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Possible Integration of PV Systems on Ferries in Boka Bay

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Abstract— **This paper explores the possibilities of integrating solar energy systems into ferries as a strategy to reduce emissions of harmful gases and conserve energy. Focusing on the use of photovoltaic (PV) technology, within the context of ferries operating on the newly planned route in Boka Bay (BB). Using PVsyst software, various factors including meteorological data, module type, inverter and batteries specifications, module inclination angle and azimuth orientation angle are analyzed to determine the feasibility and efficiency of utilizing solar energy onboard. This research highlights the possibilities of solar-hybrid Ro-Ro (roll-on/roll-off) systems in improving ferry operations while reducing their environmental impact. The conducted analysis indicates that the proposed solar-hybrid model for Ro-Ro ships on routes in BB, by implementing solar panels, can cover approximately 7% of the ferry's total energy needs.**

Keywords—solar energy, ferry, PVsyst, solar-hybrid system

I. Introduction

The maritime industry has been under pressure to address its impact on climate change, leading to the implementation of energy efficiency measures by the International Maritime Organization (IMO) since the beginning of this century. Within these measures, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), aim to reduce CO_2 emissions from global maritime traffic by promoting the adoption of energy-efficient technologies [1].

Recently, IMO member states have set targets for a 40% reduction in carbon emissions from global maritime traffic by 2030, with further reductions planned to achieve net-zero greenhouse gas emissions from international maritime transport by 2050 [2], [3].

EEDI is crucial for incorporating energy-efficient equipment into new ship designs, aiming to reduce pollution. Introduced in 2013, EEDI establishes minimum efficiency standards for different ship sizes and types, offering flexibility in technology selection while ensuring compliance. Initially focusing on large vessels, EEDI now covers emissions from various ship types, addressing about 85% of CO_2 emissions from global maritime traffic, while MEPC provides guidelines for its implementation and review [1].

In Montenegro's Maritime Economy Strategy, the focus on the oil and gas sector underscores the need for fuel efficiency and renewable energy adoption in transportation. Recommendations include exploring structural changes to reduce fuel consumption and leveraging renewable sources like biofuels and electricity. Additionally, there's a push for offshore research to tap into potential oil and gas reserves and promote the use of Liquified Petroleum Gas (LPG) as an alternative in tourism and households [4].

Aligning with these goals, integrating Renewable Energy Sources (RES) into ship power systems is key to enhancing efficiency and curbing emissions in maritime operations. This approach, in line with the EEDI, encourages the development of eco-friendly vessels by incorporating RES like solar, wind, or hybrid systems. By reducing reliance on traditional fuels, ships can save costs and contribute to environmental sustainability. Among these, solar and wind energy have gained significant traction worldwide, collectively contributing to approximately 3% of the global primary energy consumption [5].

The use of solar energy in maritime transport offers numerous benefits. Despite technical challenges and initial costs, there's growing interest in adopting solar photovoltaic systems on ships, especially for smaller setups. Research in this area is gaining importance, given new energy efficiency standards set by the IMO [6], [7], [8]. Hybrid solar ships, combining solar energy with batteries and traditional sources, are used for larger vessels needing higher speed and longer journeys. Both ship types can cut emissions and fuel costs, with further technology advancement. Installing solar panels on ships, feasible for new and existing vessels, considers factors like size, propulsion, and usage [9], [10]. On existing ships, panels are often mounted on the roof or deck, powering systems like navigation and communication while considering structural and aesthetic aspects [6], [11].

The integration of solar energy systems on ferries in BB presents a promising avenue for reducing emissions and fuel costs, while enhancing energy efficiency and reducing dependency on fossil fuels. Despite initial challenges, the adoption of solar photovoltaic systems on ferries holds significant potential in contributing to the decarbonization efforts of BB's maritime sector.

The paper is organized as follows. In Section 2, the integration of RES in the ship's electric power system is described. In Section 3, materials and methods are carried out. In Section 4, the results of the case study of a ferry in BB are given. Finally, the conclusion of the paper is outlined in Section 5.

