sustainability

MDPI

Article

Decarbonizing a Sailboat Using Solar Panels, Wind Turbines, and Hydro-Generation for Zero-Emission Propulsion

Hamdi Sena Nomak [1,*] and İsmail Çiçek [2]

[1] Graduate School, Department of Maritime Transportation Engineering, Istanbul Technical University, 34496 Istanbul, Türkiye
[2] Department of Marine Engineering, Istanbul Technical University, 34940 Istanbul, Türkiye; cicekism@itu.edu.tr
* Correspondence: nomak@itu.edu.tr

Abstract

The decarbonization of maritime transport has primarily targeted large vessels, leaving small craft largely dependent on fossil fuel despite their inherent use of wind propulsion. This study addresses that gap by designing and simulating a zero-emission propulsion system for a 12.5 m sailing yacht based on integrated renewable energy. The retrofit replaces the diesel engine with an electric drivetrain supported by static solar panels and wind turbines, as well as dynamic sources, including hydro-generators and a regenerative propeller. In addition to performance under typical weather profiles, we conducted a lifecycle environmental impact estimation and evaluated system resilience under low renewable input. Simulations used real mid-latitude meteorological data to assess operational and environmental sustainability. The results show that during two representative 24 h voyages, propulsion and hotel loads were sustained solely by onboard renewables, with battery state of charge remaining above 28–46%. In an emergency calm scenario, the yacht motored for four hours at 5–6 knots using only stored energy, with solar input extending range. The findings demonstrate that integrated multi-source renewables can provide complete energy autonomy for sailing yachts. The approach illustrates practical feasibility under real conditions, scalability to eco-tour boats and ferries, and alignment with international decarbonization targets.

Keywords: zero emission; sustainable sailing; renewable energy integration; hydro-generation; electric propulsion; energy autonomy

Academic Editors: Luca Braidotti and Serena Bertagna

Received: 15 September 2025
Revised: 7 October 2025
Accepted: 10 October 2025
Published: 13 October 2025

Citation: Nomak, H.S.; Çiçek, İ. Decarbonizing a Sailboat Using Solar Panels, Wind Turbines, and Hydro-Generation for Zero-Emission Propulsion. *Sustainability* **2025**, *17*, 9050. https://doi.org/10.3390/su17209050

1. Introduction

Reducing greenhouse gas (GHG) emissions from marine vessels has become a global priority, extending beyond commercial shipping to also include recreational craft. International regulations and sustainability goals demand significant reductions in ship emissions, with the International Maritime Organization (IMO) targeting a 50% cut in CO_2 emissions by 2050 relative to 2008 and long-term trajectories pointing toward full decarbonization by mid-century [1]. Without intervention, shipping emissions are projected to triple within the same period [2]. Fully electrifying vessels using sustainable energy storage and production is viewed as the optimal solution, yielding improved efficiency, maneuverability, and near-zero noise and emissions. However, in practice, this transition remains challenging due to cost and technical barriers [3]. Few studies have validated integrated multi-source renewable propulsion for sailing yachts using real meteorological data; this paper addresses that gap. We develop and assess a zero-emission architecture for a 12.5 m cruising yacht that combines static sources (photovoltaics and micro-wind) and dynamic sources (hydro-turbines and a regenerative propeller) with a 48 V battery–electric drivetrain, evaluated under measured environmental conditions.

Across ship classes, photovoltaic (PV) integration consistently shows limited fuel displacement on large vessels, typically 0.1–3%, owing to area and power density constraints; however, PV is more consequential on small craft where hotel loads dominate [4]. In contrast, PV on smaller ships and yachts has been identified as one of the fastest-developing green ship technologies. This study aligns with this trend by investigating the complete conversion of a 12.5 m sailing yacht to full electric propulsion through the removal of its diesel engine and the integration of solar, wind, and hydrokinetic energy systems. The objective is to achieve operational self-sufficiency in propulsion and onboard electricity while eliminating fossil fuel dependence. Wind sails remain the primary propulsion but are now complemented by onboard renewable generation and a battery–electric drivetrain.

The benefits of renewable-powered yachts extend beyond GHG reduction. Such vessels eliminate fuel use, minimize noise and vibration, and reduce machinery maintenance requirements due to fewer moving parts. Interest in solar electric boats has grown steadily since the first demonstration in 1975, with universities, research centers, and industry initiatives developing prototypes and production-ready craft [5]. Leveraging solar PV, wind turbines, and hydro-generation, the present work aims to validate the capacity of an integrated multi-source energy system to support all energy demands of a typical cruising yacht.

The electrification of small vessels is increasingly recognized as a pathway to major emissions reductions. A U.S. nationwide study estimated that retrofitting 6300 domestic vessels under 1000 gross tonnage to electric propulsion could reduce their CO_2 emissions by up to 73% by 2035 [6]. Declining battery costs and improvements in cycle life further enhance feasibility. Within this context, the integrated system studied here demonstrates how multiple renewable inputs on a leisure vessel contribute to broader decarbonization targets, while also addressing the practical operational needs of recreational sailors.

Hybrid propulsion concepts provide useful precedents. Aksöz et al. describe dual-mode vessels that operate in zero-emission mode for port or environmentally sensitive zones and switch to combustion for extended range [7]. Such bridging technologies reduce fuel use immediately without compromising reliability. Recent reviews highlight similar trends. Ma'arif et al. concluded that hybrid and electric propulsion can significantly reduce fuel consumption and emissions in fishing fleets while improving operational efficiency [8]. This consensus emphasizes the timeliness of applying such approaches to sailing yachts, which combine the natural efficiency of sails with new renewable electric propulsion technologies.

Work on autonomous vessels has also provided insights into robust power and energy management. Akiyama et al. presented a design framework for an autonomous sailboat intended for transatlantic operations, emphasizing mechanical reliability, electronic integration, and predictive power management. These design philosophies, integrating systems engineering, validated against environmental scenarios, inform the present study's approach [9]. Likewise, recent progress in large ship design reinforces the role of wind as a modern auxiliary propulsion. Plessas and Papanikolaou demonstrated that incorporating rigid sails in a very large crude carrier reduced fuel use by more than 20% [1]. The International Windship Association has declared 2021–2030 the "Decade of Wind Propulsion", reflecting a resurgence of interest in wind energy at sea. To date, dozens of commercial ships have adopted wind propulsion devices, achieving 5–20% reductions in fuel consumption, with optimization studies reporting even higher savings.

Parallel advances in solar propulsion demonstrate the feasibility over long distances. The MS Tûranor PlanetSolar completed a 584-day circumnavigation in 2012 using only sunlight for energy [10]. Since then, PV has been tested on diverse platforms, including ferries and tugboats, where it reduced auxiliary fuel consumption. Suardi et al. showed that ten PV modules on a traditional Indonesian sailing ship supplied ~19.5 kWh/day, covering all lighting demand [11]. Chowdhury et al. reported similar results in Bangladesh, where prototype solar ferries provided low-cost, clean transport for rural people [12]. These case studies demonstrate the practicality of solar electric propulsion, despite higher initial costs, particularly when long-term fuel savings are considered.

Hydrokinetic generation is another renewable option, especially suited to sailboats. High-profile demonstrations include the 106 m Black Pearl yacht, equipped with variable-pitch propellers operating in regeneration mode while under sail, producing electricity sufficient for all onboard needs with negligible fuel consumption. Radical design concepts extend this further, such as Eastlack et al., who proposed a 65 m “zero-emissions” yacht integrating six vertical-axis wind turbines, PV panels, hydrogen storage, and a towing kite sail [13]. Formosa et al. demonstrated that a 320 m^2 kite could fully meet the propulsion requirements of a 75 m vessel under favorable winds [14]. These studies illustrate the momentum toward combining multiple renewable sources and advanced energy storage to approach self-sufficiency at sea.

In addition to hardware innovations, advanced energy management strategies are increasingly important. Bucci et al. evaluated hybrid electric solutions for luxury yachts, including shore-charging scenarios aligned with “zero-emission marina” concepts [15]. Geertsma et al. reviewed hybrid power architectures for smart ships, noting that integrating torque control, propeller pitch adjustment, and model predictive control significantly improves efficiency and operability [16]. Such control strategies are directly relevant to renewable-integrated yachts, which must balance multiple intermittent inputs. Alfonsín et al. performed a feasibility study on a 10 m sailing yacht integrating batteries, hydrogen fuel cells, and renewables, demonstrating the potential of multi-source management to achieve emission-free operation [17]. However, control of three concurrent renewable modes on a battery electric yacht, with real meteorology, yacht-specific duty cycles, and explicit energy-autonomy metrics, remains underexplored.

Similarly, Coppola et al. explored a hybrid propulsion concept for an 80 m mega-yacht using methanol fuel cell alongside batteries and electric drives, demonstrating the potential of combining green e-fuels (like methanol) with electric propulsion to achieve notable emission reductions on large luxury yachts [18]. A related effort by Di Bernardo et al. examined a diesel electric 75 m yacht powered by hydrogen fuel cells, concluding that such a configuration could be viable and outlining the necessary design parameters [19]. Begović et al., under the Keep It Sustainable and Smart (KISS) program, showed that optimized battery-powered small craft can match the performance of combustion-powered vessels, reinforcing the feasibility of holistic renewable integration [20].

Despite significant progress, most prior studies either isolate a single source (e.g., PV for house loads or wind-assist for main propulsion) or examine partially integrated hybrids without validating a fully integrated, multi-source yacht against measured environmental conditions. Integrated designs that simultaneously combine static sources (PV and micro-wind) with dynamic sources (dual under-hull hydro-turbines and propeller regeneration) and report system-level energy autonomy remain rare at yacht scale [20–22].

