

Sustainable Marine Engineering Practices: Integration of Renewable Energy Systems on Ships

Igor Astrakhovych

astemio8[at]gmail.com

<https://www.linkedin.com/in/igor-astrakhovych-424298129>

Houston, TX, 77084, United States

Abstract: *The study presents a comprehensive analysis of current approaches to sustainable marine engineering, with particular emphasis on the synergistic integration of various renewable-energy technologies on board a vessel. The objective is to evaluate existing solutions including wind-assist propulsion systems, photovoltaic panels, and power plants operating on alternative fuels in terms of their combined impact on energy efficiency, economic return, and regulatory compliance. The methodological framework comprises a systematic review and meta-analysis of scientific publications and industry reports published in recent years. The results demonstrate that hybrid power arrangements combining several types of renewable energy sources achieve greater emission reductions and lower operational costs than the deployment of stand-alone technologies. Scientific novelty is represented by a comprehensive multicriteria method for selecting the optimal configuration of hybrid renewable-energy solutions that simultaneously accounts for technical, economic, and regulatory factors. The findings will be of value to naval architects, fleet owners, classification societies, and researchers engaged in the decarbonisation of maritime transport.*

Keywords: sustainable shipping, shipboard renewable energy, wind-assist propulsion, solar panels, hybrid power systems, decarbonisation, EEXI, CII, marine engineering, energy efficiency

1. Introduction

The International Maritime Organization (IMO) has tasked the shipping sector with cutting its greenhouse-gas emissions by at least 50 % by 2050 relative to the 2008 baseline [1]. To pursue this goal, the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) have been in force since 2023, imposing unprecedented pressure on shipowners and operators and prompting the adoption of new technical and operational solutions [2]. In this context, research into integrating renewable energy sources (RES) into shipboard power systems has become exceptionally timely. The existing scholarly literature focuses mainly on individual technologies such as wind-assisted propulsion systems or photovoltaic panels while giving insufficient attention to the mutual reinforcement achievable through their combined use and to the integrated consideration of technical, economic, and regulatory factors within a single framework [10].

The objective of the study is to evaluate existing solutions including wind-assisted propulsion sails, photovoltaic modules, and power units operating on alternative fuels with respect to their combined influence on energy efficiency, economic return, and regulatory compliance.

The scientific novelty lies in presenting an integrated multi-criteria method for selecting the optimal configuration of hybrid renewable-energy technologies, taking into account technical, economic, and regulatory factors.

The working hypothesis posits that a hybrid approach combining wind-propulsion systems, photovoltaic arrays, and energy-storage devices constitutes the most cost-effective and technically reliable means of reducing emissions on high-fuel-consumption vessels (e.g., tankers

and bulk carriers), in contrast to reliance on a single technology or the premature adoption of volatile alternative fuels.

2. Materials and Methods

A review of the literature reveals a range of methodological approaches to the decarbonization of maritime transport and the integration of renewable energy sources. In the regulatory domain, International Maritime Organization (IMO) instruments and related reports employ both target-based and forecast-based analyses: the IMO's resolution to reduce greenhouse-gas emissions by 50 % by 2050 is grounded in scenario modelling of the greenhouse-gas balance [1]; the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations define methodologies for calculating carbon intensity tailored to different vessel types [2]; and Zhang et al. apply macroeconomic modelling to evaluate the effects of these regulations on the fleet and logistics chains [9]. Analytical forecasts produced by DNV combine expert surveys with quantitative scenario modelling, underscoring the importance of digitalization and automation in future developments [10, 13].

Practical investigations into the integration of renewable systems at sea fall into three main categories. Li Z., Tang J. [3] design circulation-controlled wind devices featuring movable surfaces and active boundary-layer control, merging aerodynamic theory with CFD simulations to enhance thrust across various vessel operating regimes. Yin H. et al. [5] present a comprehensive classification of onboard energy systems including hydrogen fuel cells, lithium-ion batteries and microturbines and compare them in terms of energy density, reliability and integration constraints. McAllister L., Wang H. [8] analyse the performance dynamics and economic viability of photovoltaic installations, employing levelized cost of

energy (LCOE) methodologies and environmental life-cycle assessment (LCA), and propose optimal hybrid system architectures that account for geographic and operational factors.