II. Integration of RES in the ship's electric power system

The integration of novel energy sources such as solar, wind, and fuel cells into ship power systems is gaining momentum, with solar energy predominantly powering small vessels and supporting lighting/navigation on larger ships [5]. Wind energy aids propulsion through modern sails, while fuel cells show promise as a viable alternative to traditional diesel engines, potentially serving as the primary propulsion energy source. To enhance overall power output, experts recommend combining multiple sources, leading to the development of hybrid systems [12], [13].

Governments and researchers are increasingly prioritizing the adoption of these new energy sources, with solar and wind energy collectively contributing around 3% to the world's primary energy consumption [5]. Solar energy, abundant and eco-friendly, is mainly harnessed through photovoltaic (PV) generation and solar thermal conversion methods, witnessing rapid growth in application due to efficiency advancements. PV systems, operating primarily in stand-alone or grid-connected modes, are driving the expansion of renewable energy use in maritime applications [5], [14], [15].

In stand-alone mode, PV systems function independently of the main grid, providing power that is tailored to the energy demands of the load. This autonomy ensures that the operation characteristics of stand-alone PV systems remain unaffected by fluctuations in the main grid, simplifying their system structure and control mechanisms. However, if the electricity generated is insufficient to meet the load's requirements, excess power stored in battery banks can be utilized to bridge the deficit. Nonetheless, as the installed capacity of stand-alone PV systems increases, additional batteries may be necessary to match the system's capacity, potentially leading to higher initial costs [16].

Grid-connected PV systems offer advantages both for terrestrial power grids and ship-based applications. When connected to the terrestrial grid, there is no obligatory need for an energy storage system, but this consideration changes for ships. The reason lies in the significant difference in response time between power electronics and the ship's mechanical systems. If the PV system's power fluctuates excessively, synchronous generators may struggle to respond promptly, causing stability issues. Thus, integrating an energy storage system matching the PV array's capacity is vital. This allows the ship's energy management system to efficiently schedule power output, ensuring optimal use of PV power. On the other hand, grid-connected PV systems are linked to the main grid, virtually overcoming challenges related to dynamic power balance. When the PV system's output falls short of the load's demand, the main grid supplements power requirements. However, compatibility is essential; the PV system's inverter output must align with the main grid's voltage, frequency, and phase sequence. Control strategies for grid-connected PV systems are more diverse and complex compared to stand-alone systems due to managing power flow between the PV system and the main grid [5], [8].

Additionally, hybrid PV systems offer a versatile approach by operating in both stand-alone and grid-connected modes. These systems incorporate an automatic transfer switching (ATS) mechanism, facilitating seamless transitions between operational modes. In scenarios where battery banks are fully charged, surplus electricity can be directed to the main grid through a grid-connected inverter. This adaptability not only ensures optimal energy efficiency but also enhances the overall reliability and resilience of the PV generation system [17].

Solar-powered ships utilize onboard photovoltaic (PV) generation systems to convert sunlight into electricity, stored temporarily in batteries for propulsion or onboard electrical devices. While solar energy chiefly powers small-scale ships, it serves as supplementary power for larger vessels due to energy density and conversion limitations [5], [15], [18].

Solar/battery-powered ships combine PV panels with battery systems, typical for medium and small-scale vessels. For larger ships like ocean-going car carriers, hybrid solar/diesel generator/battery systems ensure continuous and reliable power supply by combining solar energy with diesel generators.

Enhancing the energy efficiency of PV generation systems is pivotal for solar-powered ships. Maximum Power Point Tracking, MPPT-based control technologies, including variable constant *k* and short current pulses, are developed to optimize output power. Simpler MPPT control methods using PV-powered microcontrollers are also explored to boost power output and efficiency [19].

