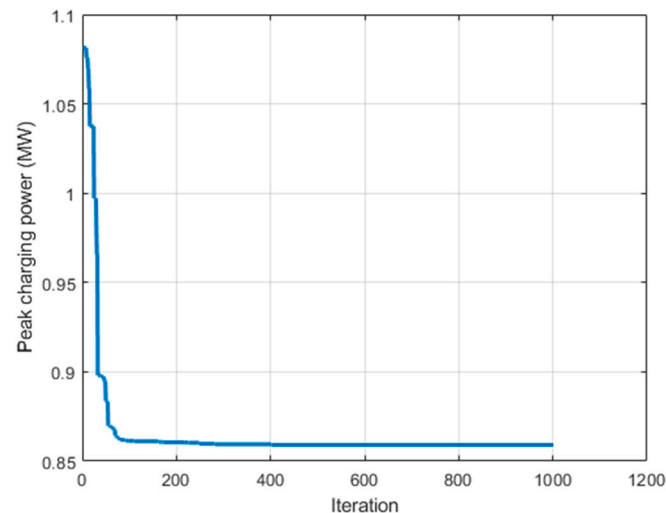


Figure 9. Convergence history when the energy requirements of “Ferry 6” are equal to 0 MW.

Furthermore, Figure 10 shows the optimization process when the daily energy needs of “Ferry 6” are 0.48 MW. The stated amount is selected because it is approximately equal to the energy needs of all other ships at peak load. It must be pointed out that the optimization procedure is complex in such a situation. During the 1000 iterations, a 0.76% decrease in peak power is achieved.

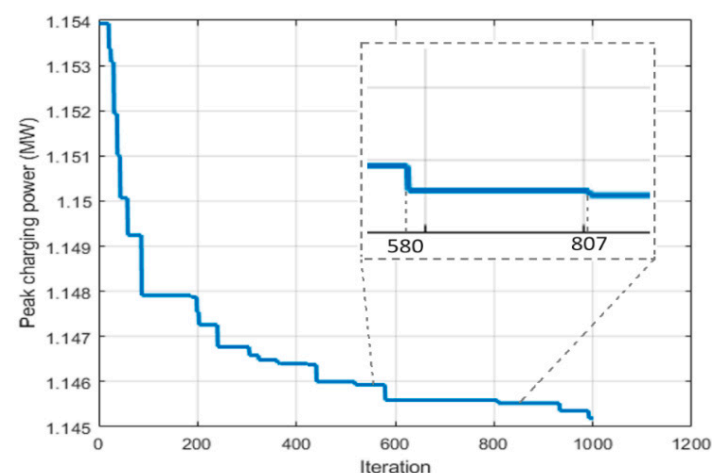


Figure 10. Convergence history when the energy needs of “Ferry 6” is equal to 0.48 MW.

Particularly interesting is the interval from iteration number 580 to iteration number 807 highlighted in Figure 10 as there is no decrease in the objective function. In this interval, the algorithm analyzes solutions where each new one generated is inferior to the previously achieved function minimum. Due to the complexity of the optimization problem, the global minimum is achieved eventually in iteration number 992. When the number of iterations is set to 20,000 at a power of $p = 0.47$ MW, the global minimum is finally achieved in iteration number 13,119. However, the reduction in required peak power when the number of iterations is set to 20,000 versus 1000 iterations is 0.00074%.

Figure 11 shows the relationship between peak power reduction and the number of iterations when the ship’s daily energy needs are 1.82 MW. It has to be pointed out that the stated power represents realistic daily energy needs. In this case, the greedy algorithm preferentially favors the ship with the highest energy needs while disconnecting all others from the shore connection. As the difference in the charging power ratio is expressed, the minimum was achieved in the first iteration, while the achieved reduction is 24%.

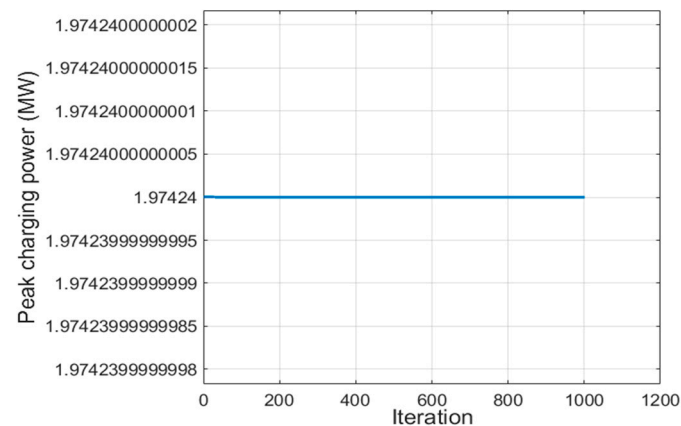


Figure 11. Convergence history when the energy needs of “Ferry 6” is equal to 1.82 MW.

The output of this optimization problem is a reduction in the peak power required to charge a certain number of ships.

The effect of the optimization depends on the number of ships, their energy needs, and mostly the sailing schedule. Figure 8 shows the required number of iterations to achieve the minimum of the function while adhering to all constraints.

Additionally, the efficiency of the optimization is analyzed, as shown in Figure 12. A correlation can be detected in relation to the required number of iterations. When the optimization results are predictable, i.e., less demanding, a significant reduction in peak power is achieved in a short time with a small number of iterations. On the other hand, when the values of the energy requirements are equalized with a large number of iterations, a relatively small reduction in the required power is achieved. For example, when the daily energy needs of “Ferry 6” are 0.48 MW, 992 iterations are needed to achieve a total peak power reduction of 0.76%. When the daily energy needs of “Ferry 6” are between 0.4 MW and 0.6 MW, a large number of iterations are required to achieve a small reduction in the charging power of the group of ships. The reason for this is that several different consumers with similar energy needs are connected to the charger at the same time. On the contrary, when the daily energy needs of “Ferry 6” are 1.82 MW, one iteration is required to reduce the peak power by 24%.

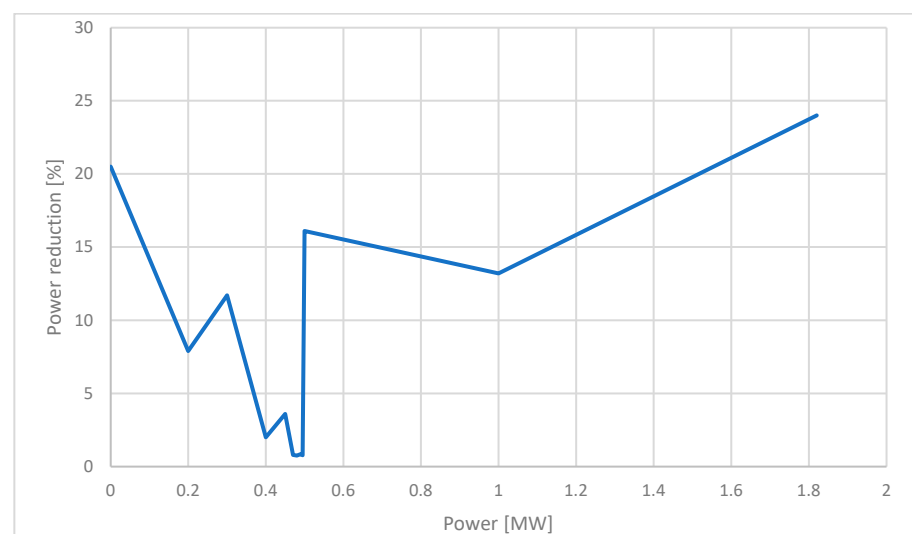


Figure 12. Dependency of power reduction in relation to the daily energy needs of “Ferry 6”.

In the case of the transition of ferries to electric propulsion, it is necessary to provide a shore connection that meets the energy needs at the most unfavorable moment when the

demand is at the highest. A model was created using the PSO and a greedy algorithm to reduce the required peak power. The model can be adjusted so that the objective function is the charging price, which depends on the price of electricity at a certain period of the day.

Furthermore, this model can be used as a tool for the optimization of various transport, energy, and production processes. Also, technical aspects and limitations are not considered when optimizing the peak load following the repetitive navigation profile of the ships. Namely, for charging the entire fleet of ships to be feasible, all docks should have sufficient power connections. However, this research assumes that the mentioned requirement is fulfilled.

PSO was used in work [40] to reduce the peak loads of the shore network in the case of charging shipboard ESSs. The optimization was achieved by using shore-based battery ESS. Further, the model created in the MATLAB/Simulink software (R2023b Update 5) package shows that the application of land-based ESS is more profitable than investments in the infrastructure of the shore power grid. Concerning the aforementioned research, it has to be pointed out that our model can reduce the peak power without applying the ESS. The paper [41] optimized the photovoltaic–wind energy system using the hybrid greedy PSO. This method was used to achieve two objective functions: reducing the total cost and increasing the system's reliability. Research [42] conducted by the interdisciplinary scientific team proposed that seaports be transformed into smart energy hubs. The authors suggest using RESs and a power management system that enables a bidirectional flow of electricity depending on current needs. For example, it is proposed to return electrical energy to the power grid of the port or ship when the port cranes lower the cargo. However, energy optimization is presented only on a conceptual level, contrary to the proposed model.

7. Conclusions

The main aim of this research is to contribute to the long-term sustainability of ferry transportation. As a rule, this type of transport is characterized by short routes with a predetermined sailing order. Furthermore, ferry docks are often located in sheltered ports, on islands, and in city ports that do not fulfill the energy needs for charging of a group of ferries. Therefore, it is necessary to optimize the charging process of the electrical ESSs of the ferry fleet. When conducting energy system optimization of different transport technologies, various techniques and methods are used. However, the most commonly used are particle swarm optimization (PSO), deep learning (DL), genetic algorithm (GA), fuzzy logic (FL), multi-objective optimization (MOO), mixed integer linear programming (MILP), and petri network (PN). In similar energy system optimization problems, PSO is often used. However, to the best of our knowledge and the available literature, we have not found an example of the application of this method in the optimization of the charging schedule of a group of electric ferries. The main objective of this paper is to develop a mathematical model based on the application of the PSO method in order to propose optimal solutions for the charging arrangement of the vessel. The objective function of this optimization task is to reduce the amount of peak charging power.

This model can be used as a tool for the optimization of various transport, energy, and production processes. Also, technical aspects and limitations are not considered when optimizing the peak load following the repetitive navigation profile of the ships. Namely, for charging the entire fleet of ships to be feasible, all docks should have sufficient power connections. However, this research assumes that the mentioned requirement is fulfilled.