In the field of alternative fuels, Zamboni G. et al. [4] conduct a full “well-to-wake” life-cycle assessment, encompassing fuel production, transportation and combustion, and identify the trade-offs among range, emissions and operating costs. Perčić M., Vladimir N., Fan A. [6] focus on the specifics of Croatia’s inland waterways, using econometric models and scenario-based cost analyses for methanol, biodiesel and hydrogen that incorporate infrastructure investment considerations.

Hybrid energy systems are surveyed by Inal O. B., Charpentier J. F., Deniz C. [7], who categorise combinations of diesel generators, batteries, fuel cells and reduction devices, and identify key technological barriers such as power management, the reliability of integrated systems and maintenance requirements.

Methods for improving vessel energy efficiency address hull optimisation and overall system architecture. Hüffmeier J., Johanson M. [11] summarise contemporary strategies streamlined hull forms, reduced hydrodynamic resistance, air-lubrication systems and waste-heat recovery while Tadros M., Ventura M., Guedes Soares C. [12] explore decision-support tools based on multi-criteria optimisation (including economic value added, genetic algorithms and fuzzy logic) for selecting design solutions that meet operational requirements.

Overall, the literature exhibits a tension between regulatory-focused studies and those centred on technical solutions: many investigations rigorously model either regulatory frameworks or individual technologies, but seldom integrate both within a unified, comprehensive strategy. Inconsistencies in LCA methodologies particularly variations in “well-to-wake” system boundaries hinder the comparability of results [4, 6]. Insufficient attention has been paid to the simultaneous deployment of multiple renewable systems (wind, photovoltaics, batteries) and their real-time management, as well as to the role of digitalization and cyber-physical systems in optimising vessel operation. Furthermore, socio-economic and regional dimensions of new technology implementation remain underexplored, especially on inland and coastal routes with limited port infrastructure.

3.Results and Discussion

The analysis conducted enables the systematization and comparative evaluation of key technologies that employ renewable energy sources in shipbuilding. Table 1 presents the integrated characteristics of the principal technologies, synthesized from data in sources [3, 5, 6, 11]. This compilation provides the methodological foundation for a subsequent multicriteria analysis focused on fuel-saving performance, technology readiness level (TRL), capital expenditure (CAPEX), and the identification of major operational and technical risks.

Table 1: Comparative characteristics of renewable energy technologies for ships (compiled by the author based on the analysis [3, 5, 6, 11]).

Technology	Capital costs (CAPEX)	Main challenges
Wind-assisted propulsion systems (WAPS)	Medium/High	Dependence on weather conditions, impact on stability and cargo operations, need for deck reinforcement
Solar photovoltaic systems (PV)	Low/Medium	Limited deck area, panel degradation in marine environment, shading from superstructures and equipment
Fuel cells (Hydrogen)	Very high	Fuel storage (cryogenic or high-pressure), lack of infrastructure, safety concerns
Fuel cells (Ammonia)	Very high	Fuel toxicity, NOx formation during combustion, lack of infrastructure, low reaction speed
Energy storage systems (ESS)	Medium	Limited battery lifespan, battery weight and volume, fire hazard, cost

As Table 1 illustrates, no universal solution exists. Technologies with the highest potential for emission abatement particularly fuel cells still exhibit low technology-readiness levels and demand enormous capital investments as well as the rollout of an entirely new global infrastructure. By contrast, the more mature options wind-assisted power systems (WAPS) and photovoltaic (PV) installations provide moderate yet presently attainable emission reductions, supported by well-established economic models. The data obtained confirm the validity of a hybrid approach. To visualise the concept of synergistic integration, Figure 1 presents a conceptual diagram of a hybrid power plant for a representative Aframax tanker.