III. Methodology of the conducted research

This research focuses on exploring the application of photovoltaic systems on the ferry ship intended to operate on a potential new route within BB, specifically Zelenika-Solila-Zelenika. The ferry prototype was built based on literature and available data on ferries already operating in BB on the route Kamenare-Lepetane-Kamenari. One of the ferries that already operates in BB is shown in Figure 1. The prototype ferry that was used for the simulation has an overall length (including ramps) of 59.75 meters and a maximum width of 16 meters. Analysis was conducted using PVsyst software.

Fig. 1. One of the ferry ship sailing on the route Kamenare-Lepetani in BB (Source: https://www.shipspotting.com/photos/3582769)

Table 1 outlines key characteristics of the ferry, highlighting diesel engines as the primary propulsion method, each rated at

447 kW, supported by two diesel generators with a total power of 200 kW.

TABLE I. KEY CHARACTERISTICS OF THE FERRY [20]

Ferry's length overall (including ramps)	59.75. m
Ferry's width	16 m
Ferry's draft	2,35 m
Passenger ferry capacity	49 vehicles
Ferry speed	9 knots
Engines	2x447kW, 1800 rpm
Diesel generators	2x100 kW
Route distance	Around 7 NM

The design of the PV system is tailored to accommodate the potential new route in BB that is shown in Figure 2. Currently, there has been no techno-economic analysis conducted by the public enterprise managing marine assets regarding the establishment of a new ferry line from the port of Zelenika near Herceg Novi to Solila in Krtole near Tivat, spanning seven NM (nautical miles). This new route aims to alleviate road and traffic congestion, offering a faster alternative to circumventing the bay and reducing the carbon footprint caused by the use of fossil fuels. The ferry should sail for approximately one hour in one way.

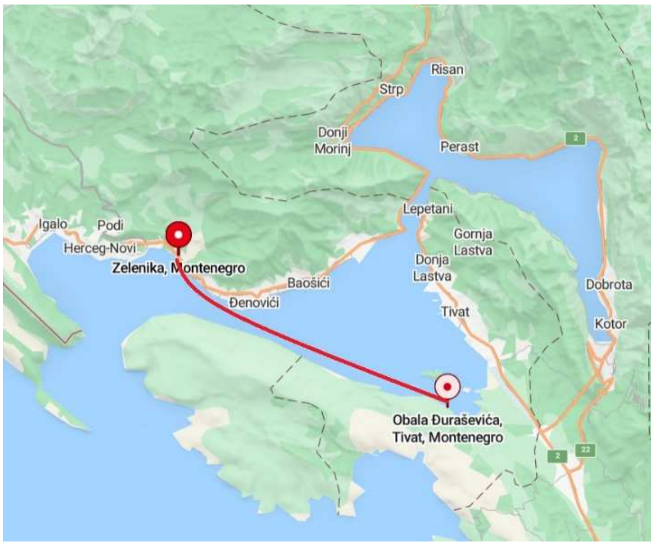

Fig. 2. Possible new ferry route from Zelenika to Solila

The paper's objective is to propose a preliminary design solution for a ferry with reduced onboard emissions compared to existing diesel-fueled ferries operating on the same route.

A. PVsyst software

PVsyst is a software application employed in the design of photovoltaic systems, providing capabilities for a range of configurations like on-grid, off-grid, and solar water pumping arrangements. Meteorological data can be sourced from various platforms such as "METEON 7.2," "NASA-SSE," or "PVGIS TIM," or entered manually depending on the project's location. The software enables the development of 3D models representing solar panel shapes and surfaces to analyze shading effects and assess their influence on power generation. PVsyst also produces comprehensive reports containing essential system information [21].

The power output of a photovoltaic system depends on the number of panels and their connections. Operational parameters are consistent for both terrestrial and marine applications, with a focus on protecting PV systems in marine environments. In marine solar installations, cell type varies based on surface area and cost, with two main types: crystalline cells (monocrystalline and polycrystalline) and thin films. Monocrystalline cells are pricier but more efficient and durable, lasting over 30 years, while polycrystalline cells are cheaper but less efficient and durable, lasting over 25 years. Thin films lack crystalline structure, are less efficient and durable, but are cheaper and can be installed on curved or flexible surfaces [22], [23].