The proposed model reduces the peak charging power in different operating conditions by up to 24%. Furthermore, robustness has been proven for states that differ significantly in daily energy profile compared to the initial state without optimization. Op-

timizing the charging process, peak charging power has been reduced without additional energy storage.

Possibilities for additional improvement of the algorithm and increasing its robustness include the following:

- Implementation of the algorithm for reducing the charging power during the entire charging period and not only for the peak load;
- Test the model under different conditions of exploitation that affect the load profile (number of ships, sailing schedule, energy needs).

Recommendations for future research include the determination of the available energy capacities of the ships' ESSs when they are not sailing. Such ESS capacities can be used to reduce the peak charging power, regulate the load of the shore power grid, and regulate the voltage and frequency of the network.

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Article

Ferry Electrification Energy Demand and Particle Swarm Optimization Charging Scheduling Model Parameters Analysis

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Abstract: Maritime transportation significantly contributes to air pollution, especially in coastal cities. Air pollution represents the greatest health risk related to the environment in the European Union. Therefore, the European Commission published the European Green Deal, which introduces the rule of zero-emission requirements for ships at berths with the mandatory use of power supply from shore or alternative technologies without emissions. The electrification of ferries has proven to be a key approach in reducing the negative impact on the environment; hence, it is necessary to provide adequate infrastructure for charging electric ferries. To determine the energy needs of the shore connection, a daily energy profile of the ferry fleet was created. Due to the sailing schedule, daily energy needs may be non-periodic. By optimizing the charging process, a reduction in peak charging power can be achieved. The charging process was optimized using particle swarm optimization. To improve the function goal, the parameters of the model were analyzed and optimized. It was found that the correct selection of population size and inertia weight factor can significantly enhance the optimization effect. The proposed model can be applied to other ports of interest, considering the specifics of the exploitation of the fleet of ships.

Keywords: particle swarm optimization; renewable energy sources; ferry electrification; charging optimization; power management system



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1. Introduction

Transportation significantly contributes to air pollution and the emission of harmful gases in the territory of the European Union (EU). According to [1], transportation is responsible for the total emissions of particulate matter PM_{2.5} (PM smaller than 2.5 µm) in certain cities, namely Malmö, 39% of overall PM; Brescia, 28%; Parma, 27%; and Angers and Verona, 26%. Maritime transport also contributes to air pollution, especially in the area of coastal cities such as Valletta, 33%; Palermo, 29%; Palma de Mallorca, 26%; Athens, 24%; and Bari, 21%. In the territory of the Republic of Croatia, as much as 95.1% of the population has been exposed to PM₁₀ (PM smaller than 10 µm) at a concentration higher than EU standards [2]. Air pollution is the main cause of premature death and disease and, as such, represents the greatest health risk related to the environment in the European Union. According to data from the European Environment Agency observed on an annual basis, in 2019 alone, acute exposure to PM caused 307,000 premature deaths in 27 EU member states [3]. The above has significant implications for reduced life expectancy, increased costs of the health care system, and reduced productivity. Therefore, in July 2023, the International Maritime Organization (IMO) revised the strategy to reduce greenhouse gases compared to the ambitions of 2018. Thus, the final goal for reducing GHG emissions in 2050,

which was 50% compared to emissions in 2008, was reduced to 0 emissions [4]. In March 2023, the European Commission published the European Green Deal [5], which introduces a zero-emission requirement for ships at berths with the mandatory use of power supply from land or alternative technologies without emissions. The main goal of this agreement is to reduce air pollution in ports, often located near densely populated areas. The Fuel EU maritime initiative [6] is an interim agreement reached in March 2023 that promotes the systematic use of renewable energy sources and low-carbon fuels. However, the forecast for assessing the use of a certain type of fuel in shipping is quite uncertain [7]. Due to technical limitations, the decarbonization of maritime transport will increase total costs by 70% to 110%. According to [8], the gradual introduction of renewable fuels is foreseen, as shown in Figure 1.

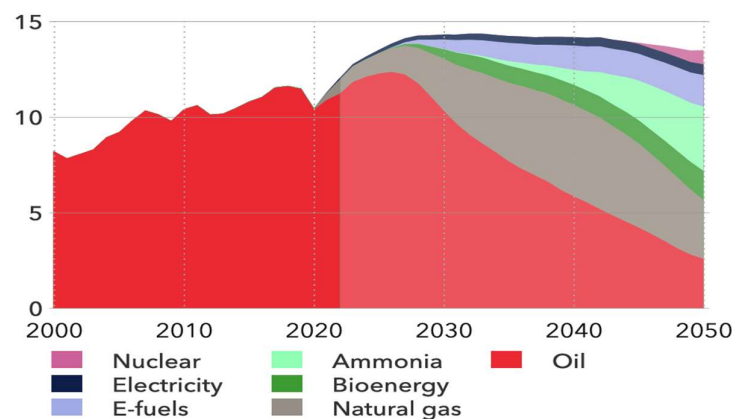


Figure 1. Review of the use of energy for ships in operation and projection for future exploitation (units: EJ/yr, natural gas includes LNG and LPG).

The European Union's current goal is to increase the share of renewable energy sources (RES) in energy consumption by 32% by 2030. In the Republic of Croatia, in 2023, 50% of the total electricity produced was produced by hydroelectric power plants alone [9].

In accordance with the energy needs of ships and the capabilities of the shore electrical system, the design of a battery charging station is proposed. The charging station can be performed in different ways; however, it is most often designed in one of the following configurations:

- Direct charging from the shore network (AC or DC);
- Combined charging using own diesel generators (DG) and shore network;
- Combined charging using a shore energy storage system (ESS) and power supply from the shore.

Direct charging from shore is the most acceptable solution if the energy infrastructure fulfills the needs of the battery charging station. The possibility of the connection is usually feasible only in large seaports with a developed energy infrastructure. The charging station can be connected to low-voltage, medium-voltage, or high-voltage levels. However, in practice, ferry docks are often located in sheltered ports without an available infrastructure that adequately meets the requirements of the charging station. Therefore, simultaneous charging using the ship's generators and a connection from shore is often applied. In this case, when ship generators are used, it is a hybrid system.

If the shore connection does not enable sufficient power, an electrical ESS can be used, which is charged when the ship is not connected to the charging station. When the ship is connected to the charging station, the energy from the shore-based ESS and the connection from the shore grid for charging the ship's ESS are simultaneously used. In this

case, investment costs are higher. Additionally, there are losses due to the charging and discharging of the terrestrial battery storage [10].

Based on the created daily profile of energy needs, optimization was carried out with the aim of reducing the peak load. In accordance with the defined problem and the subject of the research, a basic and auxiliary scientific hypothesis was set.

Hypothesis 0 (H0): *In the case of electrification of the ferry fleet, the energy needs exceed the capacities of the shore-based power infrastructure. The profile of daily energy needs is non-periodic and, therefore, not suitable for charging from a shore infrastructure.*

Hypothesis 1 (H1): *Proper model parameters selection and adjustment can additionally reduce the required installed power during the optimization process.*

2. Literature Review

In order to reduce the emission of harmful gases and the negative impact on the environment, it is necessary to use a comprehensive approach in the design, construction, and exploitation of ships. According to [11], by applying diesel/electric propulsion compared to standard propulsion, significant savings in harmful gas emissions are possible, as well as economic savings on an annual level in the amount of 22%. Electric energy sources for ship propulsion have multiple advantages. Significant savings can be achieved by optimal hull design, which reduces the ship's hydrodynamic resistance. The use of advanced protective coatings reduces the ship's resistance [12]. Additionally, during the exploitation of the ship, the overgrowth of the hull significantly affects fuel consumption [13].

The design and efficiency of the propeller contribute to the reduction of fuel consumption [14]. By choosing the optimal route and sailing speed, savings in fuel consumption are achieved [15]. With the observed type of maritime transport, the navigation route is pre-defined and can be slightly influenced. On the other hand, the speed of the ship significantly affects fuel consumption. Figure 2 shows the relationship between changes in ship speed, which affects the required power of the propulsion engine and, consequently, fuel consumption. For example, as a result of reducing the maximum speed of a ship by 20%, the power consumption and fuel consumption are reduced by 60%. Fuel consumption depends on the type of vessel and its features, but it can be generalized that the power used is proportional to the cubic speed of the vessel. As the ferry sailing routes are relatively short, reducing the peak speed does not significantly affect the length of the journey, as part of the time is spent on maneuvering when entering and leaving the port.

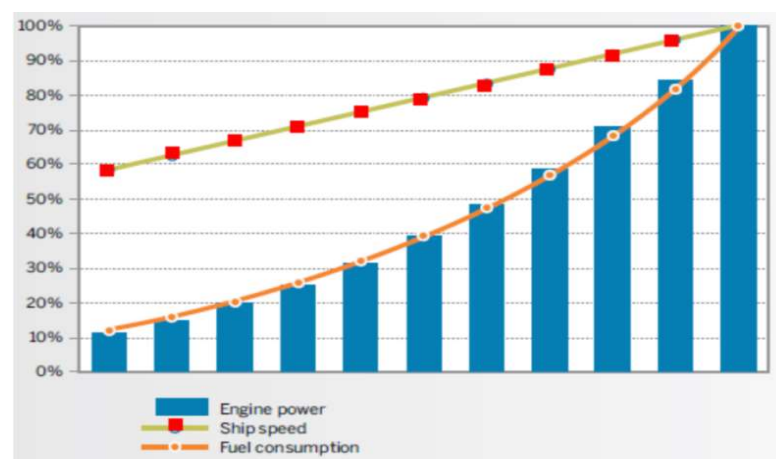


Figure 2. Relationship between ship speed, required power, and fuel consumption [16].

The aforementioned technologies and efforts are aimed at increasing the energy efficiency of fossil fuel-powered ships. Of course, the contributions are significant, but the source of energy needed to propel the ship should be renewable with as little environmental impact as possible. In this research, the use of electric energy to propel a ship, more precisely a group of ferries, is proposed.

In article [17], a model of a multi-energy ship network with combined power, thermal, hydrogen, and freshwater flows is proposed. By applying the coordinated planning model, the flexibility and practicality of the planning process is increased. Based on the case study, multiple comparative analyses confirmed the effectiveness of the method. In the research [18], energy management and voyage scheduling were modeled with the aim of increasing energy efficiency and reducing greenhouse gas emissions. Unlike previous research, this also took into account the underwater radiated noise generated by the action of the ship's propeller. The model has been verified in real conditions and shows efficiency.