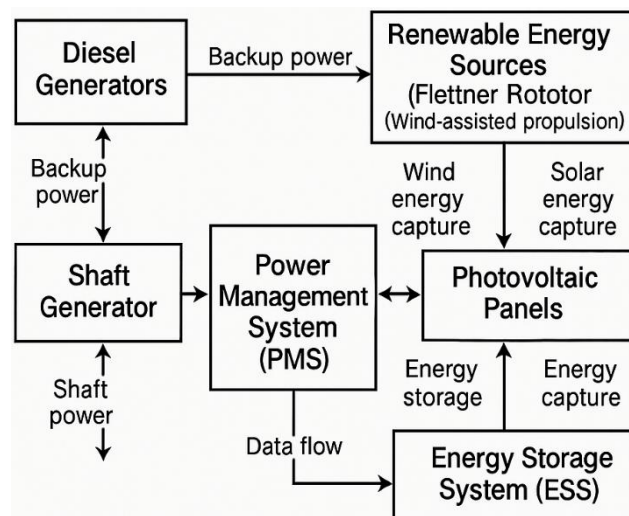


Figure 1: Basic architecture of the integrated hybrid power system of the vessel (compiled by the author based on the analysis of [4, 9, 13])

As shown in Figure 1, this configuration emphasises the primary function of the Power Management System (PMS), which serves as the intelligent hub of the entire complex. Operating continuously, the PMS collects and analyses data from all power sources diesel generators and the shaft generator as well as from consumers, renewable energy sources (Flettner rotor installations that unload the main engine, and photovoltaic panels), and the energy-storage system (ESS). The objective is to allocate energy flows rationally in order to achieve maximum efficiency. Under favourable wind conditions, for example, the PMS can reduce the load on the main engine by employing the propulsive thrust generated by the rotors, while directing any excess power produced by the shaft generator to recharge the ESS. During manoeuvring or short-term peak electrical loads, the stored energy in the ESS may be used, eliminating the need to start an additional diesel generator, thereby saving fuel and reducing equipment wear [7, 12].

The economic performance of Wind-Assisted Propulsion Systems (WAPS) is largely determined by meteorological conditions along the vessel's route. Simulation results based on the data presented in [3, 8] indicate that fuel savings display a pronounced nonlinear dependence on wind-speed parameters.

Integrating photovoltaic arrays with energy-storage systems (ESS) mitigates the output fluctuations inherent to wind turbines and maintains a minimum level of "green" generation even during periods of calm. This technological combination provides a reserve power source, reduces reliance on diesel generators, and ensures uninterrupted energy supply by storing surplus solar electricity in ESS batteries [4, 5].

Table 2 below outlines the implications of implementing renewable energy systems on board ships, from the immediate benefits and barriers to the directions that will shape the future of marine sustainable engineering.

Table 2: Aspects of Implementing Renewable Energy Systems on Vessels: From Immediate Benefits and Barriers to Directions Shaping the Future of Sustainable Marine Engineering (compiled by the author based on analyses [4, 5]).

Advantage	Disadvantage	Future Trend
Reduction of greenhouse gas emissions: direct cuts in CO ₂ and SO _x /NO _x compared with conventional engines.	High capital expenditure: initial investment required for installation of wind turbines, solar panels and batteries.	Hybridization of energy sources: combining wind and solar installations with hydrogen fuel cells.
Fuel savings: supplementary energy generation from wind and solar decreases diesel demand.	Limited deck area and weight capacity: insufficient free space for large volumes of panels or rotors.	Advanced energy storage solutions: solid-state batteries, supercapacitors, and offshore "battery hub" platforms.
Increased energy autonomy: reduced dependence on fluctuations in oil product prices.	Variable performance: energy output depends on weather conditions and route profile.	Automation and AI-driven optimization: digital twins and machine-learning algorithms for adaptive energy-flow management.
Lower operating costs: over extended service life, fuel savings outweigh initial capital expenditures.	Integration complexity: existing propulsion systems and control architectures require significant modification.	Novel lightweight materials: composite rotors and PV modules with enhanced strength and corrosion resistance.
Image and regulatory benefits: compliance with "green" standards enhances the reputation of shipping companies.	Maintenance requirements: skilled personnel needed to monitor and service novel systems.	Development of regulatory framework: unified international standards and incentives for green shipping.
		"Energy island" concepts: mobile charging platforms for vessel replenishment at sea.

The conducted study demonstrates that the future of sustainable marine engineering depends on the deployment of comprehensive hybrid systems. Isolated installation of individual renewable energy sources cannot achieve the International Maritime Organization's ambitious decarbonization goals. Only a synergistic combination of wind-propulsion devices, solar panels, and energy-storage units, incorporated into intelligent control systems, can deliver maximal technical and economic returns.