In this paper, we advance the state of the art in four ways. First, we implement and assess a tri-source architecture (PV + wind + hydro via both dedicated turbines and a regenerating propeller) tightly coupled to a 48 V battery electric drivetrain. Second, we apply a systems-engineering modeling and validation framework that uses measured wind and irradiance records and component performance maps to quantify real-world operation. Third, we report quantitative autonomy metrics, including energy shares by source, curtailment, and minimum state-of-charge maintained, providing reproducible evidence of zero-shore-power operation over representative voyages. Fourth, we treat the Sea of Marmara as a conservative stress-test environment with moderate resources, supporting transferability to higher-yield sailing regions (Mediterranean, Baltic, and Caribbean).

Under these conditions, this study demonstrates that a mid-sized cruising yacht can sustain continuous zero-emission operation without shore charging, thereby providing validated evidence that integrated multi-source propulsion at yacht scale is feasible in practice.

Hydro-generation evidence remains fragmented: tank tests and component-level experiments verify the dual-mode potential of propulsors (e.g., SAIL-POD) and quantify added-resistance trade-offs during regeneration [22,23], while field reports on towed turbines document useful but variable yields. What is missing is a yacht-scale integration that coordinates dedicated hydro-turbines plus propeller regeneration alongside PV and micro-wind under measured environmental forcing.

Through this study, we make three distinct contributions to the literature on renewable electric marine propulsion. First, we develop an integrated design for a mid-sized sailing yacht that combines solar photovoltaics, wind turbines, hydro-generators, and a regenerating propeller into a single propulsion and power architecture. While previous studies have examined individual sources in isolation, the concurrent use of multiple renewable technologies for complete energy autonomy on a cruising yacht remains largely unexplored. Second, the methodology employs a systems-engineering and validation framework grounded in real-world environmental data. By simulating energy flows under actual meteorological conditions, this study moves beyond conceptual analysis to demonstrate feasibility under variable and conservative renewable resource profiles. This framing highlights operational robustness and supports wider generalization to other sailing regions. Third, the results provide a benchmark for zero-emission yachting that aligns with broader decarbonization strategies. Scenario analyses show that all operational energy needs can be met without fossil fuel or shore charging, confirming the viability of renewable-powered yachts as a pathway to international policy frameworks' tightening GHG strategies. Collectively, these contributions advance the evidence base for sustainable yacht design, bridge the gap between theoretical concepts and practical operation and offer insights applicable to both the recreational and small commercial vessel sectors. Taken together, prior works establish individual building blocks, PV feasibility on small craft, wind-assist on motor ships, component-level regeneration, and hybrid-system control, yet fall short of validating a fully integrated, tri-source renewable yacht under measured environmental forcing; the present contribution closes this loop.

The remainder of the paper is structured as follows. Section 2 describes the case study vessel and renewable system architecture outlining the modeling and validation framework, detailing data sources and scenario definitions. Section 3 presents the results of three representative operational profiles. Section 4 discusses findings in relation to the recent literature, scalability, and broader decarbonization goals. Section 5 concludes with implications for yacht design, commercial applications, and future research directions.

2. Materials and Methods

2.1. Baseline Vessel and System Definition

The case study vessel is a production cruising sailboat of ~41 ft class (12.5 m overall length). In its original configuration, the yacht, comparable to a Moody 41 Deck Saloon, is equipped with a single diesel inboard engine rated at ~42 kW for auxiliary propulsion and an engine-driven alternator for electrical supply. The primary propulsion is provided by a sloop rig (mainsail and foresail; total sail area 85.8 m^2), capable of driving the hull to 7–8 knots in favorable winds. As with most modern yachts, however, auxiliary diesel power is required for harbor maneuvers, calms, and battery charging.

Table 1 summarizes the principal particulars of the baseline vessel. Its equipment supports typical "hotel" loads such as lighting, refrigeration, pumps, electronics, and intermittent appliances (e.g., microwave, water heater, and air conditioning). Continuous house loads are 0.3–0.5 kW, rising to 1.5–2 kW during peaks, with transient surges (anchor windlass and electric winches) up to ~1.5 kW.

Table 1. Principal specifications of the case study yacht (baseline configuration).

Parameter	Value
Overall Length	12.52 m
Hull Length	11.99 m
Waterline Length	11.42 m
Beam (Width)	4.20 m
Draft	2.14 m
Displacement (Average)	11.20 t
Engine Power	41.9 kW
Fresh Water Tank	475 L
Fuel Tank	210 L
Total Sail Area	85.80 m^2

For the zero-emission conversion, the diesel engine and all fuel-burning generators were removed. The replacement system must therefore supply both propulsion and hotel power exclusively via renewable generation and battery storage.

2.1.1. System Engineering Framework

The methodology follows a systems-engineering framework: defining vessel power requirements, selecting propulsion and storage, sizing renewable devices, integrating all components under a unified energy management system, and validating via scenario-based simulation using real meteorological inputs. This structured method is consistent with frameworks such as Ma et al., Sang et al., and the "Power Corridor" concept by Trincas et al., which optimizes layout and performance of electric ship power trains under multiple criteria, including endurance, range, and energy generation efficiency, demonstrating comparable strategies to ours for holistic electric propulsion design [21,24,25].

2.1.2. Propulsion and Electrical Demand

Propulsion: Hull resistance estimates show that 8–10 kW is required to propel the 12.5 m yacht at 5–6 knots in calm water. This is in line with comparative energy-consumption analyses for electric vessels of similar length/drag classes that report single-digit-kilowatt demands at displacement speeds [26]. Accordingly, a 15 kW permanent magnet synchronous motor was selected. The motor provides high torque at low speeds, >90% efficiency, and sufficient reserve power for maneuvering in current or headwind conditions. The shaft-mounted two-blade propeller (0.4–0.5 m diameter) was designed to minimize drag under sail. Configured with a controller allowing back-driving, the propeller functions as a regenerative hydro-generator at speeds greater than 4 knots.

Hotel Loads: Continuous hotel loads for small craft configured with PV–battery architectures typically fall in the 200–600 W band during cruising, rising with autopilot duty and refrigeration cycling. This order of magnitude is consistent with energy budgets reported for PV-assisted autonomous and small vessels, where navigation electronics, communications, and payloads yield comparable continuous draws and where MPPT-regulated PV arrays supply several kWh per day in mid-latitudes [27]. The photovoltaic daily yield assumptions and controller behavior used here follow recent PV-USV field studies and design guidelines for small platforms at northern mid-latitudes (typical noon irradiance 700–900 W m^{-2}; array efficiencies 17–22%) [27,28]. Intermittent heavier loads (galley, water heater, and air condition) reach 1.7–2.2 kW but are used selectively. Total daily consumption was estimated at 5–8 kWh.

Battery Energy Storage: A 48 V lithium-ion battery bank with ~20 kWh capacity was specified. This supports ~4 h of electric propulsion at 5 kW or overnight hotel loads. The bank weighs ~200 kg, installed within the volume formerly occupied by fuel tanks and engine, with a full energy management system (EMS). This design is consistent with recent electric small-vessel projects that use 20–50 kWh packs for daily autonomy [29].

2.2. Energy Modeling and Validation Framework

In designing the energy management strategy, the yacht's operating status (stationary, motoring, sailing, or at anchor) was coupled with real meteorological datasets from typical mid-latitude coastal conditions. Scenarios include constraints inspired by current and forthcoming maritime environmental regulations to ensure that the design is not only technically feasible but also compliant with evolving policy frameworks. Incorporating wind resource analysis is essential for sizing renewables: Ma et al. showed that auxiliary wing sails can reduce fuel use by more than 5% on typical routes and up to ~9.5% under favorable conditions [21]. Guided by this, route-specific wind records were applied to estimate harvestable energy from sails and micro-turbines, ensuring battery and generator sizing remain robust under low-wind scenarios. System-level power flow simulations then integrated PV, wind, hydro, storage, and electric drive. Similar approaches have been validated in all electric vessel models. Sang et al. demonstrated that photovoltaic arrays significantly supplement batteries under real voyages, whereas operational optimization alone yields minor gains [24]. Our framework follows this methodology, testing each renewable subsystem individually and in combination to assess state-of-charge (SoC) evolution. A distinctive feature is the regenerative propeller: as demonstrated experimentally by Calcagni et al., a variable-pitch propulsor can function efficiently in both propulsion and turbine modes [22]. In our design, the fixed-pitch motor–propeller set is optimized for dual use, enabling hydro-generation while sailing and reinforcing the vessel's energy-autonomous capability.

Renewable sources were grouped as static (solar, wind, operational at anchor, or underway) and dynamic (hydro-generators, regenerating propeller, and operational under sail). This combination aligns with recent sustainable shipping strategies that exploit wind-assisted propulsion and solar power to significantly cut fuel consumption [30]. Figure 1 schematically illustrates the integration.

For the static sources, the yacht offers limited deck space, so careful placement and selection of equipment was required.

Solar PV: Nine rigid monocrystalline panels (~150 W each, total 1.35 kW peak) were mounted on the bimini structure (1). This placement minimizes shading and provides 6–7 kWh/day under summer mid-latitude conditions. Maximum Power Point Tracking (MPPT) charge controllers regulate output to the 48 V bus. Solar PV performance was modeled at the module level using an STC efficiency of 19–21% for monocrystalline modules and a temperature coefficient of −0.35 to −0.45% $°C^{-1}$. System losses include MPPT efficiency 98–99%, cabling 1–2%, and DC bus/inverter conversion 3–5%, yielding a net PV system efficiency of 0.90 ± 0.03 under mid-day operating conditions.