Table 1 shows examples of the application of RES on electrically powered ferries. Although there are earlier examples of the use of electric ferries, vessels launched in the period from 2012 to 2023 were taken into consideration.

Table 1. Examples of electric ferries.

Ref. No.	Ship Name	Year	Length Overall (m)	Passengers No.	Vehicle No.	Speed (kt)	Power (kW)	Battery Capacity (kWh)
[19]	MV Hallaig Scotland	2012	43	150	23	9	750	700
[20]	MV Lochinvar Scotland	2013	43	150	23	9	750	700
[21]	Ampere Norway	2014	80	360	120	10	900	1000
[22]	M/F Deutschland Germany *	2014	142	1200	364	18.8	12,000	2600
[23]	Prins Richard Denmark *	2014	142	1140	364	18.5	12,000	1600
[24]	Prinsesse Benedikte Denmark *	2015	142	1140	364	18.5	12,000	1600
[25]	MV Catriona Scotland	2016	43	150	23	9	750	700
[26]	MF Tycho Brahe Denmark *	2017	111	1250	240	14.5	6000	4160
[27]	Elektra Finland	2017	98	375	90	11	1800	1060
[28]	Aurora Electric Ferry Denmark *	2017	238	375	90	11	6000	4160
[29]	MS Color Hybrid Norway	2019	160	2000	500	17	-	5000
[30]	Herjólfur IV ferry Iceland	2019	71.78	540	70	12.8	-	2983
[31]	Ellen E-ferry Danmark	2019	59.4	198	31	15.5	1500	4300
[32]	Island Discovery Canada	2020	80.80	450	47	14	1800	800
[33]	Basto electric Norway	2021	139.2	600	200	15	4800	4000
[34]	Wolfe Islander IV Canada	2021	99.30	399	75	12	2080	4500
[35]	MV Amherst Islander II Canada	2021	68	300	42	12.3	-	-
[36]	Grotte ferry Danmark	2021	49.9	303	23	11	750	1107
[37]	MF Hella	2022	84.2	300	80	10	2000	1582
[38]	MF Dragsvik	2022	84.2	300	80	10	2000	1582
[39]	MF Leikanger	2023	84.2	300	80	10	2000	1582
	Average		91.5	553	139.5	12.8	3328	2177

* Retrofitted vessel.

Table 1 shows 21 ferries that were designed for electric propulsion or were retrofitted for electric propulsion during their lifetime. Analyzing the data from the table, certain conclusions can be drawn to predict the trend in the case of the electrification of the observed ferry fleet that uses the port of Split. Thus, the average length of the vessel is 91.5 m, the average passenger capacity is 553, the average vehicle capacity is 139.5, the average speed is 12.8 kt, the average power is 3328 kW, and the average battery capacity is 2177 kWh.

Comparison with Other Recent Research

The PSO method is used for energy management of the hybrid system of an electric vehicle charging station [40]. In this paper, the PSO method of energy management has been developed, taking into account active power loss, reactive power loss operation cost, power flow, and voltage deviation. Although the research is applicable to smart grid applications, the primary function of the goal is to reduce operating costs. In the study [41], PSO was used to optimally coordinate the charging schedule of electric vehicles, considering the habits of users. In this paper, the function of the goal is to minimize power loss. The results show that coordinated charging can optimize the load and reduce energy network losses. Article [42] uses an improved PSO aiming to increase the energy efficiency of the ship. The microgrid model minimizes system costs and improves system management with proper scheduling. Research [43] based on the Swarm Exchange Particle Swarm Optimization Algorithm reconfigures the power grid of a circular power system with the aim of extending the lifespan of a ship's power station. The simulation model reduces the time required for reconfiguration and improves the performance of the ship's power system. As the ports are important consumers of electricity, their energy efficiency is attracting more and more attention. For ports to comply with increasingly stringent regulations, it is crucial to apply new technologies of renewable energy sources and alternative fuels with the aim of optimizing operations or, for example, reducing peak shavings [44]. In the research [45], a mixed linear programming model was proposed with the aim of energy management considering the uncertainty of energy generation through renewable sources. The study shows that by using a smart grid, significant economic savings are possible compared to conventional settings. In most research, the goal is to reduce economic costs. However, in this study, the goal is to reduce the peak power required for charging groups of ferries. Given the research gap, this research represents a novelty.

3. Materials and Methods

3.1. Split City Port Features

The Republic of Croatia is a maritime country with a thousand-year tradition. Due to the extremely indented coast with a length of 6278 km and 1244 islands, islets, rocks, and reefs, maritime transport is of particular importance for the coastal and island populations [46].

Split is the second-largest city in the Republic of Croatia and the largest Croatian city on the eastern coast of the Adriatic Sea [46]. Split is an important cultural and traffic center, the second-largest Croatian port, and the third-largest passenger port in the Mediterranean. In 2024, the city of Split was visited by 1,040,300 tourists and had 3,130,060 overnight stays [47]. The port of Split is the most important passenger port in Croatia; it connects the large islands of the Croatian coast. Moreover, it also takes part in international passenger traffic from Italy. In addition, the port has a cargo port with a relatively modest local hinterland consisting of the Dalmatia region and parts of Bosnia and Herzegovina. The port of Split is a port open to international public traffic, and according to its size and significance, it is a port of special (international) economic interest for the Republic of Croatia [48]. Figure 3

shows the plan of the City Port of Split. The land area of responsibility of the Split Port Authority is marked in gray.

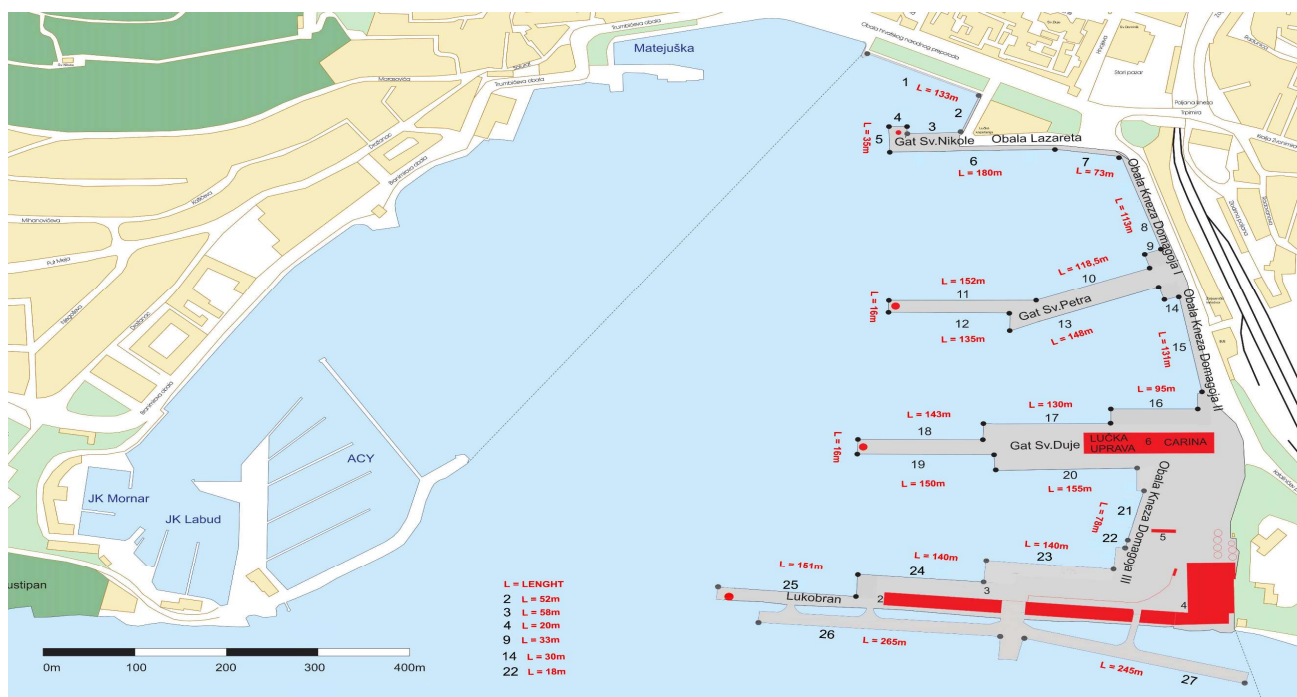


Figure 3. Plan of the City Port of Split [49].

Emissions of harmful gases into the environment in the Split waterway are generated by vessels that maintain state ferry lines, high-speed shipping lines, and long-shore and international lines. Furthermore, large cruise ships, fast private and public ships, and recreational vessels that use the nautical port within the City Port of Split also contribute to emissions of harmful gases. Figure 4 shows the type of vessels that sail into the City Port of Split [50]. Ferry transport accounts for one part of the emissions of harmful gases generated in the Split waterway. Observing the planned quotas for fuel procurement of the state operator Jadrolinija in 2023 [51], it is evident that the analyzed ferry fleet accounts for 60.8%. The remaining part of the procurement refers to high-speed shipping lines and international lines. In the case of electrification of all vessels entering the City Port of Split, an analysis of energy needs should be performed for each group of vessels separately.

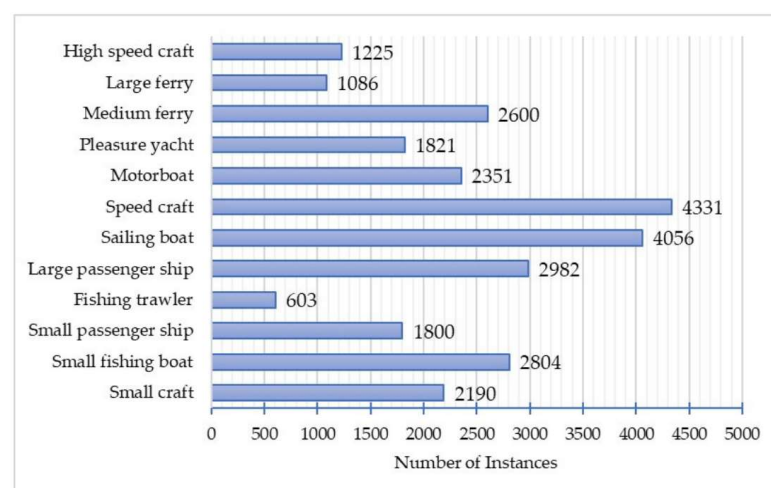


Figure 4. Types of vessels using the City Port of Split [48].