Horizontally installing solar panels on vessels yields the most efficient electricity output, as observed [24]. A simulation was conducted to assess the performance of solar panels horizontally installed on the roof structure of a proposed ferry, featuring 264 modules covering a surface area of 592 m^2. For the ferry's roof structure, monocrystalline solar panels (Mono 440 Wp, 72 cells) were selected. These panels are high-efficiency, capable of generating 440 watts of power under standard conditions, with 72 cells and bifacial technology to capture sunlight from both sides.

Number of 264 modules are arranged in 33 strings of 8 modules in series each, resulting in a total system nominal power of 116 kWh. Utilizing monocrystalline solar panels in maritime applications presents several advantages: high efficiency, durability in harsh marine environments, space-saving design, and reduced reliance on fossil fuels for environmental sustainability. Figure 3 presents the typical layout of a stand-alone system in PVsyst software. Figure 3. presents the typical layout of a stand-alone system given in PVsyst software.

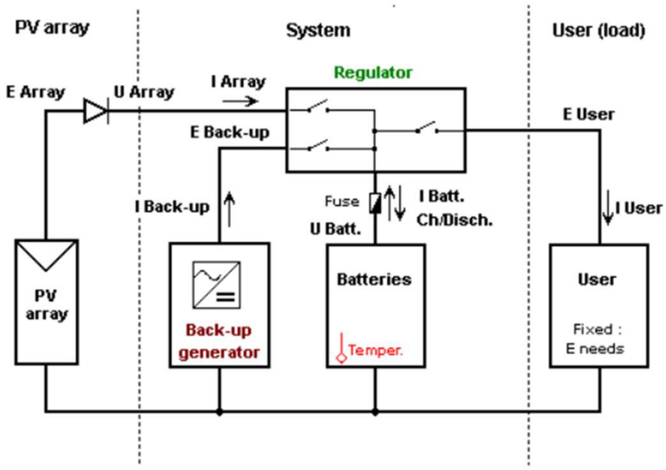

Fig. 3. Typical layout of a stand-alone system

IV. RESULTS

The integration of a photovoltaic (PV) system on the proposed ferry, which sails between Zelenika and Solila, contributes to the decarbonization of the BB, aiming for more environmentally sustainable maritime transport. The duration of the journey between these two destinations is approximately one hour, posing specific demands on the capacity and efficiency of the PV system.

The Loss Diagram, from the PVsyst simulation highlights key factors contributing to energy loss within the solar power system. Battery self-discharge current accounts for 13.57% of the loss, reflecting gradual energy depletion over time due to internal chemical reactions. Additionally, battery inefficiencies contribute to a 4.17% loss, while converter inefficiencies during operation result in a 4.48% loss. Understanding these losses is essential for optimizing system performance, guiding adjustments to enhance efficiency, minimize waste, and ensure cost-effective energy utilization in the long term.

Using PVsyst software, modeling was conducted to analyze the ferry's specific electrical energy needs, including estimating the capacity required for the main engine and other operational requirements such as auxiliary systems and the hotel section, with a daily consumption estimated at around 7170 kWh from April until the end of September.