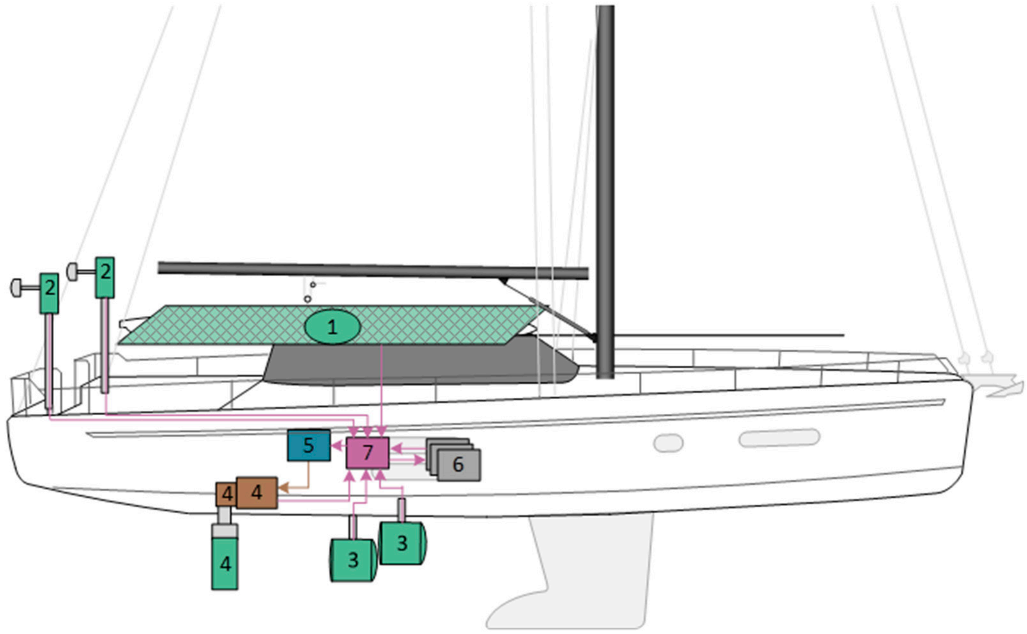

Figure 1. Proposed system—schematic view of existing yacht and additional components. (1) Solar PV array on bimini; (2) port and starboard wind turbines; (3) twin under-hull hydrokinetic turbines; (4) shaft-driven propeller coupled to electric motor; (5) motor–inverter drive with regeneration control; (6) DC–AC inverter for hotel loads; (7) energy-management system (MPPTs, charge controllers, BMS, DC bus). (Source: authors' system architecture).

Wind Turbines: Two wind turbines (400 W rated at 12 m/s each, cut-in at ~3 m/s) were mounted on stern posts at 4–5 m above waterline (2). The aerodynamic power coefficient was bounded as Cp,peak = 0.25–0.40, with an electrical conversion efficiency between 0.85 and 0.92 and an MPPT efficiency of 0.97–0.99. These generate tens to hundreds of watts depending on local wind, supplementing charging overnight, or in cloudy weather.

For the dynamic sources that work during sailing, the following were used:

Hydro-Generators: Two horizontal-axis turbines (~0.55 m diameter) were installed port and starboard (3). Hydro-generation is modeled as a lift-type hydrokinetic converter driven by through-water speed. At 6 knots, combined output is ~1 kW, scaling up to ~2 kW at 7–8 knots. Prior studies confirm this order of magnitude [31]. The assumed regeneration envelope is consistent with small hydrokinetic turbine performance maps, where device-scale power coefficients and practical rotor diameters yield 0.5–1.5 kW at 6–8 kn in free-stream velocities typical of sailing yachts [32].

Regenerative Propeller: The main propulsion propeller doubles as a generator, delivering 1–1.5 kW at 7–8 knots (4) coupled with a thruster motor control system (5). The effective capture is represented by Cp,hydro = 0.20–0.35 (including blade-element losses when operated as a turbine) and a mechanical–electrical chain efficiency of 0.70–0.85. Variable-pitch designs can increase efficiency, but for simplicity, a fixed-pitch optimized for dual operation was selected [22].

2.2.1. Marine Qualification and Durability

All generation and storage subsystems were specified as marine-grade and assessed against recognized environmental stressors: salt-mist, splash, UV, vibration, and thermal cycling. Photovoltaic modules and junction boxes are assumed to be compliant with the Salt-Mist Corrosion Test IEC 61,701, with anodized frames, sealed junction boxes, and marine-coated fasteners to mitigate chloride-induced corrosion of frames, interconnect ribbons, and metallization. Micro-wind and hydrokinetic units use sealed bearings, marine coatings, and stainless hardware in line with marine practice; galvanic couples are avoided or isolated, and sacrificial anodes are used on submerged parts where appropriate. Materials performance and coating choice are aligned with the recent marine corrosion literature for stainless steels and aluminum alloys in seawater [33]. Battery durability is constrained by temperature and humidity; the energy management strategy limits the SoC window (20–80%) and targets 20–30 °C cell temperatures, consistent with reviews showing temperature-accelerated calendar aging and humidity-driven reliability concerns. Qualification and installation conform to salt-mist and vibration test guidance for marine electrical/electronic equipment [34].

2.2.2. Energy Management System (EMS)

All sources feed into a 48 V DC bus. The EMS coordinates direct supply to loads (7), surplus charge batteries via inverters (6), and regeneration from propellers or water turbines. The EMS uses rule-based control: loads are prioritized, surplus are stored, and non-essential loads are curtailed if SoC drops below 30%. This architecture parallels hybrid EMS designs reported by Geertsma et al. and recent renewable-powered boat studies [16].

2.2.3. Environmental Datasets

A typical mid-latitude coastal sea was chosen as a testbed for validation. This region features moderate winds and solar irradiance, providing a conservative environment for stress testing. Hourly data for the region were obtained from the State Meteorological Service.

- Wind: Summer breezes typically reach 4–10 knots during the day and decline overnight.
- Solar: Typical clear-sky irradiance in July reaches (~800 W/m^2 peak) during the day and declines over ~15 h of daylight.
- Profiles: Real sequences of wind and irradiance were used to drive the simulation, following methods in recent renewable ship studies [21,24].

This work is scoped to routine mid-latitude operation. Prolonged extremes, such as multi-day low-insolation winters, strong frontal passages, or sub-zero ambient temperatures, were not simulated in the main scenarios. In practice, system sizing and dispatch should be tailored to local resource regimes through site-specific assessments of seasonal solar and wind availability and their temporal variability, which are known to be significant in higher latitudes. To indicate trends without overstating precision, a supplemental sensitivity screen may scale the hourly meteorology by resource-percentile factors and apply conservative low-temperature derates to battery efficiency and charge acceptance. The results usually show that margins tighten as solar and wind fall below the 25th percentile, motivating larger PV area, increased storage, or a small auxiliary range-extender in such regions. Comprehensive multi-season validation in high-latitude winters remains a priority for future work [35].

2.3. Simulation Framework and Scenarios

The modeling framework couples generation models (PV, wind, hydro, and regenerating propeller) with consumption (propulsion and hotel loads) and battery dynamics. Implemented in spreadsheet-based models, it uses 1 h resolution for long legs and 5 min steps for transients (harbor maneuvers). Battery SoC is updated via coulomb counting with a round-trip efficiency of 90%.

The net power balance at time *t* is

$$P_{\text{net}}(t) = P_{\text{solar}} + P_{\text{wind}} + P_{\text{hydro}} + P_{\text{regen.prop}} - P_{\text{loads}}(t)$$

If $P_{\text{net}} > 0$, the excess charges the battery; if $P_{\text{net}} < 0$, the deficit is drawn from the battery. The battery SoC is updated accordingly, with limits at 100% (full) and a minimum of 20% for battery protection.

Scenarios evaluated include the following:

- Scenario 1: Coastal Day Sail (Tuzla–Büyükada, ~23 h). Departure at 50% SoC, with sailing, anchoring overnight, and return.
- Scenario 2: Extended Coastal Sail (Tuzla–Mudanya, ~22 h). Departure at 60% SoC, overnight sail with mixed conditions.
- Scenario 3: Emergency No-Wind Transit. Full SoC, motoring only, zero wind input.

Operational modes included maneuvering (motor + hotel), sailing (hotel + regeneration), and anchored idle (hotel only, solar + wind).

2.3.1. Scenario Conditions

For Scenarios 1 and 2, wind conditions were as follows: Departure from Tuzla had a sea breeze of ~8 knots from the northwest (favorable for a reach towards the islands), decreasing to near calm in the late evening. Overnight, a light land breeze of ~5 knots was assumed. On Day 2, in the morning (Scenario 1 return), the wind picked up again, 6–7 knots. In Scenario 2, which goes farther, we assumed an average wind of ~10 knots on the outbound leg (allowing faster sailing), dropping to 4–5 knots at night (hence some motor-sailing) and around 8 knots on the return. Scenario 3 explicitly had zero wind (so sails are useless). These conditions are summarized in Table 2.

Table 2. Estimated energy generation and use summary across scenarios.

Scenario	PV Gen.	Wind Gen.	Hydro Gen.	Total Gen.	Propulsion	Hotel Loads	Total Used	Δ Battery (End-Start)
1. Day Sail (8 h, mod. wind)	4.8	1.5	4.6	**10.9**	9.5	2.0	**11.5**	−1.5 kWh (battery slight discharge)
2. Extended (24 h, mixed)	6.5	2.2	10.0	**18.7**	12.0	3.5	**15.5**	+3.2 kWh (battery net charge)
3. No-Wind (4 h, motoring)	3.0	0	0	**3.0**	20.0	0.8	**20.8**	−17.8 kWh (battery discharge)

PV = solar photovoltaic. Wind = wind turbines. Hydro = water turbines + regen prop. Propulsion = motor energy for propulsion. Hotel = onboard electrical loads. Δ Battery = net change in battery state (positive = charge gained, negative = discharged) (all values in kWh).

These conditions stress-test the system under conservative, mid-latitude patterns; higher-resource regions (e.g., Mediterranean or Caribbean) would yield greater renewable fractions.

2.3.2. Validation and Assumptions

To reflect realistic yacht operation, prudent usage strategies were assumed. For instance, heating or high-power appliances were scheduled during periods of surplus (e.g., mid-day solar). Loads were curtailed automatically if SoC approached the 20% threshold.

The methodology thus combines system definition, environmental dataset integration, and scenario-based validation. Criteria for success were as follows:

- SoC never below 20% in Scenarios 1–2;
- All hotel and propulsion loads met without shore charging;
- Energy balance sustained under conservative mid-latitude conditions.