The study [52] analyzes the inventory of pollutants generated by line vessels during the maneuvering and hoteling phase in the area of the City Port of Split. The total inventory of harmful effects on the environment in the observed three-year period is as follows: non-methane volatile organic compounds (NMVOC) 38.31 (t), PM 33.97 (t), CO₂ 38,908.95 (t), NO_x 675.17 (t), SO₂ 368.15 (t). In the case of a transition to fully electric propulsion, where ESS is charged via RES, there would be zero emissions.

3.2. Split City Port Study Case—Ferry Fleet Energy Demand Analysis

Split is connected by state ferry lines with ports on the central Dalmatian islands, as shown in Table 2 [53,54]. The ferry lines connecting Split with international ports are not taken into consideration in this work. The table shows the average annual number of passengers and vehicles, the duration of sailing in one direction, the number of sailings, and the number of sailing hours on an annual basis. The presented statistical data take into account the period from 2019 to 2022.

Table 2. State ferry lines of the Split waterway that use the City Port of Split.

Line No.	Destination	Passengers No.	Vehicles No.	Sailing Duration (min)	Sailings No.	Sailings Total (h)
631	Supetar (Brač)	1,684,035	399,329	50	3664	3053
635	Stari Grad (Hvar)	620,665	169,719	120	1485	2970
636	Rogač (Šolta)	341,128	86,797	60	1611	1611
602	Vis (Vis)	244,185	61,358	140	780	1820
604	Vela Luka (Korčula)—Ubli (Lastovo)	203,712	55,447	240	880	3520
Total on an annual basis		3,093,725	772,650		8420	12,974

In order to determine the requirements that must be met by the shore-based power grid, it is necessary to determine the energy needs of ships that use the City Port of Split as one of their base ports. Different approaches can be applied in the analysis of the energy needs of the ferry fleet. The most reliable way would be to analyze the total annual consumption of diesel fuel of the observed fleet.

In the observed period, due to the introduction of new vessels, the needs of the operator, and the operational status of the vessel, there were minor changes in the navigation schedule. However, using the list of ships of the Jadrolinija fleet in national and international navigation, in which the annual fuel quotes are listed, the total annual fuel consumption can be determined [51]. The planned annual consumption of diesel fuel by the ferry fleet of the Split waterway for ships that maintain the lines is 15,717,041 L of diesel fuel. Table 3 lists all the ferries of the Split waterway that maintain the observed state ferry lines [53]. The overall length, maximum speed, passenger and vehicle capacity, the line served by the ferry, and the annual fuel consumption rate are shown.

First, it is necessary to determine how much useful work can be generated by the fuel used. Modern medium-speed diesel engines have a high degree of useful action, which amounts to about 50% of the energy contained in the fuel [55]. However, in real conditions, only 30–45% of energy is used for useful work [56]. The reason for this is mainly the unfavorable exploitation of the propulsion system. When sailing short distances, a significant part of the time is spent on maneuvering the vessel, which is a mode in which the efficiency of the engine is considerably reduced. Furthermore, it is necessary to consider the average age of the propulsion system of the observed fleet, which is over 23 years [53].

Table 3. List of ferries maintaining state ferry lines that use the city port of Split.

No.	Ship Name	Length (m)	Max. Speed (kt)	Passenger No.	Vehicles No.	Line No.	Fuel 2023. (L)
1	M/V Biokovo	87.6	13	1200	138	636	984,713
2	M/V Faros	105	14	650	170	635	1,072,720
3	M/V Hrvat	87.6	13	1200	138	631	674,235
4	M/V Korčula	101.4	16	685	150	604	4,064,960
5	M/V Marjan	87.6	12.3	1200	130	631	663,506
6	M/V Petar Hektorović	91.8	15.5	1080	120	602	2,183,173
7	M/V Tin Ujević	98.3	14	1000	200	631	1,100,000
8	M/V Valun	81.2	13	730	60	631	866,232
9	M/V Zadar	116	17.5	1109	280	635	4,107,502
	Average/Total	92.13	14.13	935.4	143		15,717,041

Diesel fuel compliant with EN 590:2013 (Automotive fuels—Diesel—Requirements and test methods) is used as fuel. The specific density of diesel fuel, according to the EN590 norm, is between 820 and 845 kg/m³ at 15 °C, while the typical average value is 835 kg/m³ [57]. The mass of loaded fuel is calculated according to the formula:

$$m = \rho \times V \quad (1)$$

where ρ is the specific density and V is the volume of the loaded fuel. Therefore, 16,805,374 L of diesel fuel has a mass of 13,123,729 kg. The upper heating power H_g , i.e., the maximum possible energy that can be obtained by burning the fuel used is 45 MJ/kg [58]. The total heating power H is calculated according to the formula:

$$H = H_g \times m \quad (2)$$

The total heating power of the fuel used on an annual basis is 590,567 GJ. Therefore, the total heating power is the equivalent of 164 GWh. In accordance with the efficiency of the diesel engines observed in this analysis, a lower efficiency limit of 30% was taken for calculation according to the formula; annual energy needs are calculated according to:

$$E_{\text{ANNUAL NEEDS}} = \frac{P_{\text{ENERGY DELIVERED TO THE SHAFT LINE}}}{P_{\text{TOTAL ENERGY CONTAINED IN FUEL}}} \quad (3)$$

Based on a previous formula, the annual energy needs amount to 49.2 GW/h. Furthermore, the question arises whether the required power of an electrified fleet of ferries would be equal to the needs of the existing fleet. First of all, it depends on the design requirements and the specifics of the waterway. However, observing the maximum speed of the electrified ferries from Table 1 in comparison with the existing ferries that maintain the considered lines, a decrease in the average peak speed can be observed from 14.13 to 12.8 kt (the difference is 1.33 kt). The regression curve connecting the required propulsive power P_p and the speed of the ship v can be defined as a power function with added estimated parameters of the thrust functions a and c .

$$P_p = a \times v^c \quad (4)$$

Using data from the World Register of Ships database for ferries sailing on the Croatian side of the Adriatic Sea, parameter a is 0.0757, parameter c is equal to 3.987, while the

correlation factor $R^2 = 0.91$ [59]. Considering the correlation factor, it can be concluded that there is a strong connection, i.e., that the model is representative. However, the almost insignificant reduction in peak speed in the amount of 9.5% results in a reduction of the required propulsive power by 32.6%. The mentioned saving is not only reflected in fuel consumption but also in the reduction of the required installed power of the propulsion system, which significantly reduces investment costs. Furthermore, the introduction of new technologies in the optimization of the hull and ship's propeller and the use of ship coatings contribute to the reduction of fuel consumption. Certainly, in the case of electrification of ferries, all the mentioned methods of reducing energy consumption would be applied. However, for the sake of objectivity, in this energy analysis, possible savings in energy consumption will not be considered in order to make the analysis as objective as possible. Losses of the shaft line and propeller were not considered because they are common to both versions of the propulsion system.

As with internal combustion engines, losses also occur with electromotive systems. The chemical energy contained in the batteries needs to be converted into electricity, and then the electricity into mechanical work, which is transferred to the shaft transmission line. The efficiency of modern high-voltage electric motor drives in favorable conditions can be over 98% [60]. Losses of the battery system depend on the state of charge, the technology used, and other different parameters. Losses occur during charging, storage, and discharging of the battery. According to a study [61], the efficiency of the entire process of the battery system is 81%.

The amount of energy required to drive the state ferry fleet on the shaft line is 49.2 GW/h. Considering the efficiency of the electric drive and the battery, the required energy delivered from the shore connection to the ship is calculated according to the formula:

$$E_{SC} = P_{\text{ENERGY DELIVERED TO THE SHAF LINE}} + \text{Losses}_{\text{BATTERY+ELECTROMOTIVE SYSTEM}} \quad (5)$$

where E_{SC} is shore connection required energy.

Therefore, the required energy delivered from the shore connection to the ship is 62 GWh. In this research, the losses of the charger, which can be performed in different ways, were not considered.

If the batteries of the observed ferry fleet were charged under ideal conditions at constant power, the current load of the connection from the mainland would amount to 294 kW, which on a daily basis is 7.07 MWh. However, in practice, there are significant deviations because ferry transport is seasonal. In the summer months, there is an increase in the number of sailings and, therefore, an increase in the required energy. Figure 5 shows the number of departures per month for the state ferry line 604 Split—Vela Luka—Ubli in 2022.

In order to be able to determine the required installed power of the shore connection, it is necessary to know the peak daily load. According to [48], the highest daily number of sailings was achieved in July 2021 and August 2022. For the six observed state ferry lines, the daily maximum is 37 outbound and return trips. The peak load is 62% higher than the average daily load in the observed four-year period. Due to the non-periodic number of departure and return trips, a connection from the mainland with an installed power of 477 kW is required, which is 11.45 MWh on a daily basis. The required power is shown if the charging of the battery energy storage was continuous at a constant power throughout the day. However, this implies the availability of charging ferries at the optimal time, which is not feasible in practice.

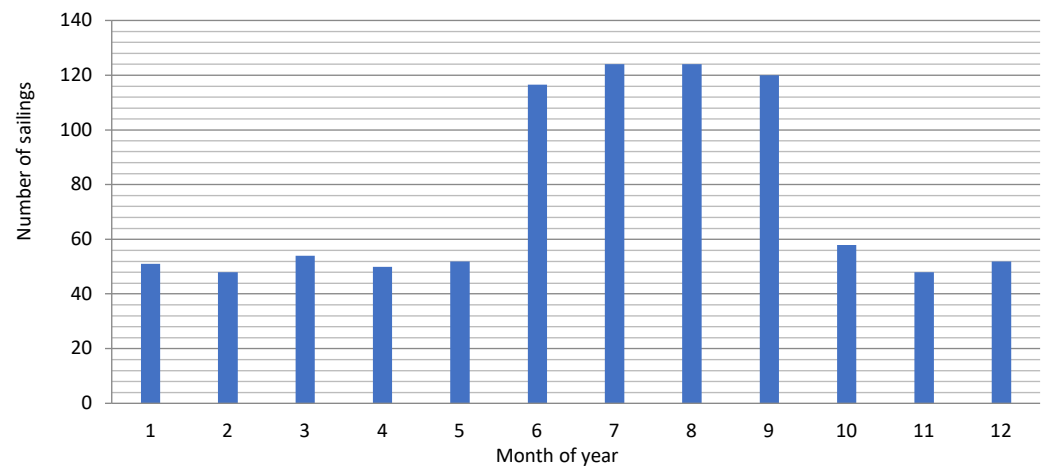


Figure 5. The average annual number of sailings by month on line 604 [48].