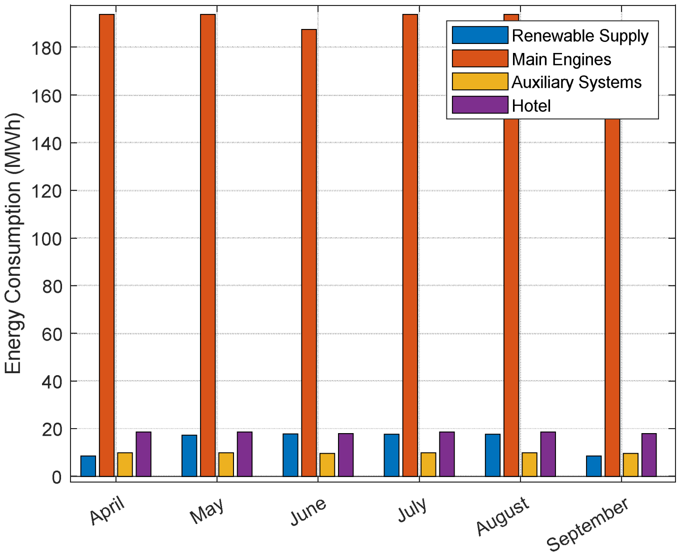

Fig. 4. Comparison of required energy and energy obtained from PV systems

A PV system of 116 kWh, equipped with 264 solar modules and lithium-ion batteries with a capacity of 146,520 Ah, forms the basis for this analysis. Simulation of the PV system's operation was performed considering the available installation area for panels on the ferry, local meteorological parameters based on NASA-SSE satellite imagery, relevant for the period from June to September, as well as the specificities of the solar cell and battery technologies selected for this project. The calculation of the ferry's electricity demand shows that the main engine requires 625 kWh of energy, while the auxiliary systems and hotel section require 33.2 kWh and 60 kWh, respectively for one hour sail [20]. However, simulation results indicate that the installed PV system could meet approximately 7% of the total energy demand during the period from April until September, which could cover the energy required for auxiliary systems and the hotel, as depicted in Figure 4.

In Figure 5, the monthly distribution of the total electrical energy generated by the PV system over the period from April until September is shown. It is noticeable that the highest amount of electrical energy is obtained during the seasonal summer months, peaking in June and July, coinciding with the period of most intense solar radiation.

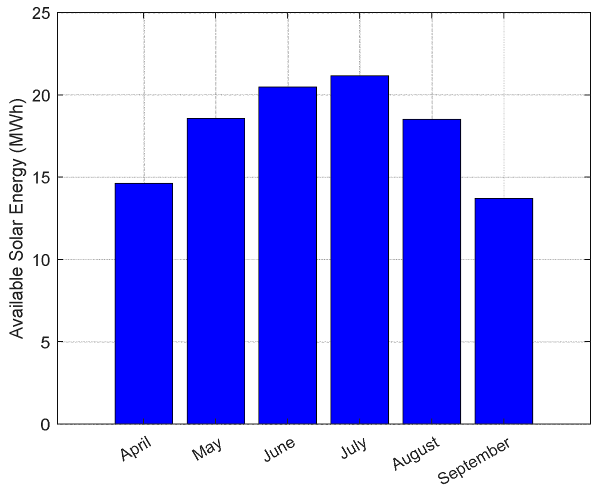

Fig. 5. Total electrical energy obtained from the PV system

Figure 6 illustrates the direct correlation between global horizontal radiation and the amount of electrical energy generated by the PV system throughout the year. The highest energy production occurs during the summer months when radiation is most intense, while cloudy days and fog reduce panel efficiency. As global horizontal radiation increases, solar panels have the ability to generate more electrical energy. To fully utilize the PV system's potential, it is crucial to consider factors such as optimal tilt angle and precise panel orientation, ensuring maximum energy production efficiency.

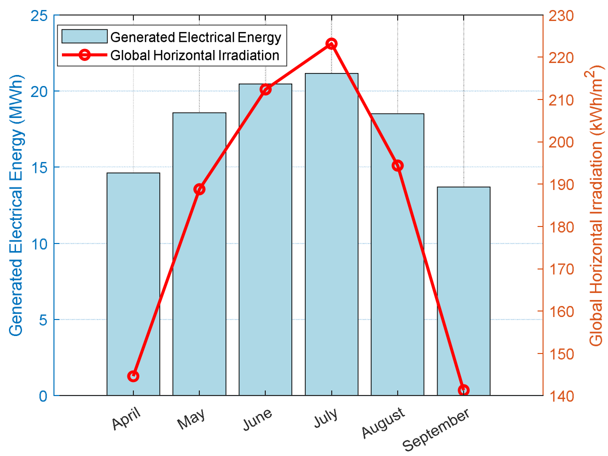

Fig. 6. The relationship between global horizontal radiation and energy production