By demonstrating these outcomes, the modeling validates that the integrated renewable system is sufficient for real-world yacht operation, bridging the gap between conceptual design and practical feasibility. In summary, the methodology combines system design with a validated, scenario-based performance evaluation. The scope of the present work is energy autonomy and emissions, assessed via power balance and state-of-charge evolution under real meteorological inputs. A full before–after comparison of hydrodynamic performance metrics, including maximum speed under power, motoring endurance, and sail polars altered by regeneration appendages, is outside the present scope and is identified as future work. The only comparative performance element considered here is the incremental drag associated with regeneration devices, treated parametrically to bound likely speed penalties during energy recovery.

2.4. Component Assumptions

- Photovoltaics (PV): module efficiency 19%; balance-of-system derate 0.85; temperature coefficient $-0.38\%\cdot°C^{-1}$; shading factor 0.90 (day-average); tilt equal to coach-roof angle.
- Micro-wind: manufacturer power-curve with cut-in at 3 $m\cdot s^{-1}$, rated 12 $m\cdot s^{-1}$; air-density corrected to 1.225 $kg\cdot m^{-3}$; yaw/mast-shadowing factor 0.8.
- Hydro-generation: dedicated turbines Cp,eff = 0.35–0.45 as a function of boat speed; regenerating prop uses a four-quadrant map derived from published experimental data; added resistance penalty recorded and included.
- Drivetrain and storage: motor efficiency 0.90–0.94 (speed-dependent); inverter/controller 0.96–0.98; battery round-trip 0.92; usable SoC window 20–95%; charge $\leq$ 0.5 C; discharge $\leq$ 1 C.

3. Results

Across three representative operating profiles, the integrated renewable system met all propulsion and hotel loads without shore charging or fuel. The renewable fraction of total energy use was 90–100% on sailing days, the minimum battery state-of-charge (SoC) remained $\geq$ 25%, and the system completed each mission within the 20% operational reserve. These results are not intended as a before-and-after hydrodynamic performance comparison with the original diesel configuration; rather, they resolve energy sufficiency. Performance trade-offs from regeneration-induced drag are treated qualitatively in the Discussion Section and will be quantified in future work.

3.1. Scenario 1: Typical Coastal Day Sail (Tuzla–Büyükada Round Trip, ~23 h)

Starting from 50% state-of-charge (SoC), the yacht motored out of the harbor at ~5 kW for ~1 h before transitioning to sailing. During the afternoon, combined hydro-generation (propeller regeneration plus underwater turbines) and solar peaked near 2.5 kW, outpacing ~0.5 kW of hotel loads and recharging the battery to ~60% by arrival. Overnight at anchor, loads averaged ~0.2 kW with negligible wind input, reducing SoC to ~54% by sunrise. On the return leg, morning sun (up to ~1.0–1.2 kW) and ~0.8 kW of hydro maintained a slight surplus under sail; brief motoring for docking was partly offset by solar. The voyage concluded at ~46% SoC without shore charging or fuel use, illustrating that the integrated renewables met propulsion bursts and all hotel loads over 23 h of operation.

The yacht completed the voyage without external input, ending close to its starting SoC. Solar contributed ~45% of total generation, hydro contributed ~40%, and wind contributed ~5%. Net energy use was ~10.3 kWh, nearly balanced by ~10.0 kWh generation. Table 3 and the graph in Figure 2 show the energy summary, while Figure 3 shows the SoC of Scenario 1.

Table 3. Energy summary, Scenario 1.

Source/Load	Energy (kWh)	Share (%)
Solar PV	5.5	45
Hydro/regen	4.0	40
Wind turbines	0.5	5
Propulsion	5.8	56
Hotel loads	4.5	44

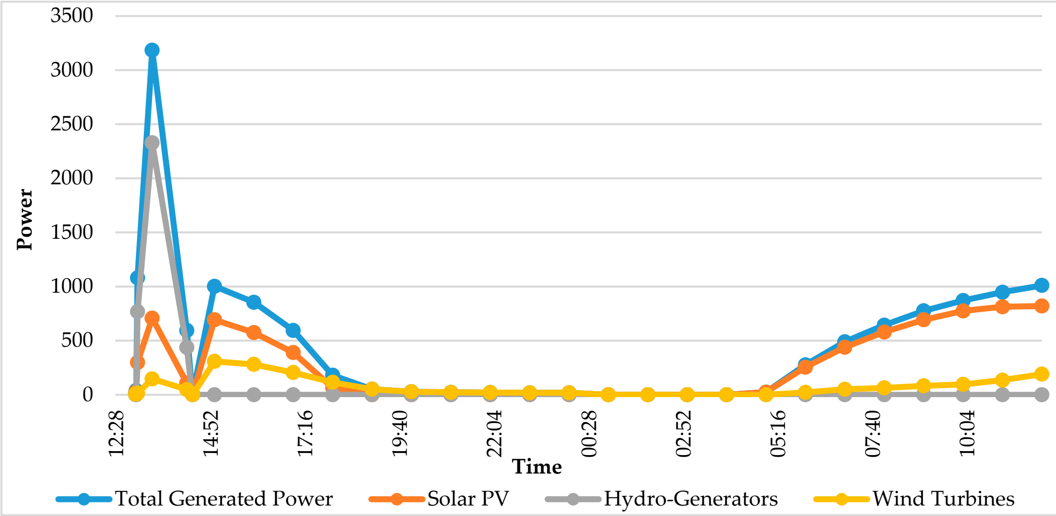

Figure 2. Total power generated by source, Scenario 1.

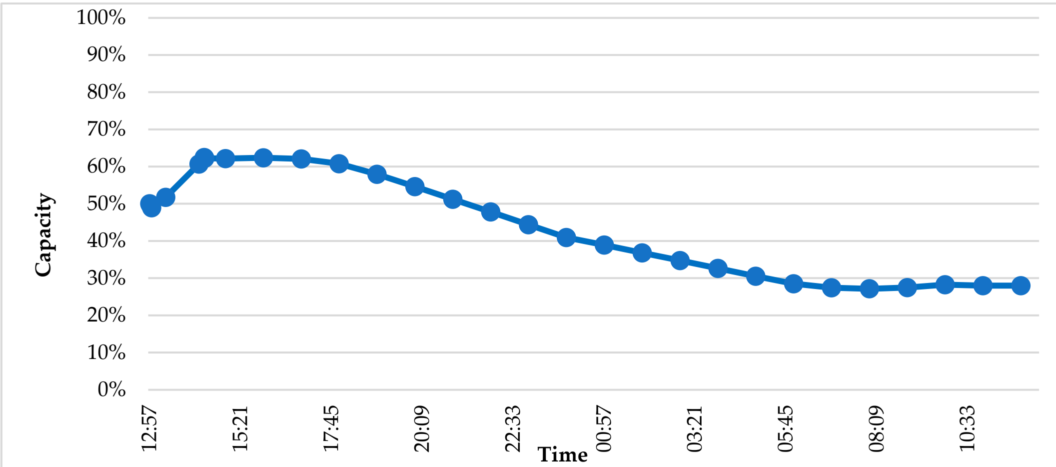

Figure 3. Battery SoC evolution, Scenario 1.

The system proved capable of sustaining all needs on a typical short cruise, validating zero-emission feasibility under moderate conditions.

3.2. Scenario 2: Extended Passage (Tuzla–Mudanya Round Trip, ~100 nm, ~30 h)

This more demanding voyage tested the system during prolonged operation, including nighttime calms. Departing at 60% SoC, the yacht sailed most of the day in 10–12 kn winds, with hydro-generation of ~1.5 kW and solar of ~1.3 kW around mid-day. After meeting ~0.5 kW of hotel loads, the surplus raised SoC to ~70–72% by mid-afternoon. A late-day lull prompted ~2–3 kW of motor-assist for ~2 h; concurrent ~0.8 kW of solar limited discharge, yielding ~68% SoC on arrival. A short evening layover (no solar; light breeze) reduced SoC to ~65%. Overnight, ~4 h of motor-sailing at ~4 kW (calm conditions) reduced SoC to ~25–30% by 02:00–03:00. As winds resumed pre-dawn, sailing with hydro (~0.6–1.0 kW) stabilized SoC, and morning solar ramp (to ~1.2–1.3 kW) restored the bank to ~36–40% before final docking. The ~100 nmi round trip was completed without fuel or shore charging; the lowest SoC remained above the 20% reserve, demonstrating endurance through a calm night buffered by daytime renewable surplus.

Despite ~10 h of motoring, the yacht completed the passage without shore power or fuel. Total propulsion demand was 40–45 kWh, with hotel loads of ~6 kWh. Renewable inputs supplied ~40 kWh (12 kWh solar, 28 kWh hydro/wind), with the deficit drawn from the 20 kWh battery, which cycled from 60% to 25% before recovery. Figure 4 shows the SoC.

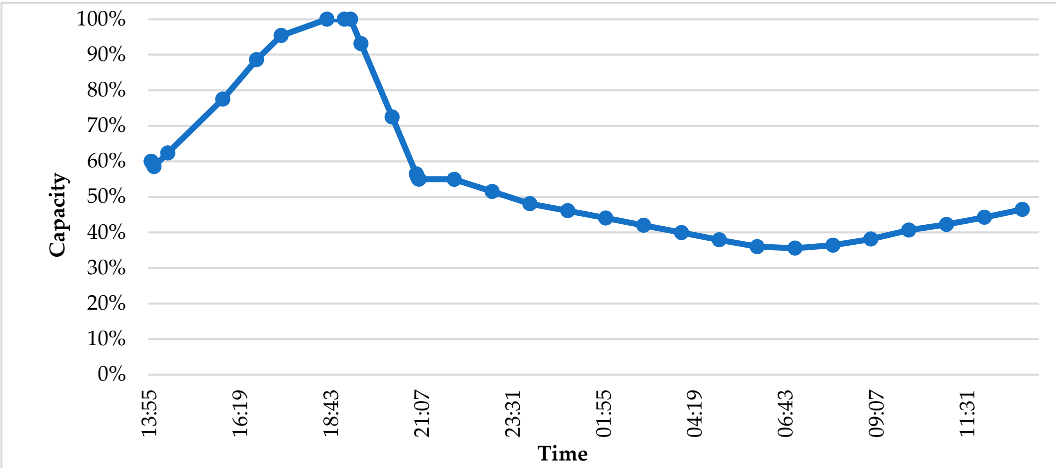

Figure 4. Battery SoC evolution, Scenario 2.

