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Renewable Energy Technologies and Their Potential Applications in Naval and Maritime Engineering

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Abstract

The maritime sector faces growing pressure to reduce greenhouse gas emissions, improve fuel security, and limit environmental harm, while navies add requirements for endurance, resilience, and operational flexibility. Renewable energy technologies offer options for addressing these pressures across commercial shipping, ports, offshore installations, and naval forces. This article examines renewable energy technologies and their potential applications in naval and maritime engineering. It reviews the drivers of change, then analyses wind assisted propulsion, solar photovoltaic systems, wave, tidal, and offshore wind energy, energy storage and hybrid power architectures, and renewable fuels and hydrogen carriers. It then considers naval applications and operational constraints, and economic, regulatory, and environmental assessment. Drawing on research in marine engineering, renewable energy, and ship power systems, the analysis finds that renewable technologies can reduce fuel consumption and emissions, extend endurance, and improve resilience, but that their contribution varies widely by vessel type, route, and mission, and that high power and energy density requirements limit direct use on large combatants. The study concludes that the most promising path combines efficiency measures, hybrid systems, shore connections, and renewable fuels, supported by research, standards, and carefully targeted demonstration projects.

Keywords: renewable energy, maritime engineering, wind assisted propulsion, hybrid power systems, naval sustainability

INTRODUCTION

Ships have always been shaped by the energy sources available to them. Sail gave way to coal and then to oil, which offered high energy density, easy storage, and reliable power. Today the maritime sector relies overwhelmingly on

petroleum fuels, and the consequences are visible in emissions, air quality, and exposure to fuel price and supply risk. The Fourth International Maritime Organization Greenhouse Gas Study estimated that shipping accounts for a little under three percent of global anthropogenic carbon dioxide emissions, and that emissions could grow without further measures (Faber et al., 2020). The International Maritime Organization has adopted a strategy that aims to reduce the carbon intensity of shipping and to pursue a pathway toward the elimination of greenhouse gas emissions from ships (International Maritime Organization, 2018). Naval forces face similar pressures with additional considerations. Fuel logistics are a major burden and vulnerability, since warships and their supporting tankers require continual replenishment, and supply lines can be disrupted. Reducing fuel consumption extends range and endurance, reduces dependence on vulnerable supply chains, and may reduce thermal and acoustic signatures in some operating modes. At the same time, naval vessels demand high power for speed and combat systems, and they cannot compromise on reliability, safety, or survivability. Renewable energy technologies, including wind, solar, wave, tidal, and the fuels produced from renewable electricity or biomass, offer potential contributions. They may be used directly on vessels, as in wind assisted propulsion or solar panels, or indirectly through shore power, offshore generation, and renewable fuels. Their suitability varies enormously, and an honest assessment requires attention to energy density, power requirements, space, weight, cost, and safety. This article explores the applications of renewable energy technologies in naval and maritime engineering. It proceeds through nine thematic sections addressing energy demand and decarbonisation pressures, wind assistance, solar systems, marine renewable energy, storage and hybrid power, renewable fuels, naval applications, economic and regulatory assessment, and challenges with future directions. A summary and a list of references follow.

Energy Demand and Decarbonisation Pressures in Maritime Engineering:

Understanding the potential of renewable technologies begins with understanding energy demand. Ships require energy for propulsion, which usually accounts for the largest share, and for electrical loads such as hotel services, auxiliary machinery, cargo handling, refrigeration, and, on naval vessels, sensors, communications, and weapons. The balance varies by ship type. A cargo vessel on a long passage devotes most of its energy to propulsion, while a cruise ship or a naval auxiliary may have a large electrical demand. Eyring and colleagues reviewed the impacts of shipping on atmosphere and climate and showed that emissions of carbon dioxide, sulphur and nitrogen compounds, and particles have implications for both climate and air quality, which creates multiple reasons for reducing dependence on conventional fuels (Eyring et al., 2010). Regulatory pressure from international and regional authorities is increasing, and commercial charterers, financiers, and ports are adding their own expectations. Bouman and colleagues reviewed technologies and measures for reducing greenhouse gas emissions from shipping and found that no single option offers a complete solution, but that combinations of efficiency improvements, operational measures, and alternative energy sources can deliver substantial reductions (Bouman et al., 2017). Renewable technologies sit within this broader portfolio. They are best understood as complements to, rather than replacements for, measures such as hull optimisation, speed management, and waste heat recovery. For navies, demand is shaped by mission. Patrol vessels, auxiliaries, and amphibious ships spend much of their time at modest speeds, where renewable contributions may be significant, while combatants require bursts of high power. Operating profiles, rather than maximum capability, determine the average energy that renewable sources could displace. Detailed analysis of operational profiles is therefore a prerequisite for assessing any technology.