V. Conclusion

Integration of PV systems on the ferry for the Zelenika-Solila-Zelenika route is significant for decarbonizing the BB, as well as sustainability in the maritime sector. Analysis indicates that during the summer months, generated solar energy can cover a significant portion, approximately 7%, of the ferry's total energy needs. Surplus unused energy and limited battery storage capacities point to the need for further optimization of the planned PV system on the ferry. This research confirms the potential and importance of integrating renewable energy sources into maritime transport, highlighting opportunities for savings and improvements in terms of energy efficiency and environmental sustainability. Future research will focus on a more detailed analysis and optimization of the system, including evaluating long-term benefits and potential challenges in implementing it across a wider range of vessels navigating the BB.

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REFERENCES

[1] International Maritime Organizatio, "Improving the energy efficiency of ships", Accessed: Oct. 03, 2024. [Online]. Available:https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx

[2] L. Laffineur, F. Spiegelenberg, and I. S. Jegou, "The implications of the IMO Revised GHG Strategy for shipping", Accessed: Mar. 15, 2024. [Online]. Available: https://www.gov.me/en/documents/452e9a0d-305d-41a4-bd57-e5d8c0ae869d

[3] D. Englert, I. Rojon, R. Salgmann, and S. Sulikova, "A new climate deal for shipping: Three decades to zero", Accessed: Oct. 03, 2024. [Online]. Available: https://blogs.worldbank.org/transport/new-climate-deal-shipping-three-decades-zero

[4] Government of Montenegro, "Strategy for Development of Maritime Economy 2020-2030." Government of Montenegro, 2021.

[5] P. Pan, Y. Sun, C. Yuan, X. Yan, and X. Tang, "Research progress on ship power systems integrated with new energy sources: A review," Renewable and Sustainable Energy Reviews, vol. 144, p. 111048, Jul. 2021, doi: 10.1016/j.rser.2021.111048.

[6] I. Knežević, S. Dragićević, M. Ćalasan, and T. Dlabač, "Paramterske analize fotonaponskog sistema na brodu," presented at the Crnogorski komitet CIGRE, Jun. 2023.

[7] Z. Ma, Y. Zhang, and H. Li, "Energy efficiency analysis of inland ship photovoltaic system based on PVsyst," IOP Conf. Ser.: Earth Environ. Sci., vol. 242, p. 022057, Mar. 2019, doi: 10.1088/1755-1315/242/2/022057.

[8] Y. Sun et al., "The application of hybrid photovoltaic system on the ocean-going ship: engineering practice and experimental research," Journal of Marine Engineering & Technology, vol. 18, no. 1, pp. 56–66, Jan. 2019, doi: 10.1080/20464177.2018.1493025.

[9] M. Kalajdžić, M. Vasilev, and N. Momčilović, "Assessment of Energy Efficiency for the Existing Cargo Ships," JMS, vol. 23, no. 1/2022, pp. 33–46, Jun. 2022, doi: 10.56080/jms220502.

[10] D. Tamunodukobipi, N. Samson, and A. Sidum, "Design Analysis of a Lightweight Solar Powered System for Recreational Marine Craft," WJET, vol. 06, no. 02, pp. 441–456, 2018, doi: 10.4236/wjet.2018.62027.

[11] W. Kapuścik, J. Maraszek, M. Borowicz, and K. Sornek, "AGH Solar Boat –the analysis of energy and ecological parameters of the solar powered boat," IOP Conf. Ser.: Earth Environ. Sci., vol. 214, p. 012143, Jan. 2019, doi: 10.1088/1755-1315/214/1/012143.