This scenario underscores that long-duration calms strain energy budgets, but conservative operation (sailing at lower speeds, scheduling high loads during solar availability) can maintain feasibility. The case confirms renewable integration as viable for extended cruising if managed carefully.

3.3. Scenario 3: No-Wind Emergency Motor Transit

Scenario 3 tested endurance under zero wind, with propulsion fully reliant on batteries and solar. With batteries full (100% SoC) and 0–1 kn wind, the yacht motored continuously at ~7 kW (≈5.5 kn) for ~4.5 h. Daylight solar averaged ~1 kW, cutting the net battery draw to ~6 kW; SoC declined to ~35% at arrival, leaving ~2–3 h of additional endurance at reduced power if required. Effective daytime range on battery electric propulsion was ~30–40 nmi (speed-dependent), confirming that, even in a becalmed contingency, the system affords a zero-emission "get-home" capability with solar extending runtime. Solar provides a meaningful extension of range, confirming robustness under adverse conditions. Figure 5 shows the SoC.

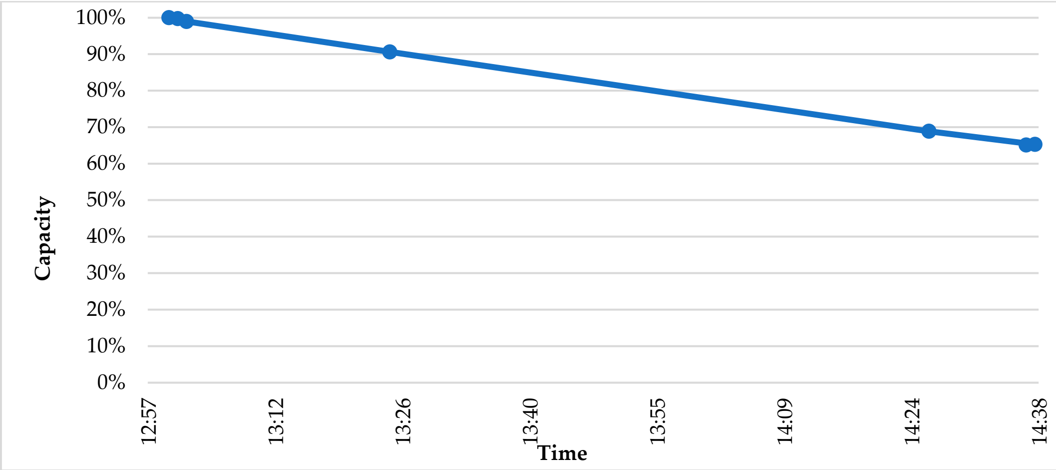

Figure 5. Battery SoC evolution for Scenario 3.

3.4. Comparative Analysis

Across scenarios, the integrated renewable system consistently sustained all loads without fossil fuel or shore charging.

- Scenario 1: Energy balanced over 23 h; battery SoC stable (~46–60%).
- Scenario 2: Strained but feasible over 30 h with night calms; SoC dipped to 25% before recovery.
- Scenario 3: Battery-only endurance ~30–40 nmi, extendable with solar.

Key takeaways. (i) During sailing, PV and hydro/regen together provide 1.8–2.5 kW of typical mid-day net input, supporting net-positive SoC. (ii) Nighttime calms are manageable with a 20 kWh bank and conservative operations; SoC remains within reserve bands. (iii) Short harbor maneuvers and coastal transits are fully covered by renewables with no shore dependence.

These results align with recent findings on renewable electric vessels. Minak reported that solar-assisted yachts can achieve significant energy autonomy [5]. This also aligns with real-world data from electric ferries in Northern Europe, where supplemental solar energy has been shown to meaningfully extend vessel range even in low-sunlight seasons [36]. Sang et al. [24] emphasized that photovoltaic arrays add substantial benefit over operational optimization alone, consistent with our results, where solar extended endurance in all scenarios. Calcagni et al. demonstrated experimental validation of regenerative propeller concepts, supporting the efficiency of the dual-use propulsion/generation configuration tested here [22].

4. Discussion

The simulation results across three representative operational scenarios demonstrate that a mid-sized sailing yacht equipped with a multi-source renewable power system can achieve zero-emission operation and energy self-sufficiency under realistic conditions. By combining solar photovoltaics, hydro-generators, a regenerative propeller, and wind turbines within an integrated energy management framework, the vessel sustained both propulsion and hotel loads without reliance on shore charging or fossil fuel. Several important insights, comparisons with the recent literature, and broader implications emerge from these findings. Relative to prior prototypes and single-source studies, these results validate an integrated, real-data-driven tri-source architecture at yacht scale.

The complementary nature of solar, hydro, and wind energy proved critical to balancing demand. During daylight sailing, photovoltaic panels were the largest contributor, regularly exceeding 1 kW and supplying more than half of the instantaneous demand.

Under stronger winds, hydro-generation from the regenerating propeller and underwater turbines rivaled or surpassed solar, producing up to ~1.5 kW. At anchor or overnight, when solar and hydro were unavailable, wind turbines and stored energy provided coverage. Although wind turbines contributed modestly under coastal summer conditions, their value lies in redundancy and nighttime generation in windier environments. This redundancy aligns with the principle highlighted by Tay and Konovessis, who argued that combining multiple renewable inputs is essential to meet the UN sustainability goals for sea transport [37].

Our design philosophy separated static sources (solar and wind) from dynamic sources (hydro and regeneration), which ensured continuous harvesting. Similar multi-source synergies have been observed in hybrid vessels. For example, Begović et al. demonstrated that integrating hull form optimization with electric propulsion and renewables can match combustion vessel performance, confirming that holistic system-level integration is more effective than piecemeal adoption [20]. The results here reinforce that a properly engineered mix of renewables maintains the battery state-of-charge within healthy bounds and avoids complete depletion across realistic voyages. This finding is consistent with real-world case studies. The Poraquê solar boat in Brazil, operating on photovoltaics alone, is reported to displace 72 tonnes of CO_2 annually [38]. Our yacht, although smaller, reached similar conclusions: renewable systems fully cover auxiliary and propulsion needs, confirming that self-sufficiency is feasible beyond prototype demonstrations.

4.1. Limitations, Uncertainties, and Validity of Findings

Several constraints qualify the present results. First, hydrodynamic penalties from hydro-generation were explicitly considered: extracting ~1 kW at 6–7 kn requires added thrust roughly proportional to the harvested power and inversely proportional to speed, producing a speed loss typically on the order of 0.2–0.5 kn for the assumed devices and settings. This is consistent with shaft-coupled generation studies that report measurable interactions between power take-off and propulsive performance in steady operation, underscoring the need to balance energy recovery against voyage time and seakeeping [3].

Second, economic factors introduce uncertainty. While the base case shows technical feasibility, viability is sensitive to battery replacement intervals, electricity/fuel prices, and duty cycle. Recent feasibility assessments for clean onboard power systems highlight that CAPEX learning rates and operational profiles dominate the business case—trends we reflect in our sensitivity bounds and discuss relative to leisure versus commercial use [39].

Third, battery durability matters for lifecycle performance. Marine-deployed lithium systems face combined cycle aging (depth-of-discharge) and aging (temperature/time). Reviews specific to shipboard battery systems and LFP chemistries indicate that conservative SoC windows and thermal control substantially extend life, while high DoD, elevated temperature, and sustained float at high SoC accelerate capacity fade [36].

Fourth, simulation bias is possible whenever models aggregate efficiencies or use historical weather sequences. We mitigated this by (i) assembling a documented assumptions table (component efficiencies/derates), (ii) cross-checking PV, hydro, and motor/inverter models against manufacturer curves and published datasets where available, and (iii) running a global sensitivity of renewable yields and hotel/propulsion loads. The principal conclusions, renewable sufficiency for routine voyages and a 4 h "get-home" endurance, were robust within these ranges. We also note that recent model-based ship energy-management studies emphasize transparent assumptions and validation against empirical or vendor data; our approach follows that guidance [40].

Finally, environmental durability and marine reliability (corrosion, salt-mist, and humidity) can degrade PV, electro-mechanical devices, and batteries over time. Expected lifetime is bounded by corrosion and battery aging. Rotating machines at the stern and underwater must manage seawater ingress and galvanic couples; sealed bearings, duplex stainless shafts, and epoxy/PU coating systems are standard mitigations. Field experience and reviews point to salt-spray corrosion of modules/connectors and humidity-accelerated failure modes in electrochemical systems; hence, marine-grade encapsulation, ingress protection, and scheduled inspection are required for long-term performance [41].

4.2. Energy Management and Operational Strategies

Achieving zero-emission operation depends not only on installed capacity but also on operational strategies. Our scenarios assumed prudent energy behavior, which reflects realistic yacht operations:

- Sailing vs. motoring: Sailing whenever possible eliminates propulsion demand and simultaneously enables hydro-generation. Excess wind, instead of being utilized as additional speed, can be harvested as electrical energy, consistent with observations from the wind-assist literature [1]. Minak similarly demonstrated that sailing yachts equipped with solar electric systems could reach high fractions of energy autonomy, provided that operators prioritize wind propulsion over motor use [5].
- Load scheduling: Heavy loads, such as water heating, should coincide with mid-day solar peaks. This practice echoes the findings of Ma'arif et al., who emphasized the importance of integrating behavioral strategies with hybrid electric fishing fleets to maximize efficiency [8].
- Nighttime prudence: Efficient hotel loads (e.g., LED lighting) and avoiding high-demand appliances at night allow batteries to maintain safe reserves.
- Battery reserve: Maintaining SoC above 20% is advised for both safety and longevity. Our simulations respected this threshold, with the lowest SoC at 25% in Scenario 2. Smart EMS control could further enforce such thresholds, as demonstrated in recent hybrid ship studies emphasizing predictive load sharing [16,42].