Wind-Assisted Propulsion and Sail Technologies:

Wind is the oldest renewable energy source used at sea, and modern technologies aim to harness it as a supplement to engine power. Several concepts are in use or under development. Rotor sails, also known as Flettner rotors, are spinning cylinders that generate lift through the Magnus effect. Rigid wing sails and suction wings use aerodynamic profiles to produce thrust. Soft sails and kites offer lightweight options, and turbine based systems are also being explored. Traut and colleagues examined the propulsive power contribution of a kite and a Flettner rotor on selected shipping routes and found that the contribution varied substantially with route and wind conditions, with significant savings on favourable routes (Traut et al., 2014). Lu and Ringsberg studied the energy performance of three wind assisted propulsion technologies and conducted a parametric study of the Flettner rotor, showing that fuel savings depend on rotor size, wind conditions, and ship speed and heading (Lu and Ringsberg, 2020). These results suggest that wind assistance offers meaningful but route dependent gains. The technology suits ships with large deck space, moderate speeds, and long ocean passages, such as bulk carriers, tankers, and some auxiliary vessels. Routing that takes advantage of prevailing winds, supported by weather routing software, can increase benefits. Integration challenges include the effect on stability, visibility from the bridge, interference with cargo operations and helicopter or crane use, structural loads, and clearance under bridges. For naval applications, wind assistance is more constrained. Superstructures are crowded with sensors and weapons, and wind devices may interfere with arcs of fire, radar performance, and signature management. Nevertheless, naval auxiliaries, sail training vessels, survey ships, and some patrol vessels with spacious decks may benefit. Wind assistance can reduce fuel consumption on long transits,

extending range and reducing the logistic burden, provided that devices are robust, retractable where necessary, and compatible with mission needs.

Solar Photovoltaic Systems on Ships and Ports:

Solar photovoltaic panels convert sunlight directly to electricity and have been installed on vessels ranging from small craft to large car carriers and ferries. Their advantages include silent operation, no fuel consumption, modest maintenance, and scalability. Their main limitation is low power density relative to the energy needs of ships. Even a large deck area yields only a fraction of the power required for propulsion, so solar energy typically supplies auxiliary and hotel loads or charges batteries. Lan and colleagues examined the optimal sizing of hybrid photovoltaic, diesel, and battery systems in ship power systems and showed that combining solar generation with storage and conventional generators can reduce fuel consumption and emissions while meeting load demand, with the economics depending on sizing, operating profile, and fuel prices (Lan et al., 2015). Their work illustrates that the value of solar lies in integration with a wider hybrid architecture rather than in standalone use. Marine conditions create engineering challenges. Panels must withstand salt spray, humidity, vibration, and shading from superstructure. Placement competes with other uses of deck space, and the effect on radar cross section, electromagnetic compatibility, and visual signature is relevant for naval vessels. Flexible and lightweight panels, and integration into surfaces such as hatch covers and deckhouses, may help address some of these concerns. Ports and naval bases offer large areas for solar installations, on rooftops, car parks, and reclaimed land. Shore based solar generation can supply power to vessels at berth through shore connections, reduce reliance on onboard generators, and provide resilience when combined with storage and microgrids. For naval installations, on site renewable generation can improve energy security by reducing dependence on external grids, an advantage that is receiving increasing attention in defence energy policy.