[12] M. S. Hossain, N. A. Madlool, N. A. Rahim, J. Selvaraj, A. K. Pandey, and A. F. Khan, "Role of smart grid in renewable energy: An overview," Renewable and Sustainable Energy Reviews, vol. 60, pp. 1168–1184, Jul. 2016, doi: 10.1016/j.rser.2015.09.098.

[13] F. Diab, H. Lan, and S. Ali, "Novel comparison study between the hybrid renewable energy systems on land and on ship," Renewable and Sustainable Energy Reviews, vol. 63, pp. 452–463, Sep. 2016, doi: 10.1016/j.rser.2016.05.053.

[14] A. C. Köberle, D. E. H. J. Gernaat, and D. P. Van Vuuren, "Assessing current and future techno-economic potential of concentrated solar power and photovoltaic electricity generation," Energy, vol. 89, pp. 739–756, Sep. 2015, doi: 10.1016/j.energy.2015.05.145.

[15] S. Mekhilef, R. Saidur, and A. Safari, "A review on solar energy use in industries," Renewable and Sustainable Energy Reviews, vol. 15, no. 4, pp. 1777–1790, May 2011, doi: 10.1016/j.rser.2010.12.018.

[16] A. Mohammed, J. Pasupuleti, T. Khatib, and W. Elmenreich, "A review of process and operational system control of hybrid photovoltaic/diesel generator systems," Renewable and Sustainable Energy Reviews, vol. 44, pp. 436–446, Apr. 2015, doi: 10.1016/j.rser.2014.12.035.

[17] Y. Qiu, C. Yuan, and Y. Sun, "Review on the application and research progress of photovoltaics-ship power system," in 2015 International Conference on Transportation Information and Safety (ICTIS), Wuhan, China: IEEE, Jun. 2015, pp. 523–527. doi: 10.1109/ICTIS.2015.7232167.

[18] B. Bacalja Bašić, M. Krčum, and A. Gudelj, "Adaptation of Existing Vessels in Accordance with Decarbonization Requirements—Case Study—Mediterranean Port," JMSE, vol. 11, no. 8, p. 1633, Aug. 2023, doi: 10.3390/jmse11081633.

[19] Y. Sun et al., "The application of hybrid photovoltaic system on the ocean-going ship: engineering practice and experiment research".

[20] M. Kalajdžić, N. Momčilović, L. Mijatović, University of Belgrade, Faculty of Mechanical Engineering, Department of Naval Architecture, and University of Belgrade, Faculty of Mechanical Engineering, Department of Naval Architecture, "Decarbonizing the Bay of Kotor: Preliminary Electrification Concept of a Ferry," JMS, vol. 24, no. 1, pp. 22–35, May 2023, doi: 10.56080/jms230503.

[21] Ž. Vojvodić, M. Ćalasan, "Potencijal solarne energije u gradovima Crne Gore," VIII Savjetovanje Crnogorskog Komiteta CIGRE, Budva, Crna Gora, Maj 9-12., 2023.

[22] I. Kobougias, E. Tatakis, and J. Prousalidis, "PV Systems Installed in Marine Vessels: Technologies and Specifications," Advances in Power Electronics, vol. 2013, pp. 1–8, Mar. 2013, doi: 10.1155/2013/831560.

[23] Y. Siregar, Y. Hutahuruk, and Suherman, "Optimization Design and Simulating Solar PV System Using PVSyst Software," in 2020 4rd International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM), Medan, Indonesia: IEEE, Sep. 2020, pp. 219–223. doi: 10.1109/ELTICOM50775.2020.9230474.

[24] H. Lan, J. Dai, S. Wen, Y.-Y. Hong, D. Yu, and Y. Bai, "Optimal Tilt Angle of Photovoltaic Arrays and Economic Allocation of Energy Storage System on Large Oil Tanker Ship," Energies, vol. 8, no. 10, pp. 11515–11530, Oct. 2015, doi: 10.3390/en81011515.