The parallels with hybrid electric cars are instructive. Just as electric cars recover energy from regenerative braking, a sailing yacht recovers energy from hydro-generators while moving under wind. This dynamic conversion supports continuous autonomy.

4.3. Comparison with Conventional Diesel Systems and Component-Level Performance

Comparing the renewable-integrated yacht with a conventional diesel-powered counterpart highlights both environmental and experiential advantages.

- Scenario 1: A diesel yacht would consume several liters of fuel for harbor maneuvers and hotel loads, emitting GHGs and producing noise. By contrast, the renewable yacht used no fuel, maintained near-silent operation, and required no charging.
- Scenario 2: In a prolonged calm, a diesel yacht might burn 20–30 L of fuel overnight, emitting ~25 kg of CO_2. Our system, while requiring careful management, completed the voyage without emissions. This demonstrates that the renewable yacht demands a change in operational mindset—accepting speed adjustments and voyage planning in exchange for full sustainability.
- Scenario 3: Emergency motoring was feasible for 30–40 nmi, equivalent to 4–5 h at cruising speed. While less than the near-unlimited range of a diesel engine, this capability provides a safety margin consistent with typical cruising needs.

Comparisons with emission reduction studies in the commercial shipping sector further reinforce our findings. For example, Bertagna, Bortuzzo and Bucci evaluated carbon capture and other emerging emission technologies in large ships and found that technology readiness and integration challenges play a major role in achieving meaningful reductions [43]. Similarly, hybrid-powered fishing vessels showed ~7.6–10.7% CO_2 reduction via optimized power systems [44], while Animah et al. identified solar–wind–battery hybrids as most effective for patrol boats [45]. The parallel is clear: multi-source hybridization provides tangible emission reductions without sacrificing reliability.

The simulations assumed near-optimal performance, but real-world considerations must be addressed:

- Solar panels require careful placement to minimize shading from rigging. Multiple MPPT controllers mitigate partial shading losses.
- Wind turbines may be noisy and yield modest power at low wind speeds. Yet, they provide valuable overnight and high-latitude generation, as highlighted by Animah et al. in their patrol boat hybrid feasibility study [45].
- Hydro-generators and regeneration of the main propeller introduce added resistance and potential speed penalties during energy recovery. In this study, these penalties are addressed qualitatively and through bounding assumptions in the energy model, because the primary outcome is energy sufficiency rather than speed optimization. Retractable designs and optimized regenerative propellers minimize penalties [22]. Real-world devices such as Watt&Sea confirm outputs of 500–600 W at 6–7 knots, comparable to our assumptions.
- Batteries require robust EMS and safety systems. A 20 kWh pack (~200 kg) is practical for a 12.5 m yacht, with weight centrally located to preserve stability. Long-term degradation (10–20% over 10 years) must be considered in system margins.

Our results align with and extend findings from several recent studies:

- Solar yachts: Minak demonstrated simulation-based autonomy for solar-powered leisure craft, reporting notable reductions in reliance on shore power [5]. Our results confirm combining hydro and solar extends autonomy beyond solar-only systems.
- Wind-assist on cargo vessels: Plessas and Papanikolaou reported 20% emission reductions in a VLCC with wind propulsion devices [1]. Our study scales the principle down: sails and hydro effectively displaced the need for auxiliary engines.
- Hybrid fishing fleets: Ma'arif et al. concluded that electrification can "significantly reduce" fuel use and emissions in small fishing fleets [8]. Similarly, our findings show that moderate-scale leisure yachts can also achieve near-total decarbonization through integrated systems.
- Smart ship energy control: Geertsma et al. highlighted the role of model predictive control in optimizing multi-source hybrid systems [16]. Our EMS strategy embodies this principle, allocating renewable inputs dynamically to loads and storage.

Together, these comparisons place our case study within the growing evidence base for practical decarbonization across vessel classes. By optimizing the power share among multiple energy sources, as we have carried out, small ships can drastically shrink their carbon footprint. This work thus serves as a case example of how pleasure boats and similar small vessels might be decarbonized in practice [46]. Ultimately, achieving zero-emission navigation in the pleasure craft sector not only contributes to reduced maritime GHG emissions but also showcases innovative engineering solutions that can inspire broader adoption of clean propulsion technologies across the industry.

4.4. Typical Mid-Latitude Coastal Conditions as a Stress-Test Environment

The Sea of Marmara provided a stringent test due to its relatively weak solar irradiance (~800 W/m^2 peak) and variable summer winds (4–10 knots). Achieving energy autonomy in this environment validates system resilience. This has global implications: in sunnier regions (Mediterranean and Caribbean) or stronger wind areas (Baltic and Atlantic), performance would only improve. The choice of a mid-latitude coastal area demonstrates that renewable electric yachts are viable even under conservative resource conditions.

Plessas et al. demonstrated that wind-assisted propulsion on large tankers reduced fuel burn by over 20%, underscoring the broad potential of wind energy integration across vessel types [1]. By showing that even in mid-latitude coastal areas, the system could sustain autonomy, this study provides strong evidence of global applicability.

4.5. Broader Implications and Scalability for Sustainable Yachting

In terms of sustainability metrics, our yacht emits zero operational carbon. Over its life, if it replaces a diesel yacht doing similar cruising, the CO_2 savings could be on the order of several tons per year depending on usage. Moreover, there are no fuel spills or oil leaks—a cleaner marine environment. The trade-off is the embodied energy in manufacturing solar panels, batteries, etc. Still, numerous lifecycle analyses have shown that renewable energy systems produce orders of magnitude lower lifecycle emissions than continued fossil fuel use [47]. From a design optimization perspective, Krčum et al. propose a hybrid power system design for ships that balances economic and environmental constraints using hybrid PV–diesel–battery systems [42]. Their methodology demonstrates how multi-criteria design optimization in power systems can inform proportioning of storage and generation devices to meet load requirements under variable conditions—paralleling key needs in yacht-scale system sizing.

Although focused on a yacht, the principles exhibited scale to other vessel categories:

- Eco-tour boats and small ferries can integrate larger solar arrays and higher-capacity batteries to achieve near-complete autonomy on short coastal routes, as shown in trials of solar ferries in Bangladesh [12]. Zito et al. reported lifetime fuel savings for a solar-assisted ferry, illustrating strong economic drivers [48].
- Fishing fleets could reduce emissions substantially through hybrid electrification; Ma'arif et al. emphasized efficiency and resilience benefits [8].
- Large commercial vessels such as cargo and passenger ships are unlikely to be powered solely by renewables. Still, wind-assist, solar integration, and battery peak-shaving can provide incremental but meaningful reductions, aligning with environmental goals [49].

By validating zero-emission feasibility at yacht scale, this study contributes to the evidence base that informs such broader applications. This scalability is echoed by Krčum et al., who proposed hybrid system optimization for ships, balancing environmental and economic objectives [42]. Our methodology applies the same systems-engineering logic to yacht scale, demonstrating its effectiveness.

4.6. Summary of Findings, Limitations, and Future Work

The findings derive from a validated, scenario-based modeling framework, and historical meteorological forcing; nevertheless, hydrodynamic-energy-harvesting trades (drag vs. charge), cost uncertainty (battery replacement and energy prices), battery aging under marine thermal/humidity conditions, and model-aggregation bias remain salient. These have been bounded through explicit efficiencies/derates, cross-checks to published/vendor data, and $\pm$20%/$\pm$10% sensitivity sweeps, which leave the main conclusions unchanged.

- Multi-source renewable integration ensures energy self-sufficiency for a 12.5 m sailing yacht, even in low-resource conditions.
- Complementary sources (solar by day, hydro under sail, and wind at anchor) stabilize energy availability.
- Scenario simulations validated the feasibility for both short and extended voyages.

- Conservative "stress-test" conditions imply stronger performance in sunnier or windier regions.
- Results align with and extend recent findings on solar electric yachts, wind-assisted cargo vessels, and hybrid fishing fleets.

The methodology demonstrates transferability to commercial craft and supports decarbonization goals. Prior studies equally stress that shaft-coupled or hydrokinetic generation interacts with propulsive performance, requiring device-specific optimization that is best finalized during prototyping and sea trials. Future work will therefore focus on the following:

- Instrumenting an on-water demonstrator for speed-loss vs. harvested-power characterization;
- Logging in situ battery temperatures/SoC windows to model aging and replacement intervals with higher fidelity;
- Executing year-round routes (including cloudy/low-sun and high-latitude seasons) to refine EMS policies and re-size solar/hydro arrays accordingly [3];
- Integrating fuel cells or hydrogen for backup power [19];
- Adopting solar sails or PV-coated composites for increased generation area;
- Embedding AI-driven EMS to forecast weather and schedule loads dynamically, while conducting lifecycle assessments to quantify embodied vs. operational carbon impacts, as emphasized by Wang et al. [50].

5. Conclusions

This study demonstrates, with a validated systems-engineering model driven by real meteorological data, that an integrated multi-source renewable architecture on a mid-size sailing yacht can sustain typical propulsion and hotel loads without shore charging or fuel. Using a systems-engineering modeling framework and real meteorological data, the analysis validated that solar panels, wind turbines, hydro-generators, and a lithium-ion battery bank can collectively sustain both propulsion and hotel loads without reliance on fossil fuels or shore charging. Even under the relatively modest solar and wind resources of a mid-latitude coastal region, the system achieved energy autonomy across diverse operational profiles. The outcome is environmentally transformative-eliminating fuel consumption and exhaust emissions in a sector traditionally reliant on petroleum. Beyond proving a single-case feasibility, the findings have broader significance for sustainable marine engineering: the techniques and architecture presented here can be adapted to other small craft and potentially scaled to larger vessels, contributing to the decarbonization of maritime transport. By aligning recreational boating with clean energy utilization, this study supports the vision of maritime sustainability and offers a concrete step toward the efficient marine transportation of energy, as the yacht carries and generates its own renewable power. Future work should explore long-term field testing and economic analysis, but the present results are a compelling proof-of-concept for green yachting and beyond.