Wave, Tidal, and Offshore Wind Energy:

The ocean itself is a large energy resource, and maritime engineering is central to harnessing it. Falcão reviewed wave energy technologies and described a wide variety of device types, including oscillating water columns, oscillating bodies, and overtopping systems, noting that the field had produced many concepts but that reliable, cost effective, and survivable devices remained a challenge (Falcão, 2010). Wave energy converters must withstand extreme storms while efficiently capturing energy from everyday waves, a demanding engineering combination. Bahaj reviewed the generation of electricity from the oceans and highlighted the predictability of tidal energy, which follows astronomical cycles, as a major advantage compared with wind and solar (Bahaj, 2011). Tidal stream turbines, tidal barrages, and lagoons exploit currents and level differences. Their deployment depends on suitable sites with strong currents and on dealing with the harsh and difficult conditions for installation and maintenance. Offshore wind is the most mature of the marine renewable sectors, and it has created a large demand for vessels and infrastructure. Installation vessels, crew transfer vessels, service operation vessels, cable layers, and ports for assembly and maintenance form a growing segment of the maritime industry. Floating wind platforms extend the resource to deeper water and bring naval architecture, mooring design, and marine operations to the centre of the energy transition. These technologies serve maritime engineering in several ways. They generate power for shore grids that supply ports and ships at berth, and for the production of renewable fuels. Smaller devices can power offshore installations, navigation aids, sensors, and unmanned vehicles, reducing the need for diesel generators or battery replacement in remote locations. For naval organisations, marine energy may offer independent power for underwater surveillance networks, offshore bases, and forward facilities, although survivability and security of such installations require careful attention.

Energy Storage, Batteries, and Hybrid Power Systems:

Because many renewable sources are intermittent and ship loads fluctuate, storage and power management are essential. Batteries, especially lithium ion types, have become practical for several maritime uses. Fully electric ferries and short sea vessels are in service on routes where charging is available at terminals, and hybrid ships use batteries to supplement engines, shaving peak loads, providing spinning reserve, and allowing engines to operate at their most efficient points. Geertsma and colleagues reviewed developments in the design and control of hybrid power and propulsion systems for smart ships and found that combining engines, electric motors, and energy storage can reduce fuel consumption and emissions, improve manoeuvring and redundancy, and enable new operating modes, while requiring sophisticated energy management strategies (Geertsma et al., 2017). The key point is that hybridisation creates a platform on which renewable sources such as solar and wind assistance can be integrated more effectively. Other storage options include supercapacitors, which supply short bursts of power, flywheels, and, in some applications, fuel cells that convert hydrogen or other fuels to electricity. Direct current distribution systems can improve efficiency and flexibility by allowing engines to run at variable speed and by simplifying connection of batteries and renewable sources. Intelligent energy management systems optimise the dispatch of power from different sources according to load forecasts, efficiency curves, and operational priorities. Safety is an important consideration. Battery fires are difficult to extinguish and can propagate quickly, so ship designs and classification rules emphasise thermal management, compartmentation, detection, and suppression. For naval vessels, which must withstand battle

damage, battery installations require particular protection and survivability engineering. Weight and volume of batteries remain limiting factors for high power or long range applications, because their energy density is still far lower than that of liquid fuels.

Renewable Fuels and Hydrogen Carriers:

For vessels that cannot rely on direct electrification or wind and solar contributions, renewable fuels offer a path to lower emissions while retaining high energy density. These fuels are produced from renewable electricity or sustainable biomass. They include hydrogen produced by electrolysis, ammonia synthesised from hydrogen and nitrogen, methanol produced from captured carbon dioxide and hydrogen, and biofuels and synthetic hydrocarbons that can be used in existing engines with limited modification. Van Hoecke and colleagues reviewed challenges in the use of hydrogen for maritime applications and noted that hydrogen offers zero emissions at the point of use, but that its low volumetric energy density, storage requirements, safety issues, and the lack of bunkering infrastructure present significant obstacles, particularly for large ocean going ships (van Hoecke et al., 2021). Carriers such as ammonia and methanol are easier to store and handle but bring their own concerns, including toxicity in the case of ammonia and the need for sustainable carbon sources for methanol. The fuel choice has far reaching consequences for ship design. Lower energy density fuels require larger tanks, which affect cargo capacity, stability, and arrangement. Engines and fuel systems need to be designed or converted for the new fuels, crews need training in their safe handling, and ports need infrastructure for production, storage, and bunkering. Lifecycle emissions depend on how the fuel is produced, so renewable electricity and sustainable feedstocks are essential for real climate benefit. For navies, drop in renewable fuels that are compatible with existing engines and logistic systems are especially attractive, since they can reduce carbon intensity without redesigning platforms or fuel supply chains. Using such fuels in naval vessels and aircraft is a pragmatic route to reducing emissions while maintaining interoperability with allies. Alternative fuels with different properties would need extensive testing for safety, performance, and compatibility with weapons and aircraft operations.

Naval Applications and Operational Considerations:

Naval vessels differ from commercial ships in ways that shape the potential for renewable technologies. Doerry described the evolution of naval power systems and the importance of integrated power systems that supply electricity for both propulsion and ship services, increasing flexibility and enabling the sharing of generation capacity across loads (Doerry, 2015). Such architectures create opportunities to integrate batteries, fuel cells, and renewable sources, and they support the growing electrical demand of sensors and advanced systems. Operational requirements impose constraints. Naval vessels must achieve high speeds, survive damage, remain quiet, and operate under combat conditions. Wind devices and large solar arrays may conflict with sensor arcs and signature requirements. Batteries must be protected from shock and fire, and any new fuel must be safe in magazines and flight decks. Maintenance and logistics must function in remote theatres, and personnel must be trained to handle new systems. Within these constraints, several applications are promising. Auxiliary vessels, such as replenishment ships, survey ships, and training vessels, can adopt wind assistance and solar power. Patrol craft and small combatants can use hybrid propulsion to operate silently at low speed on batteries and to reduce fuel consumption on long patrols. Shore power and renewable microgrids at bases reduce fuel use alongside and improve resilience. Unmanned systems, which have limited energy needs, can use solar panels and efficient batteries to extend endurance. Benefits extend beyond emissions. Reduced fuel consumption lengthens range and time on station, reduces the number of replenishment evolutions, and lessens exposure of logistic ships to attack. Energy independence at forward locations may improve resilience. The figure below presents an illustrative comparison of the share of energy demand that renewable technologies might plausibly supply across several vessel types, expressed as a percentage. The values are stylised to show relative magnitude and should not be read as measured data.

Economic, Regulatory, and Environmental Assessment:

The decision to adopt a renewable technology rests on economics as well as engineering. Capital costs for wind devices, solar panels, batteries, and new fuel systems must be weighed against savings in fuel and potential carbon costs. Bouman and colleagues found that many efficiency and operational measures offer attractive returns, while deeper reductions require more expensive options, and that costs vary with ship type, size, and operating profile (Bouman et al., 2017). Fuel price volatility adds uncertainty, though it also raises the value of technologies that reduce fuel use. Regulation is a major driver. International standards on carbon intensity and efficiency, regional carbon pricing, and requirements for ports to provide shore power all affect the economics. The strategy adopted by the International Maritime Organization signals a long term direction that influences investment decisions in shipbuilding and fuels (International Maritime Organization, 2018). Navies are generally exempt from many commercial regulations but increasingly adopt national energy and climate policies, which create their own targets and incentives. Environmental assessment should consider the full life cycle. Manufacturing of panels, batteries, and rotors consumes materials and energy, and end of life disposal and recycling matter. Marine renewable devices may affect marine