Due to the sailing schedule, which is adapted to the needs of the island's population, the sailing profile is extremely unfavorable in terms of the available time for charging electric batteries. Figure 6 shows the operational navigation profile for the observed ferry fleet. In the figure, the time the ship spends on navigation is marked blue, while the time the ship is available for charging in the City Port of Split is marked in green. The period that is not shaded refers to the rest of the ship outside the City Port of Split.

For example, if observing state line 636 maintained by the ferry Biokovo and connecting the island of Šolta with the City Port of Split, it is evident that the only available time for charging is between 2:00 p.m. and 4:15 p.m. The remaining time the ship sails, maintaining the line with a break of 15 min, which is necessary for the operation of disembarking and loading passengers and vehicles. At night, the ship is stationed at the port of Rogač (Šolta island).

The availability of an individual ferry for charging is an important factor from the aspect of optimizing the charging process. However, an even more important factor is the amount of energy needed in the time available to charge the ship's battery storage of electricity. Table 4 shows the daily energy needs of the ferry fleet, the percentage share of each ship in total consumption, the available time for charging, and the necessary continuous power of the connection for each ship during the charging process.

Table 4. Energy needs of the ferry fleet.

Ship	Daily Energy Needs (MWh)	Percentage Share (%)	Time Available (h)	Constant Power (MW)
M/V Biokovo	0.71737	6.26526	2.25	0.318831964
M/V Faros	0.78149	6.8252	3	0.260495259
M/V Hrvatska	0.49119	4.28983	17.66	0.027813478
M/V Korčula	2.96136	25.8634	1.5	1.974238959
M/V Marjan	0.48337	4.22157	15.17	0.031863536
M/V Petar Hektorović	1.59046	13.8905	2.5	0.636184148
M/V Tin Ujević	0.80136	6.99877	15.42	0.051968839
M/V Valun	0.63106	5.51142	15.6	0.040452403
M/V Zadar	2.99235	26.1341	5.75	0.520408809

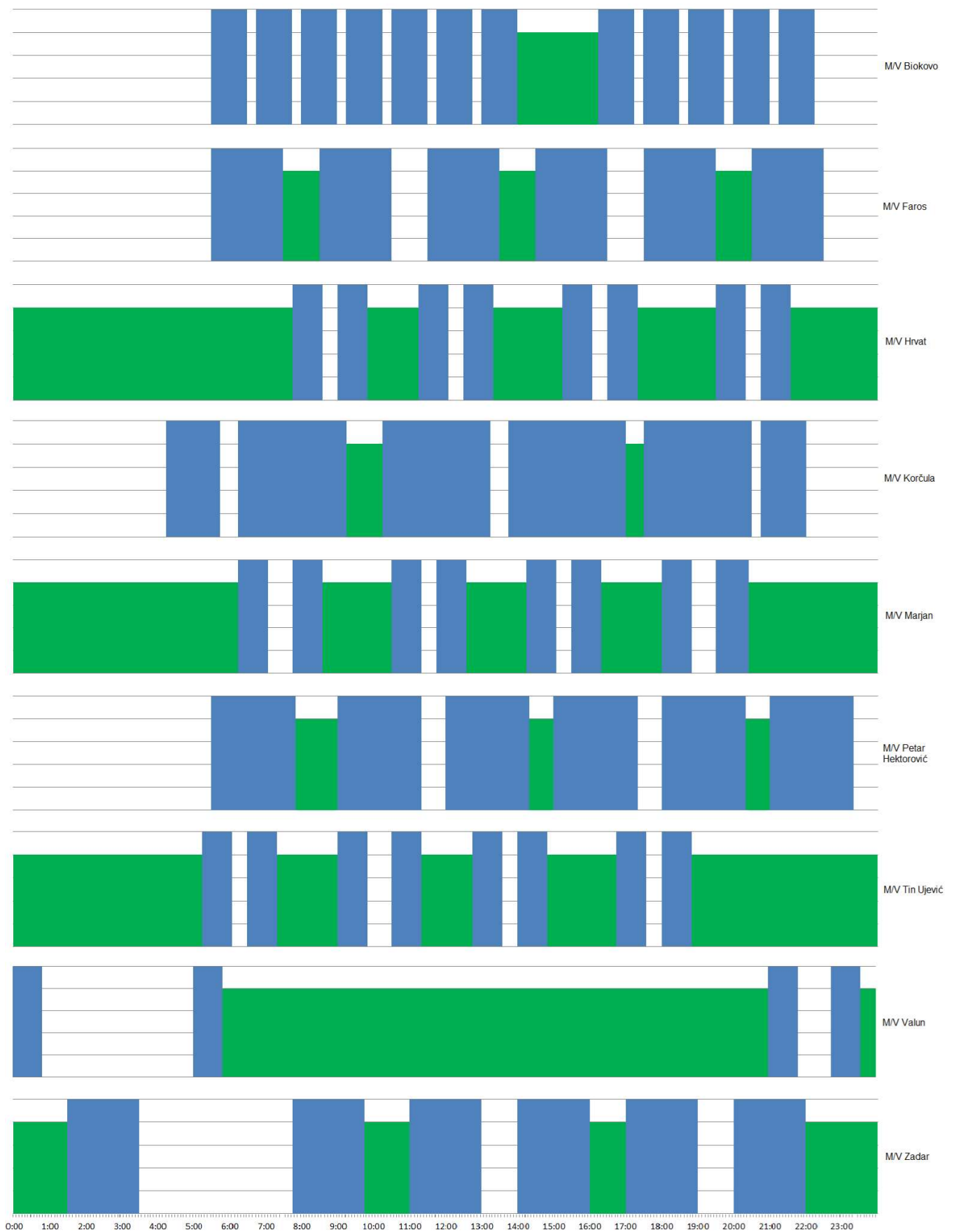


Figure 6. Daily operational profile of the observed fleet of ships.

In relation to the land-based power system, the energy needs of the ferry fleet are represented as a variable consumer of electricity in a 24-h time interval, which is called a daily energy load diagram. The amount of energy consumed by the E_{CON} is defined by the expression:

$$E_{CON} = \int_{t_1}^{t_2} P_{CON}(t)dt = \int_{t_1}^{t_2} u(t) \cdot i(t)dt \quad (6)$$

where P_{CON} indicates the instantaneous power with which the consumer group loads the network, $u(t)$ the instantaneous network voltage, and $i(t)$ the instantaneous current of the consumer group, while t represents time. The average load value refers to the power value in the case of charging the electrical ESS on ships with constant power and is defined by the expression:

$$P_{AVG} = \frac{\text{Daily energy needs}}{\text{24-hour interval}} \quad (7)$$

The amount of peak or maximum power P_{MAX} is defined by the expression:

$$P_{MAX} = \int_{t_{n1}}^{t_{n2}} u_{MAX}(t) \cdot i_{MAX}(t)dt \quad (8)$$

where P_{MAX} indicates the maximum power with which the group of consumers loads the network, u_{MAX} is the maximum voltage of the network, and i_{MAX} is the maximum current of the group of consumers, while t represents time.

Considering the energy needs of each individual ship in accordance with the available charging time, maximum charging power is estimated. The peak power required to charge a group of ferries in the most demanding moment amounts to 2.594 MW. Compared to the average annual energy needs of 0.477 MW, this represents an increase of almost 5.5 times, which significantly exceeds the capacity of the port infrastructure. Therefore, it is concluded that the energy needs of electric ferries in this particular case are extremely non-seasonal, i.e., non-periodic.

3.3. Optimization Methods and Methodology

Optimal network load can be achieved in different ways. In the case of a transition to electric propulsion, each of the solutions proposed below would probably be used to a greater or lesser extent depending on the specifics of a particular ferry line:

- Change of navigational schedule,
- The introduction of additional vessels on certain lines;
- Installation of diesel generators;
- Application of a battery ESS on the shore;
- Construction of electric energy charging stations on island piers;
- Charging optimization.

By changing the navigational schedule, the ship's available time for battery charging can be optimized. However, the sailing schedule is designed to meet the needs of the island's population first and foremost. Furthermore, the sailing schedule considers the availability of ships, the workload of the crew, and the possibility of docking ships in the City Port of Split. By introducing additional ships that maintain certain lines, it is possible to charge one ship while another sail maintains the line. Consequently, this represents additional investment and operating costs. By installing diesel generators, it is possible to charge the ship's battery ESS when the ship is not available for charging from shore. However, the use of diesel generators ultimately has a negative impact on the environment, which is exactly what should be avoided by electrifying ferries. If the infrastructure on shore does not meet the energy needs of ship charging stations, electricity storage facilities on land are used. If the needs are of low intensity, the shore ESS is charged. When the ship

is connected to the charging station, energy is used from the shore connection as well as from the shore ESS. At night, most of the fleet of ships are stationed at the island's docks. The shore energy infrastructure of the City Port of Split can be alleviated in such a way that the ship's ESS is charged at night while they are docked on the islands. Considering the limitations in the capacity of the electrical infrastructure on the islands, this model is difficult to implement.

The scientific research is divided into three phases: the restriction stage, the problem formulation stage, and finally, the optimization stage. Due to legal restrictions caused by the negative impact on the environment, a transition to RES is necessary. In accordance with the availability of a certain type of RES, the most suitable solution is selected. After choosing the electrification of ferries, it is necessary to analyze the energy needs of the fleet of ships and create a daily energy profile. After that, the creation of a model is approached. In this way, the transition to RES is achieved with the aim of fulfilling legal regulations and reducing emissions on the environment.

The most important part of the presented methodology is the creation of an optimization model based on PSO and a greedy algorithm. A greedy algorithm was introduced to narrow the search area when it comes to a situation where there is a ferry with dominant charging needs, as shown in Figure 7. In an imaginary multidimensional space, using a greedy algorithm, the search area is narrowed down to a specific area (rectangle shaded blue in the figure). In this way, the required number of search particles is reduced, as well as the number of iterations required to reach the global optimum solution. Search particles vectors are displayed as black arrows defined by speed and direction of movement.