Immediate contributions (proof-of-concept and validated findings) are as follows:

- This study presents a documented modeling and validation framework for yacht-scale multi-source integration, including transparent efficiency assumptions and sensitivity bounds.
- It provides evidence that routine coastal passages can be completed with zero operational emissions while maintaining conservative SoC margins, and that a four-hour "get-home" endurance on batteries is achievable at modest speed with solar assist.

- The quantified source contributions show the complementary roles of PV (daytime dominance), hydro-generation under sail, and secondary wind input, enabling stable SoC in mid-latitude conditions.

Long-term implications (design and policy) are as follows:

- The architecture is transferable to small commercial platforms, such as eco-tour vessels and day ferries, where predictable routes and layovers can further enhance renewable utilization.
- Hydrodynamic energy-harvesting settings should be co-optimized with voyage time, using speed-loss budgets to tune regeneration set-points.
- Marine-grade reliability, lifecycle battery health, and techno-economic performance must be addressed in deployment planning to align with decarbonization targets.

Key outcomes are as follows:

- Robust Energy Balance: Across three representative scenarios, the vessel maintained safe battery reserves while completing typical voyages. In Scenario 1 (day sail, 23 h), batteries never fell below ~45% SoC, confirming resilience under routine conditions. In Scenario 2 (extended voyage, ~36 h with overnight calm), the system drew heavily on storage but recovered with subsequent solar and hydro input, finishing above the 25% SoC reserve threshold. In Scenario 3 (pure motor transit), the yacht achieved over 4 h of continuous motoring (>10 nautical miles) with a significant margin remaining, aided by daylight solar contribution.
- True Zero-Emission Operation: At no point did the simulated yacht require fossil fuel or external charging. Propulsion and auxiliary needs were entirely covered by renewable generation and storage, confirming practical energy self-sufficiency. This outcome not only eliminates greenhouse gas emissions but also reduces noise, vibration, and operating costs. These outcomes provide empirical support for full energy self-sufficiency in small craft—comparable to recent studies of hybrid and all electric ferries and eco-boats that often still rely on shore power or backup engines.
- Synergistic Integration: The combined use of solar, wind, and hydro sources proved more effective than reliance on a single technology. Solar arrays supplied consistent daytime energy, wind turbines offered low-level but continuous generation when conditions permitted, and hydro-generators transformed sailing motion into electrical power. The electric propulsion motor further acted as a generator under sail. The battery bank provided essential buffering, ensuring an uninterrupted supply despite resource variability.
- Operational Practicality: The scenarios reflected realistic cruising itineraries—short coastal passages, overnight voyages, and emergency motoring. Results show that normal recreational use can be fully sustained without diesel. The operational profile does demand prudent energy management, such as scheduling heavy loads during mid-day solar peaks and conserving at night, yet this mirrors traditional sailing practices of weather-aware planning. The absence of fuel dependence or need for marina charging expands autonomy and facilitates remote cruising.

Beyond technical validation, this case study contributes to the broader discourse on maritime decarbonization. While commercial vessels face scale-specific challenges, success at the yacht scale offers proof-of-concept that modern renewable and storage technologies can deliver practical zero-emission navigation today. The results highlight that combining the oldest propulsion source—sails—with 21st-century solar, hydro, and battery systems provides a robust and sustainable design pathway.

5.1. Future Work and Recommendations

Several directions are essential to translate simulation into widespread adoption:

- Experimental Validation: Sea trials on a prototype vessel should be conducted to verify real-world performance, capture degradation effects, and refine system design (e.g., propeller optimization for regeneration, solar shading mitigation, and structural durability of hydro-turbine mounts).
- Scaling Studies: Application of the framework to different vessel classes, from small leisure boats to larger yachts and ferries, is warranted. Scaling analyses will clarify economic trade-offs, spatial constraints, and system dimensioning across vessel sizes. For motor-only craft (e.g., ferries and eco-tour boats), hybrid renewable setups may provide substantial reductions aligned with decarbonization targets.
- Reliability and Economics: Long-term durability of batteries, inverters, and renewable devices under marine conditions requires assessment. Comparative lifecycle costing should include capital investment, avoided fuel and maintenance expenses, and potential incentives such as carbon credits or green marina programs.
- Advanced Energy Management: Incorporating predictive control and weather-aware optimization could significantly extend endurance. For example, AI-based energy management could pre-emptively store surplus when forecasts predict calm periods or strategically deploy hydro-turbines when higher wind is expected.
- Crew Training and Adoption: Effective adoption depends on awareness and familiarity. Training programs, demonstration projects, and integration into yachting education can accelerate acceptance. Early adopters and retrofitted prototypes can serve as ambassadors for renewable-integrated sailing.

5.2. Closing Statement

Through this research, we confirm that zero-emission sailing yachts are not a distant aspiration but an achievable reality with current technologies. The vessel modeled here operated entirely in harmony with its environment-drawing energy from the sun, wind, and water without pollution or external supply. The findings reinforce that small craft can serve as testbeds and exemplars of sustainable propulsion, inspiring adoption across broader maritime sectors. By aligning with global decarbonization goals and advancing clean recreational boating, renewable electric yachts exemplify how traditional seamanship can converge with modern engineering to chart a sustainable course for the future of marine transport.

Author Contributions: Conceptualization, H.S.N. and İ.Ç.; Methodology, H.S.N.; Investigation, H.S.N.; Data curation, H.S.N.; Writing—original draft, H.S.N.; Writing—review & editing, İ.Ç.; Visualization, H.S.N.; Supervision, İ.Ç. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding and The APC was funded by the Authors.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: This article has been prepared by the first author as part of a graduate thesis study, carried out under the academic supervision and guidance of the second author. The authors gratefully acknowledge the support provided by Istanbul Technical University. ChatGPT (GPT-4.1) from OpenAI was used solely to support translation and text revision.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EMS	Energy Management System
GHG	Greenhouse Gas
IMO	International Maritime Organization
KISS	Keep It Sustainable and Smart
MPPT	Maximum Power Point Tracking
nmi	Nautical Miles
PV	Photovoltaic
SoC	State of Charge

References

1. Plessas, T.; Papanikolaou, A. Multi-Objective Optimization of Ship Design for the Effect of Wind Propulsion. *J. Mar. Sci. Eng.* **2025**, *13*, 167. [CrossRef]
2. Mofor, L.; Nuttall, P.; Neweil, A. Renewable Energy Options for Shipping. January 2015. Available online: https://www.irena.org/ (accessed on 24 August 2025).
3. Koumaniotis, E.K.; Kanellos, F.D. Optimal Routing and Sustainable Operation Scheduling of Large Ships with Integrated Full-Electric Propulsion. *Sustainability* **2024**, *16*, 10662. [CrossRef]
4. Mallouppas, G.; Yfantis, E.A. Decarbonization in Shipping industry: A review of research, technology development, and innovation proposals. *J. Mar. Sci. Eng.* **2021**, *9*, 415. [CrossRef]
5. Minak, G. Solar Energy-Powered Boats: State of the Art and Perspectives. *J. Mar. Sci. Eng.* **2023**, *11*, 1519. [CrossRef]
6. Moon, H.S.; Park, W.Y.; Hendrickson, T.; Phadke, A.; Popovich, N. Exploring the cost and emissions impacts, feasibility and scalability of battery electric ships. *Nat. Energy* **2024**, *10*, 41–54. [CrossRef]
7. Aksöz, A.; Asal, B.; Golestan, S.; Gençtürk, M.; Oyucu, S.; Biçer, E. Electrification in Maritime Vessels: Reviewing Storage Solutions and Long-Term Energy Management. *Appl. Sci.* **2025**, *15*, 5259. [CrossRef]
8. Ma'arif, S.; Budiyanto, M.A.; Sunaryo; Theotokatos, G. Progress in hybrid and electric propulsion technologies for fishing vessels: An extensive review and prospects. *Ocean Eng.* **2024**, *316*, 120017. [CrossRef]
9. Akiyama, T.; Bousquet, J.F.; Roncin, K.; Muirhead, G.; Whidden, A. An engineering design approach for the development of an autonomous sailboat to cross the atlantic ocean. *Appl. Sci.* **2021**, *11*, 8046. [CrossRef]
10. Barry, K. World's First Circumnavigation By Solar Powered Ship A Success | WIRED. Available online: https://www.wired.com/2012/05/worlds-first-circumnavigation-by-solar-powered-ship-a-success/ (accessed on 24 August 2025).
11. Suardi, S.; Maulana, M.K.; Ikhwani, R.J.; Pawara, M.U.; Mahmuddin, F.; Tasrief, M. Design and Implementation of Solar Cells as an Alternative Power Source for Pinisi Ships. *Comput. Exp. Res. Mater. Renew. Energy* **2024**, *7*, 93–104. [CrossRef]
12. Chowdhury, T.H.; Islam, R.; Alam, F.; Murad, E.A.; Hasan, R.; Lipu, H.R. Design of a boat powered by solar energy with an 180° rotating solar tracking system. *SEU J. Electr. Electron. Eng.* **2024**, *4*, 9–14.
13. Eastlack, E.; Faiss, E.; Sauter, R.; Klingenberg, S.; Witt, M.; Szymanski, S.; Lidqvist, A.; Olsson, P. Zero emission super-yacht. In Proceedings of the 2019 14th International Conference on Ecological Vehicles and Renewable Energies, EVER 2019, Monte-Carlo, Monaco, 8–10 May 2019. [CrossRef]
14. Formosa, W.; Sant, T.; Muscat-Fenech, C.D.M.; Figari, M. Wind-Assisted Ship Propulsion of a Series 60 Ship Using a Static Kite Sail. *J. Mar. Sci. Eng.* **2023**, *11*, 117. [CrossRef]
15. Bucci, V.; Mauro, F.; Vicenzutti, A.; Bosich, D.; Sulligoi, G. Hybrid-electric solutions for the propulsion of a luxury sailing yacht. In Proceedings of the 2020 2nd IEEE International Conference on Industrial Electronics for Sustainable Energy Systems (IESES), Cagliari, Italy, 1–3 September 2020.
16. Geertsma, R.D.; Negenborn, R.R.; Visser, K.; Hopman, J.J. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Appl. Energy* **2017**, *194*, 30–54. [CrossRef]
17. Alfonsin, V.; Suarez, A.; Urrejola, S.; Miguez, J.; Sanchez, A. Integration of several renewable energies for internal combustion engine substitution in a commercial sailboat. *Int. J. Hydrogen Energy* **2015**, *40*, 6689–6701. [CrossRef]
18. Coppola, T.; Micoli, L.; Russo, R. Concept design and feasibility study of propulsion system for yacht: Innovative hybrid propulsion system fueled by methanol. In Proceedings of the 2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2022, Sorrento, Italy, 22–24 June 2022; pp. 683–688. [CrossRef]
19. Di Bernardo, R.; Di Cecca, B.; Coppola, T.; Spazzafumo, G.; Speranza, D. Preliminary design of a 75 m Mega Yacht with diesel—Electric hybrid propulsion powered with hydrogen FCs. *Int. J. Hydrogen Energy* **2024**, *137*, 917–924. [CrossRef]