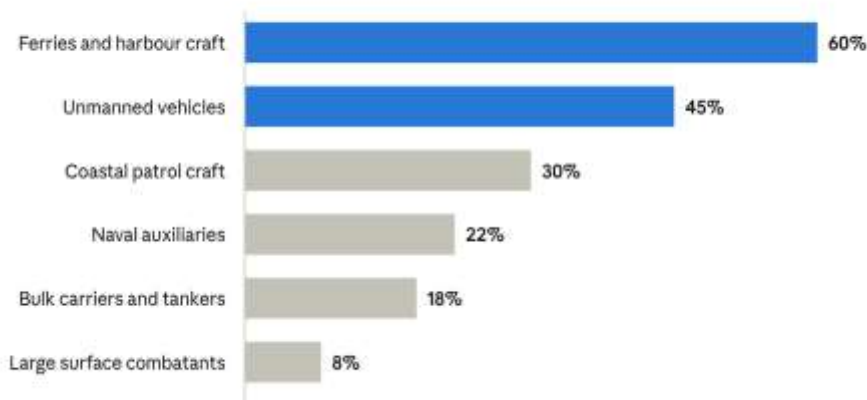
ecosystems through noise, habitat change, and collision risk. Fuels should be assessed from production to combustion to avoid shifting emissions elsewhere. A balanced assessment considers climate, air quality, resource use, and local environmental effects together. For navies, assessment must also include operational value, which is harder to monetise. Range, endurance, resilience, and reduced logistic vulnerability may justify investments that would not pass a purely commercial test. Methods that capture the fully burdened cost of fuel, including the cost of delivering it to the point of use and protecting its transport, can provide a more realistic basis for comparison.

Challenges, Recommendations, and Future Directions:

Several challenges limit the adoption of renewable energy in maritime and naval engineering. Energy density remains the central problem, since ships and combatants need large amounts of energy in compact form. Integration complexity increases as multiple sources, storage systems, and controls must work together reliably. Safety concerns about batteries and new fuels require rigorous standards. Infrastructure for charging, bunkering, and shore power is limited and unevenly distributed. Costs may be high, and uncertainty about technology and regulation can delay investment. Several recommendations follow. First, organisations should begin with detailed analysis of operating profiles to identify where renewable technologies can displace significant energy at acceptable cost and risk. Second, they should prioritise efficiency measures, which reduce the energy to be supplied by any source, before investing in new supply options. Third, they should adopt hybrid and electric architectures that provide flexibility to integrate new sources over a ship's life. Fourth, they should pursue demonstration projects, particularly on auxiliary vessels and small craft, to gather data and build experience. Fifth, they should work with industry, classification societies, and allies to develop standards for safety, interoperability, and fuels. Sixth, they should invest in shore infrastructure, including renewable generation and charging, to support vessels and enhance base resilience. Seventh, they should train personnel to operate and maintain new systems. Future developments may reshape the landscape. Advances in battery chemistry, solid state storage, and fuel cells could improve energy density and safety. Better materials may enable lighter wind devices and more efficient photovoltaic surfaces. Scalable production of renewable fuels could change the economics of alternative energy carriers. Compact nuclear options may be reconsidered by some navies in the long term, though they raise distinct regulatory and political questions. Research should evaluate lifecycle performance, operational effects, and the integration of multiple technologies, and should test systems under realistic conditions.

Renewables fit small craft well and large combatants poorly

Illustrative share of energy demand renewables could supply, percent



Summary:

This article has examined renewable energy technologies and their potential applications in naval and maritime engineering. Pressures to reduce emissions and fuel dependence, together with naval interest in endurance and resilience, create incentives for change. Wind assisted propulsion and solar systems can reduce fuel consumption on suitable vessels, marine renewable energy supplies power for ports, offshore installations, and fuel production, and batteries and hybrid architectures enable flexible integration of intermittent sources. Renewable fuels and hydrogen carriers offer routes to lower emissions where direct electrification is not feasible, though they pose challenges of storage, safety, and infrastructure. Naval applications are constrained by power density, survivability, and signature requirements, but auxiliaries, patrol craft, bases, and unmanned systems offer promising opportunities. A balanced approach that combines efficiency, hybridisation, shore connections, and renewable fuels, supported by standards, demonstration, and training, is most likely to deliver durable benefits.

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