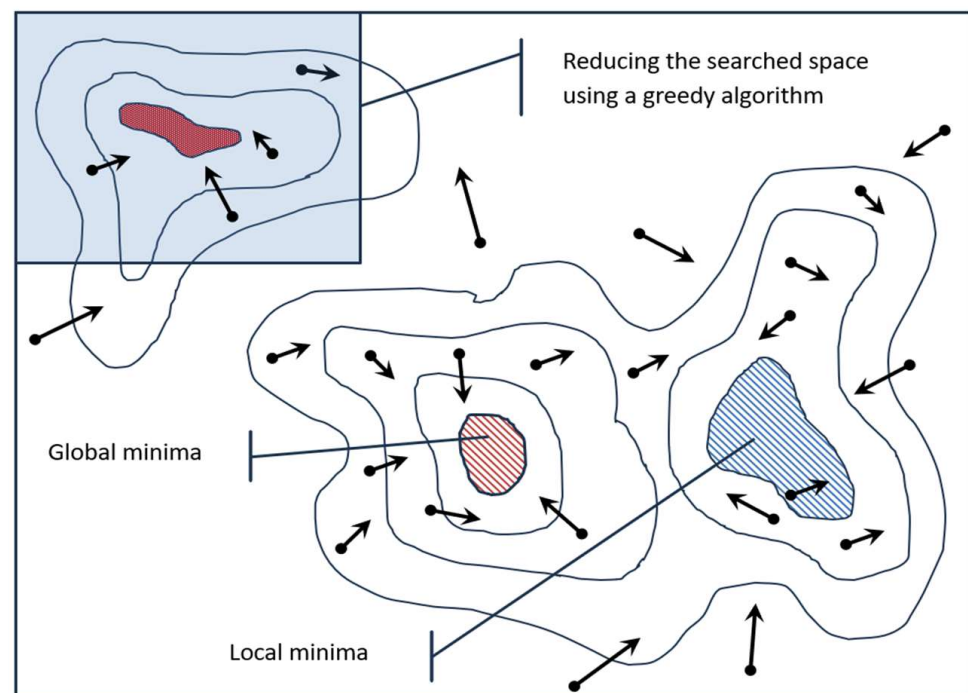


Figure 7. Applying a greedy algorithm with the aim of reducing searched space.

The description of the programming code is presented in the following paragraph, as shown in Figure 8. When generating the initial population, three classes of units were used: an individual generated by a greedy algorithm, a special individual generated by the initial schedule, and individuals generated by Poisson distribution.

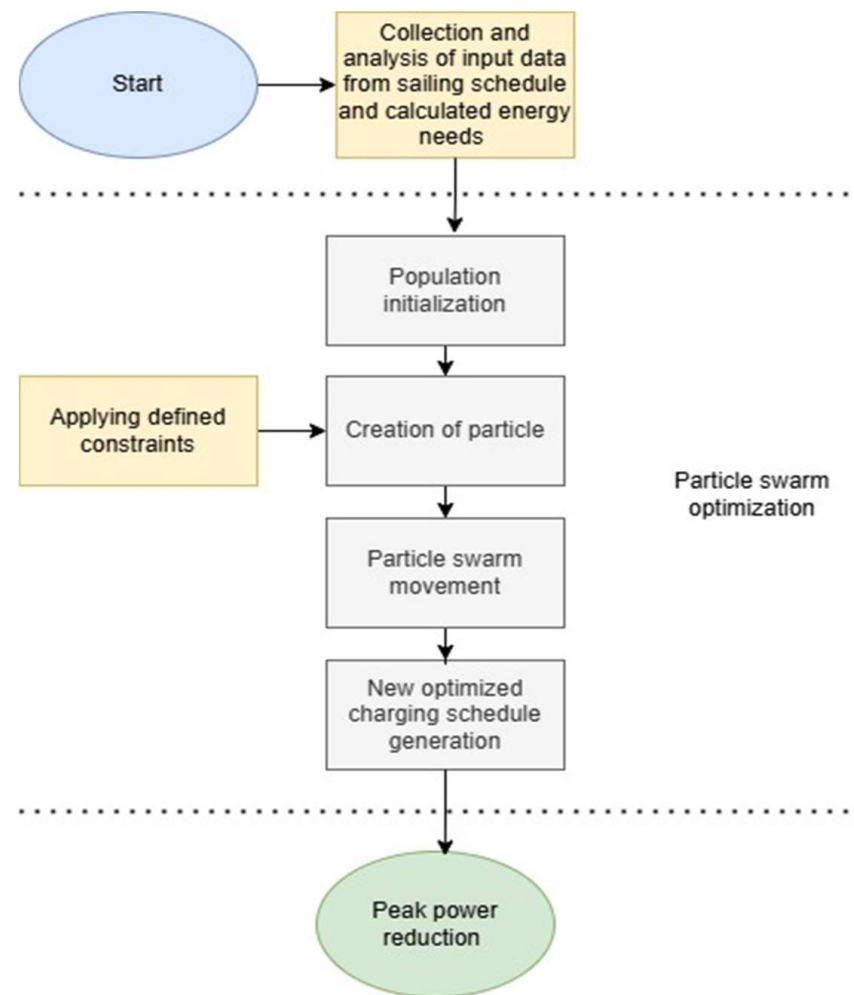


Figure 8. Algorithm flow chart.

The specific steps in the process of population initialization are as follows:

- (1) Creating initial solution particles using a greedy algorithm;
- (2) Creating reference initial solution particle used as a control dataset;
- (3) Creating random initial solution particles used for testing different scenarios;
- (4) The above particles are combined to create the initial population.

The specific steps in the process of creation of particle are as follows:

- (1) The charging schedule should be generated according to the sailing schedule and daily energy needs, considering constraints;
- (2) Discrete coding of input sailing schedule table into charge schedule;
- (3) Decoding of the repaired charging schedule due to overnight charging;
- (4) Combining created particles into the initial population;
- (5) Calculating new max power and preparing data for the Gantt chart;
- (6) Processing data for chart display;
- (7) Combining results of previous steps into single particle structure.

The specific steps of particle swarm movement are as follows:

- (1) The difference in the particle's current position vector is calculated concerning the local and global minima;
- (2) The velocity vector and the new location of the particle are calculated;
- (3) The particle is moved to a new location based on the obtained values;

- (4) The particle's movement affects the charge schedule, so the coded schedule is repaired, and then a new schedule is created;
- (5) The maximum power is calculated based on the new schedule. Data is prepared and processed to create Gantt charts;
- (6) In each new iteration, the particle is updated;
- (7) The next particle is processed;
- (8) When all initially defined particles have been processed, the algorithm stops.

Figure 9 schematically shows the energy flow of the proposed smart system for optimizing the maximum charging power.

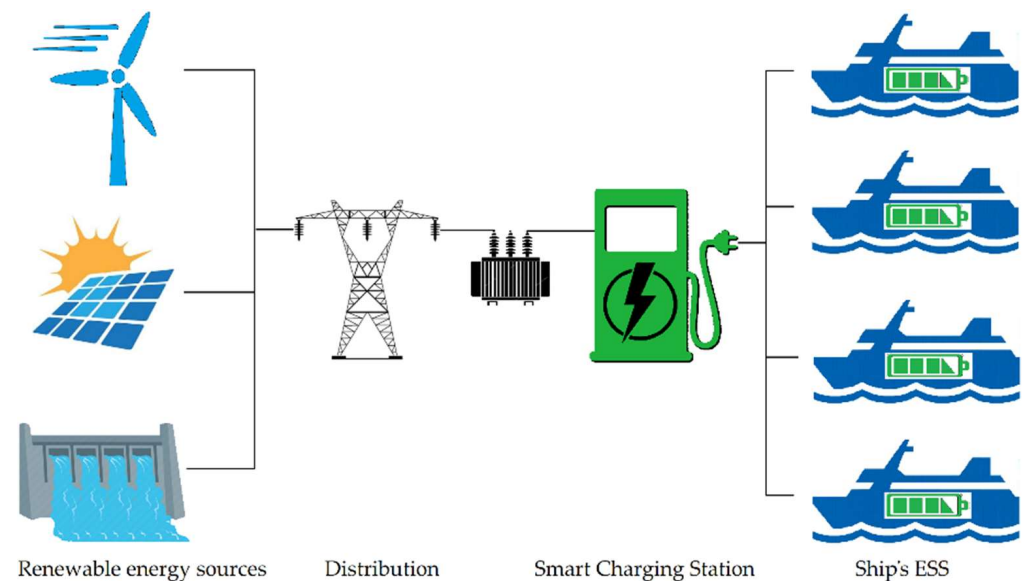


Figure 9. Schematic representation of electricity flow.

4. Results and Discussion

Due to the limited power of the shore infrastructure, it is necessary to minimize the peak load. Moreover, for some electricity suppliers, a fee is charged for the installed power. Thus, this kind of analysis can also have economic benefits. Furthermore, when carrying out the optimization of the peak load in accordance with the repetitive navigation profile of the ships, technical aspects and limitations are not considered. Namely, in order for charging the entire fleet of ships to be feasible, all docks should have connections of appropriate power. However, this research starts from the assumption that the mentioned requirement is fulfilled. The optimization is achieved in such a way that at the moment of connection of high-power ships, ships that are available for a longer period of the day are disconnected from the network.

The proposed model is applied to optimize the sailing schedule of the analyzed ferry fleet. The optimization model achieves a 24% [62] reduction in the required charging power of the electric ESS of the group of ferries. Savings were achieved by properly scheduling charging, i.e., by disconnecting less energy-intensive ships from the shore energy infrastructure. The problem arises when several ships with similar energy needs are connected to the network at the same time. In this case, a reduction of only 0.76% was achieved. The described schedule is shown in Figure 10 when the energy needs of the most demanding ship are reduced to 0.48 MW daily.