20. Begovic, E.; Bertorello, C.; De Luca, F.; Rinauro, B. KISS (Keep It Sustainable and Smart): A Research and Development Program for a Zero-Emission Small Crafts. *J. Mar. Sci. Eng.* **2021**, *10*, 16. [CrossRef]
21. Ma, R.; Wang, Z.; Wang, K.; Zhao, H.; Jiang, B.; Liu, Y.; Xing, H.; Huang, L. Evaluation Method for Energy Saving of Sail-Assisted Ship Based on Wind Resource Analysis of Typical Route. *J. Mar. Sci. Eng.* **2023**, *11*, 789. [CrossRef]
22. Calcagni, D.; Mancini, A.; Baffigo, R. Innovative dual-function SAIL-POD by Velettrica: Experimental assessment and performance calibration. *J. Mar. Sci. Technol.* **2025**, *30*, 392–407. [CrossRef]
23. Ekinci, S.; Alvar, M. Horizontal axis marine current turbine design for wind-electric hybrid sailing boat. *Brodogradnja* **2017**, *68*, 127–151. [CrossRef]
24. Sang, Y.; Ding, Y.; Sui, C.; Xiang, L. Energy analysis of battery/PV-powered all-electric ship in various operational conditions. *Ocean Eng.* **2025**, *340*, 122257. [CrossRef]
25. Trincas, G.; Braidotti, L.; Vicenzutti, A.; Tavagnutti, A.A.; Cooke, C.M.; Chalfant, J.; Bucci, V.; Chryssostomidis, C.; Sulligoi, G. Integration of the Power Corridor Concept in the Early-Phase Design of Electric Naval Ships using Mathematical Design Models. In Proceedings of the 15th International Marine Design Conference, Amsterdam, The Netherlands, 2–7 June 2024. [CrossRef]
26. Degiuli, N.; Martić, I. CFD Applications in Ship and Offshore Hydrodynamics. *J. Mar. Sci. Eng.* **2024**, *12*, 1926. [CrossRef]
27. Yang, W.; Wang, B.; Ke, W.; Shen, S.; Wu, X. Research on Photovoltaic Power Generation Characteristics of Small Ocean Observation Unmanned Surface Vehicles. *Energies* **2024**, *17*, 3699. [CrossRef]
28. Yang, Z.; Qu, W.; Zhuo, J. Optimization of Energy Consumption in Ship Propulsion Control under Severe Sea Conditions. *J. Mar. Sci. Eng.* **2024**, *12*, 1461. [CrossRef]
29. Kolodziejski, M.; Michalska-Pozoga, I. Battery Energy Storage Systems in Ships' Hybrid/Electric Propulsion Systems. *Energies* **2023**, *16*, 1122. [CrossRef]
30. Vakili, S.; Insel, M.; Singh, S.; Ölçer, A. Decarbonizing Domestic and Short-Sea Shipping: A Systematic Review and Transdisciplinary Pathway for Emerging Maritime. *Sustainability* **2025**, *17*, 7294. [CrossRef]
31. Ekinci, S.; Alvar, M. Sıfır emisyonlu yenilenebilir enerji üreten yelkenli bir tekne için sualtı türbin tasarımı. *Dicle Üniversitesi Mühendislik Fakültesi Mühendislik Dergisi* **2016**, *7*, 537–550.
32. Velásquez, L.; Rengifo, J.; Saldarriaga, A.; Rubio-Clemente, A.; Chica, E. Optimization of Vertical-Axis Hydrokinetic Turbines: Study of Various Geometric Configurations Using the Response Surface Methodology and Multi-Criteria Decision Matrices. *Processes* **2025**, *13*, 1950. [CrossRef]
33. Sakamoto, L.; Fukui, T.; Morinishi, K. Blade Dimension Optimization and Performance Analysis of the 2-D Ugrinsky Wind Turbine. *Energies* **2022**, *15*, 2478. [CrossRef]
34. Astolfi, D.; Pandit, R.; Lombardi, A.; Terzi, L. Multivariate Data-Driven Models for Wind Turbine Power Curves including Sub-Component Temperatures. *Energies* **2022**, *16*, 165. [CrossRef]
35. Sadeghi, R.; Parenti, M.; Memme, S.; Fossa, M.; Morchio, S. A Review and Comparative Analysis of Solar Tracking Systems. *Energies* **2025**, *18*, 2553. [CrossRef]
36. Otsason, R.; Tapaninen, U. Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries. *Sustainability* **2023**, *15*, 16170. [CrossRef]
37. Tay, Z.Y.; Konovessis, D. Sustainable energy propulsion system for sea transport to achieve United Nations sustainable development goals: A review. *Discov. Sustain.* **2023**, *4*, 1–34. [CrossRef]
38. de Albuquerque, B.S.; Tostes, M.E.d.L.; Bezerra, U.H.; Carvalho, C.C.M.d.M.; Nascimento, A.L.L.D. Use of Distributed Energy Resources Integrated with the Electric Grid in the Amazon: A Case Study of the Universidade Federal do Pará Poraquê Electric Boat Using a Digital Twin. *Machines* **2024**, *12*, 803. [CrossRef]
39. Elkafas, A.G.; Rivarolo, M.; Barberis, S.; Massardo, A.F. Feasibility Assessment of Alternative Clean Power Systems onboard Passenger Short-Distance Ferry. *J. Mar. Sci. Eng.* **2023**, *11*, 1735. [CrossRef]
40. Ge, Y.; Zhang, J.; Zhou, K.; Zhu, J.; Wang, Y. Research on Energy Management for Ship Hybrid Power System Based on Adaptive Equivalent Consumption Minimization Strategy. *J. Mar. Sci. Eng.* **2023**, *11*, 1271. [CrossRef]
41. Ba, L.; Tangour, F.; El Abbassi, I.; Absi, R. Analysis of Digital Twin Applications in Energy Efficiency: A Systematic Review. *Sustainability* **2025**, *17*, 3560. [CrossRef]
42. Krčum, M.; Gudelj, A.; Tomas, V. Optimal design of ship's hybrid power system for efficient energy. *Trans. Marit. Sci.* **2018**, *7*, 23–32. [CrossRef]
43. Bortuzzo, V.; Bertagna, S.; Bucci, V. Mitigation of CO_2 Emissions from Commercial Ships: Evaluation of the Technology Readiness Level of Carbon Capture Systems. *Energies* **2023**, *16*, 3646. [CrossRef]
44. Kim, S.; Jeon, H.; Park, C.; Kim, J. Lifecycle Environmental Benefits with a Hybrid Electric Propulsion System Using a Control Algorithm for Fishing Boats in Korea. *J. Mar. Sci. Eng.* **2022**, *10*, 1202. [CrossRef]
45. Animah, I.; Adjei, P.; Djamesi, E.K. Techno-economic feasibility assessment model for integrating hybrid renewable energy systems into power systems of existing ships: A case study of a patrol boat. *J. Mar. Eng. Technol.* **2022**, *22*, 22–37. [CrossRef]

46. Maydison; Zhang, H.; Han, N.; Oh, D.; Jang, J. Optimized Diesel–Battery Hybrid Electric Propulsion System for Fast Patrol Boats with Global Warming Potential Reduction. *J. Mar. Sci. Eng.* **2025**, *13*, 1071. [CrossRef]
47. Ellabban, O.; Abu-Rub, H.; Blaabjerg, F. Renewable energy resources: Current status, future prospects and their enabling technology. *Renew. Sustain. Energy Rev.* **2014**, *39*, 748–764. [CrossRef]
48. Zito, T.; Park, C.; Jeong, B. Life cycle assessment and economic benefits of a solar assisted short route ferry operating in the Strait of Messina. *J. Int. Marit. Safety, Environ. Aff. Shipp.* **2022**, *6*, 24–38. [CrossRef]
49. Zenié, A.; Lam, K.; Jobson, R.; Hinton, S.; Vasileiadis, N.; Scarbrough, T.; Condes, S.; Powell, N.; Wasil, J. Pathways to Propulsion Decarbonisation for the Recreational Marine Industry Synopsis Report. 2023. Available online: https://www.icomia.org/product/pathways-to-propulsion-decarbonisation-for-the-recreational-marine-industry-full-report-purchase-application/ (accessed on 24 August 2025).
50. Wang, Z.; Ma, Y.; Sun, Y.; Tang, H.; Cao, M.; Xia, R.; Han, F. Optimizing Energy Management and Case Study of Multi-Energy Coupled Supply for Green Ships. *J. Mar. Sci. Eng.* **2023**, *11*, 1286. [CrossRef]