4. Conclusion

The research confirms that the stated objective a comprehensive examination of the potential for integrating renewable energy sources into marine power plants has been achieved. The findings demonstrate that regulatory pressure, particularly the introduction of EEXI and CII requirements, is the primary driver stimulating innovative transformation within the shipbuilding industry. The review of specialized literature revealed considerable

progress in the development of individual renewable technologies, while exposing a shortage of studies devoted to their combined, synergistic application.

The principal conclusion validates the initial hypothesis: hybrid power systems that couple multiple renewable sources with energy-storage units represent the most promising means of decarbonizing maritime transport. Such configurations deliver substantial reductions in greenhouse-gas emissions and fuel consumption while enhancing the operational flexibility and reliability of shipboard systems. This approach enables the formation of a balanced investment strategy that reflects capital expenditures, operational benefits, and long-term environmental obligations.

Future work should refine power-management system algorithms through machine-learning-based predictive optimization and conduct expanded life-cycle assessments of hybrid vessels, encompassing the production and disposal phases of renewable-energy components.

References

to-2050-with-german-maritime-leaders.html (date of access: 15.05.2025).

- [1] IMO agrees 50% reduction in GHG emissions by 2050. [Electronic resource]. - Access mode: <https://www.ship-technology.com/news/imo-agrees-50-reduction-ghg-emissions-2050/> (date of access: 05.05.2025).
- [2] EEXI and CII - ship carbon intensity and rating system. [Electronic resource]. - Access mode: <https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx> (date of access: 08.05.2025).
- [3] Li Z., Tang J. Circulation-controlled wind-assisted ship propulsion: Technical innovations for future shipping industry decarbonization //Energy Conversion and Management. – 2024. – Vol. 319. <https://doi.org/10.1016/j.enconman.2024.118976>.
- [4] Zamboni G. et al. Comparative analysis among different alternative fuels for ship propulsion in a well-to-wake perspective //Heliyon. – 2024. – Vol. 10 (4). - pp. 1-21.
- [5] Yin H. et al. A comprehensive review of shipboard power systems with new energy sources //Energies. – 2023. – Vol. 16 (5). <https://doi.org/10.3390/en16052307>.
- [6] Perčić M., Vladimir N., Fan A. Techno-economic assessment of alternative marine fuels for inland shipping in Croatia //Renewable and Sustainable Energy Reviews. – 2021. – Vol. 148. <https://doi.org/10.1016/j.rser.2021.111363>.
- [7] Inal O. B., Charpentier J. F., Deniz C. Hybrid power and propulsion systems for ships: Current status and future challenges //Renewable and Sustainable Energy Reviews. – 2022. – Vol. 156. <https://doi.org/10.1016/j.rser.2021.111965>.
- [8] McAllister L., Wang H. Techno-Economic and Environmental Analysis of the Integration of PV Systems into Hybrid Vessels //Energies. – 2024. – Vol. 17 (10). <https://doi.org/10.3390/en17102303>.
- [9] Zhang Q. et al. Towards decarbonization: How EEXI and CII regulations affect container liner fleet deployment //Transportation Research Part D: Transport and Environment. – 2024. – Vol. 133. <https://doi.org/10.1016/j.trd.2024.104277>.
- [10] Maritime Forecast to 2050: Navigating the transition to a zero-carbon future. – Høvik: DNV, 2023. [Electronic resource]. - Access mode: <https://www.dnv.com/maritime/publications/maritime-forecast-to-2050-download.html> (date of access: 10.05.2025).
- [11] Hüffmeier J., Johanson M. State-of-the-art methods to improve energy efficiency of ships //Journal of Marine Science and Engineering. – 2021. – Vol. 9 (4). <https://doi.org/10.3390/jmse9040447>.
- [12] Tadros M., Ventura M., Guedes Soares C. Review of the decision support methods used in optimizing ship hulls towards improving energy efficiency //Journal of Marine Science and Engineering. – 2023. – Vol. 11 (4). <https://doi.org/10.3390/jmse11040835>.
- [13] ABS Explores Pathways to 2050, Automation and Digital with German Maritime Leaders. [Electronic resource]. - Access mode: <https://ww2.eagle.org/en/news/press-room/pathways->