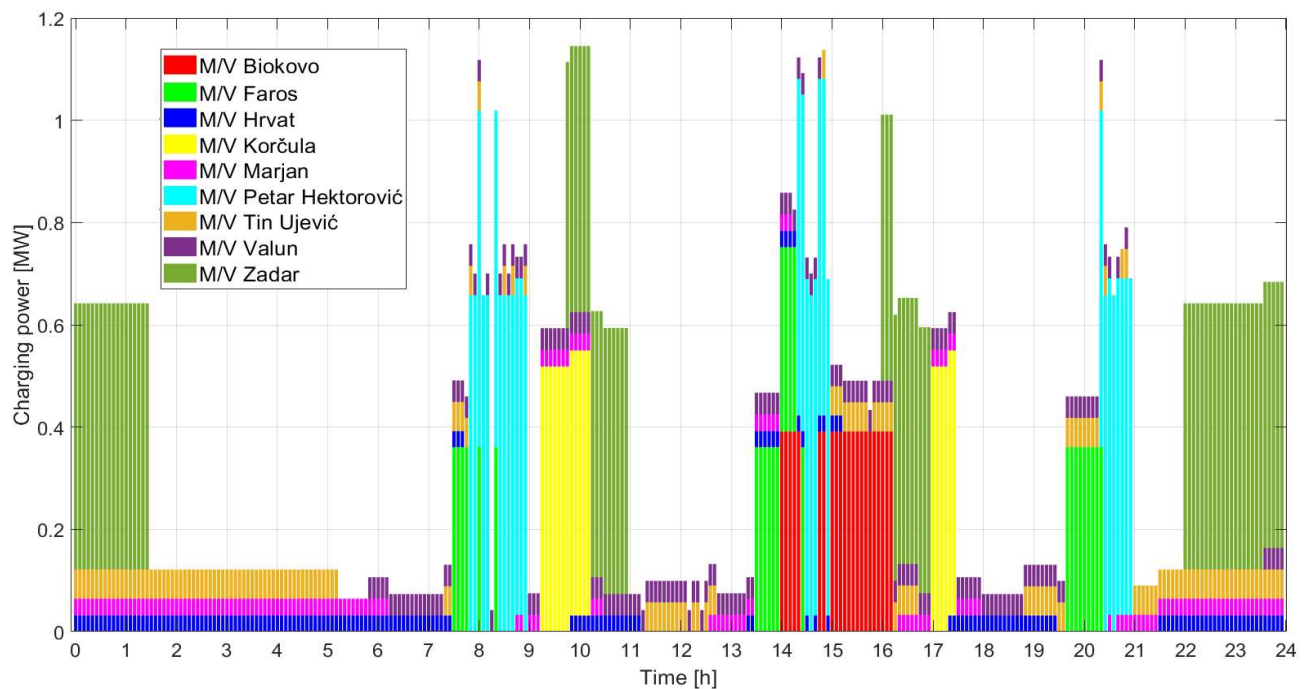


Figure 10. Optimized charging when several similar ships are connected to the shore network.

4.1. Population Size Analysis

In order for the model to be effective, it is necessary to perform the optimal setting of the model parameters. The topology of the population affects the speed of propagation, i.e., the effect of optimization [63]. An adequate selection of the population size is an important factor in the performance of this metaheuristic optimization method. According to [64], the optimal number of particles varies between 70 and 500 for the most complex optimization problems, although it is necessary to analyze the influence of the number of particles on the optimization efficiency for each individual optimization problem.

In this research, special emphasis is placed on determining the size of the population needed for the exploration of searched space. The optimal number of particles that search the area is the one where the results of the function objective are the best. Therefore, the influence of the number of particles on the optimization results was analyzed. However, due to the use of a greedy algorithm, it is not possible to examine the influence of the number of particles on the first test performed. Namely, the greedy algorithm prioritizes the most energy-demanding consumer. Therefore, the test was carried out when several ships with similar energy needs were connected to the shore-based power infrastructure. The distribution of sampling, i.e., determining the size of the population, is performed according to the exponential function $f(x) = e^x$ with the addition of one intermediate point with the aim of increasing the resolution, as shown in Figure 11. It can be seen from the figure that the greatest reduction in peak power is achieved when the number of particles is set to 256. Compared to the initial reduction of 0.76% when the number of particles was 1024, a reduction in peak power in the amount of 13.47% was achieved. The relationship of the required number of particles to achieve a certain objective function cannot be generalized and must be analyzed and optimized for each individual problem [64].

Figure 12a shows the convergence history when the population size is 1024 particles and Figure 12b when the population size is 256 particles. Although the convergence history looks similar, there is a significant difference in the achieved reduction in the required charging power of the ESS group of ferries.

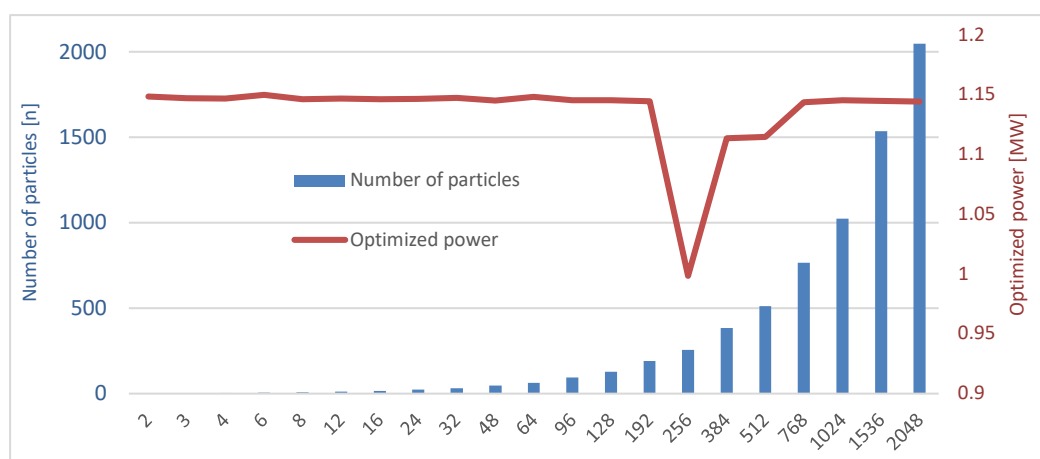


Figure 11. The influence of the selection of the number of particles on the reduction of the peak charging power.

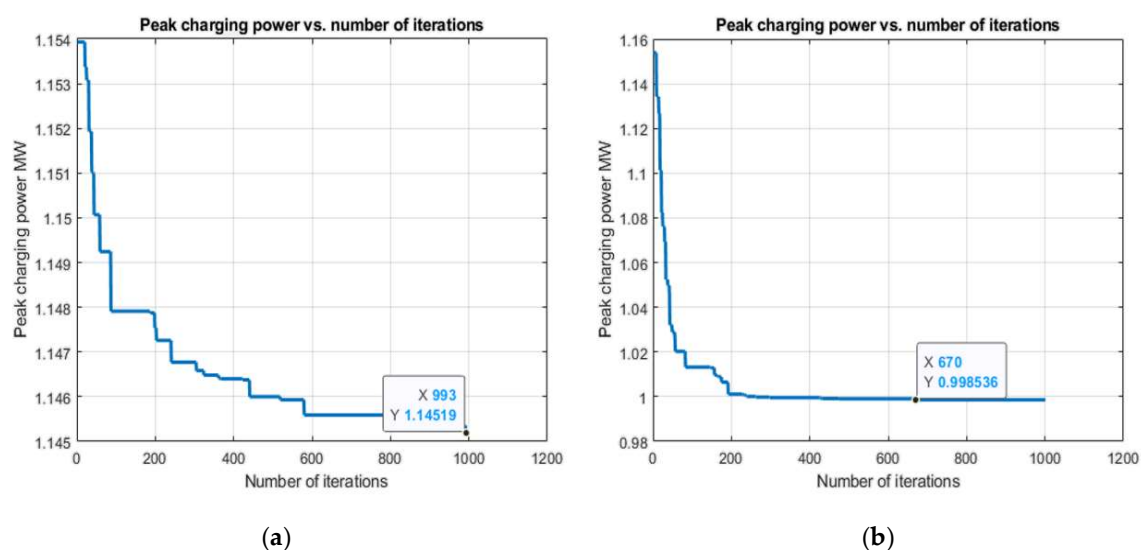


Figure 12. Convergence history (a) No. of particles = 1024 (b) No. of particles = 256.

Figure 13 displays an optimized charging schedule when the particle count is 256.

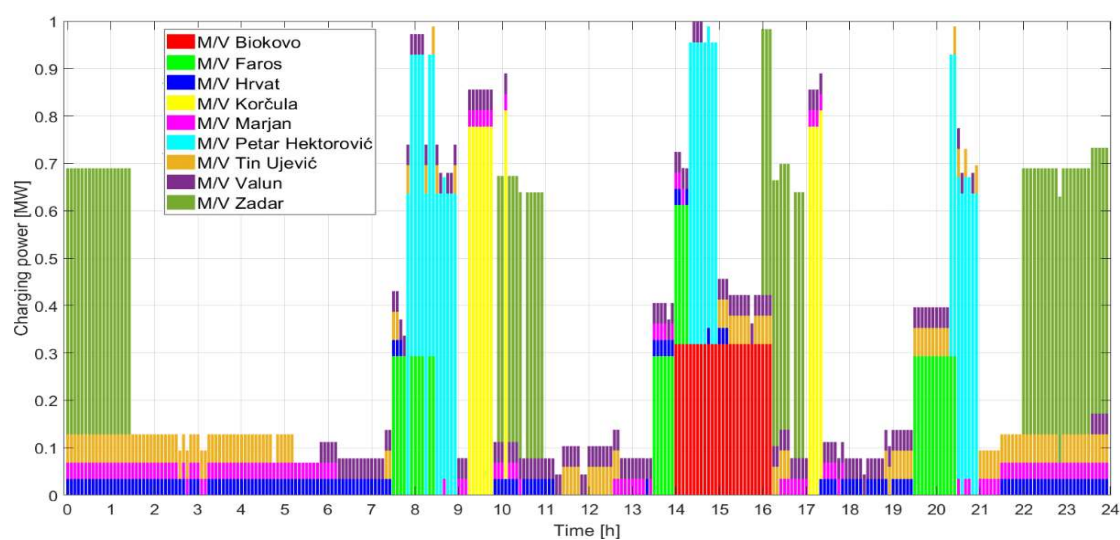


Figure 13. Optimized charging schedule when the number of iterations is set to 256.

4.2. Inertia Weight Factors Analysis

The inertia weight (global weight) is an important parameter in PSO because it affects the balance between global search and local search. A well-chosen value of inertia weight allows the algorithm to efficiently search the solution space and avoid getting stuck in local minima. When performing optimization, the inertia weight factor can be fixed or variable. The fixed factor is easy to apply and has a stable effect on most problems, while the biggest problem is that it is not variable during iterations. Therefore, the factor can be adjusted during optimization according to a certain criterion (linear, random, etc.). The weight factor can be adjusted depending on the performance of the swarm, i.e., the degree of improvement in function, and in this case, it is an adaptive weight factor [65].

The correct selection of inertia weighting factors improves the performance of the algorithm [66]. In the study [67], the influence of different inertia weight factors on the exploitation costs and lifetime of the battery ESS was analyzed. The use of an adaptive nonlinear approach to the determination of weight factors resulted in a reduction in operating costs and an extension of the lifespan of the battery energy storage system. In this research, the influence of choosing the proper size of the inertia weight on the function goal of this optimization task, which is the reduction of the peak charging power, was analyzed. There are different strategies when choosing inertia weight [68]. The usual setting is to select an initial value between [0.8 and 1.2]. However, in this optimization task, the local minimum was not reached in the interval of [0.6, 1.2]. In this research, the effect of the change in the magnitude of the inertia weight in the interval [0.2, 0.6] with a linear step of 0.05 was examined. The best result was achieved when the global weight was set to 0.55, and the number of particles was set to 2048. At such settings, the minimum amount of charging power is 0.9595 MW. With this optimization of parameters, a reduction of 16.2% was achieved in relation to the previously optimized charging power, which amounted to 1.14519 MW. Figure 14 shows the influence of the inertia weight factor on the optimization effect, i.e., on the reduction of the required peak charging power.

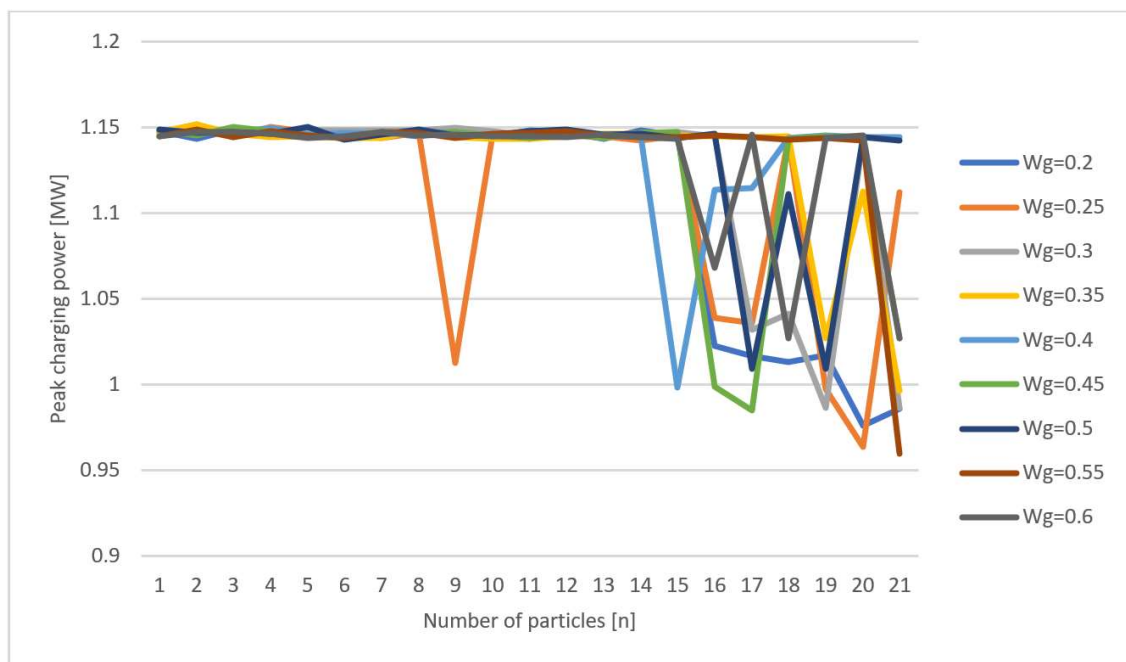


Figure 14. Influence of the inertia weight factor on the reduction of the peak charging power.

Finally, Figure 15 shows the optimized charging schedule of ships when a savings of 16.2% was achieved compared to the first optimization results.

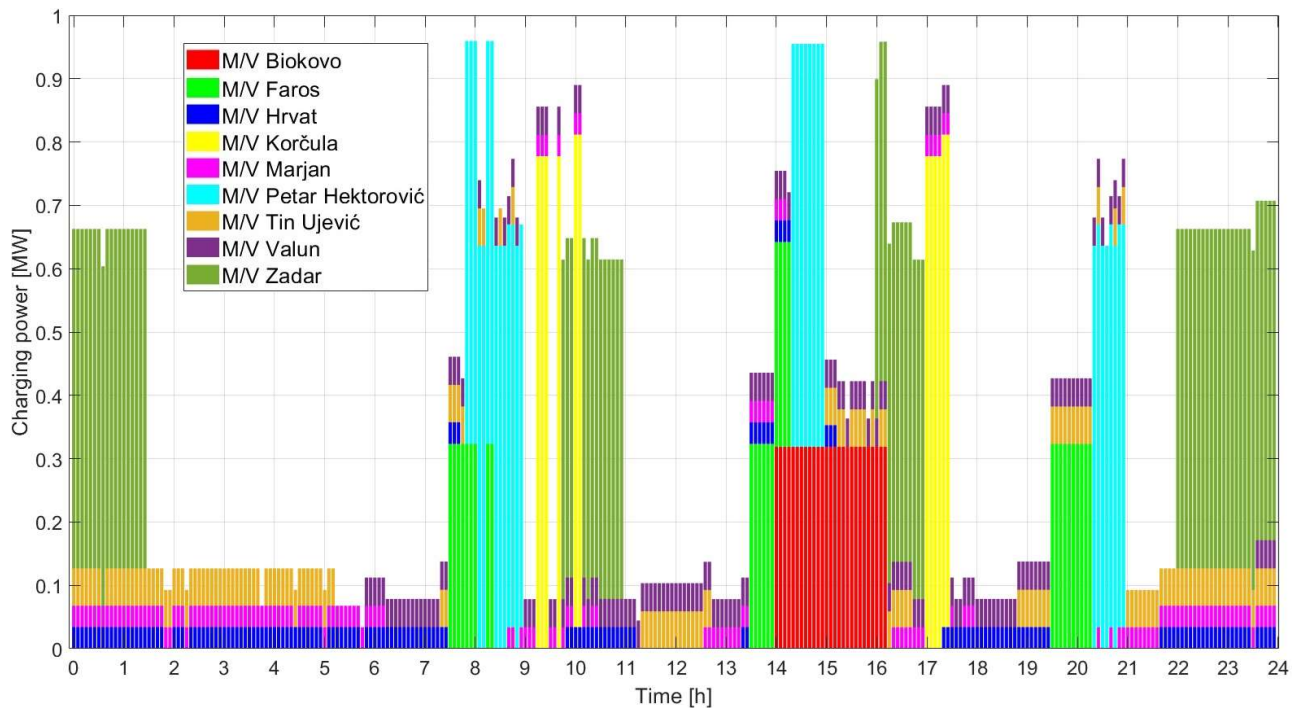


Figure 15. Optimized charging schedule when inertia weight factor is set to 0.55 while number of particles is set to 2048.

Sensitivity analysis is carried out to ensure the smooth functioning of a system, such as an energy system in which energy sources are renewable [69]. The mentioned research analyzes the optimization method for selecting the calculation of the sensitivity of dynamic characteristics and the mode of operation of the energy system. The results show that by applying the PSO algorithm, it is possible to reduce network losses and increase computing efficiency. In this particular study, the impact of the number of ferries was observed and it was concluded that the number of ferries itself does not significantly affect the results of optimization. However, the daily energy needs of each ferry significantly affect the optimization results. This is best manifested through the optimization effect and the time required to achieve the local minimum of the function goal.

5. Conclusions

This scientific research presents an analysis of the energy needs of a ferry fleet that uses the City Port of Split as one of its ports. Energy needs are determined on the basis of equivalent fuel consumption. They are non-periodic and non-seasonal. On a daily basis, they are extremely non-periodic due to the specifics of the sailing schedule in the high season. Non-periodic energy needs create a challenge when designing energy infrastructure, as it should be designed for the most unfavorable conditions that can occur. In order to reduce the amount of peak charging power, an optimization model was created that uses the PSO and a greedy algorithm. The goal function of this optimization task is to reduce the peak charging power. Furthermore, the model was optimized in such a way that the number of particles needed to search the area, i.e., to find the global minimum, was analyzed. The number of particles is defined, at which the optimization result is improved by 13.47% compared to the initial settings. The influence of the global weighting factor on the optimization of the peak charging power was also analyzed. For example, with an inertia weight factor of 0.55 with a defined particle number of 2048, a reduction in the peak charging power of 16.2% was achieved.

Recommendation for future research: Based on the obtained daily profile of the energy needs of the ship fleet, it is possible to determine the available energy capacities of the ships' ESS when the ships are not sailing. These ESS capacities can be used in the "ship-to-shore" system to reduce the load on the shore infrastructure when charging ferries that are priority for departure. Furthermore, the time a ferry spends in port is a significant parameter that affects the amount of charging power. Therefore, it is possible to optimize peak power by influencing the available charging time. It is also necessary to conduct a sensitivity analysis of the change in charging power in relation to the available charging time in future research.

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[01.04.2022. – today] Ministry of Defense of the Republic of Croatia, Croatian Military Academy, Marine Engineering Teacher

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- Chief engineer on the fast attack ship RTOP-12 "Kralj Dmitar Zvonimir"
- Chief engineer on the landing ship minelayer DBM-82 "Krka"
- Chief engineer on the fast attack ship RTOP-11 "Kralj Petar Krešimir IV"
- Chief engineer on patrol ship OB-03 "Cavtat"
- First Engineer on patrol ship OB-03 "Cavtat"

[21.08.2006. - 08.09.2008.] Ministry of Defense of the Republic of Croatia, Croatian Army, 4th Guards Brigade, Machine Gunner

[01.09.2005. - 18.08.2006.] Production and trade craft GRAFOPAK, line operator

[01.04.2005. - 31.07.2005.] VELO d.o.o. Split, Equipment Assembler

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[September 2016.- February 2017.] Croatian Military Academy, Advanced Officer Education

[2008-2010] - University of Split, Faculty of Maritime Studies, Master study

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[2001-2007] - University of Split, Faculty of Maritime Studies, Undergraduate study

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