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## NAVIGATING TOWARDS SUSTAINABILITY: A REVIEW OF GREEN SHIPPING PRACTICES

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**Abstract:** The maritime industry is undergoing a profound shift towards environmental sustainability through the adoption of green shipping. This paper examines the pivotal role of marine engineering in advancing sustainable practices and enhancing pollution control within the sector. It highlights the role of advanced propulsion systems, including methanol engines, ammonia-based propulsion, and hydrogen fuel cell alongside digital monitoring technologies that help optimize energy use and emissions control. The paper also assesses the economic feasibility of transitioning to sustainable shipping practices. Additionally, it emphasizes the crucial involvement of port authorities, who contribute through targeted incentives and green infrastructure programs. Regulatory frameworks, international maritime regulations and industry collaboration for sustainable shipping strategies further underscore the urgency of these efforts. As the industry embraces a greener future, marine engineers play a crucial role in shaping a more sustainable and resilient marine transport system that benefits both the environment and society.

**Keywords:** pollution control, sustainable shipping strategies, international maritime regulations, innovative propulsion systems, methanol engines, ammonia propulsion.

### 1. INTRODUCTION

Green shipping is a significant way to reduce the environmental impact of the marine industry, one of the principal sources of greenhouse gas emissions and for marine pollution. This paper analyses the concept and practical application of green shipping policies and technologies as well as their practices globally and within India. The study begins by identifying key environmental concerns introduced by

traditional shipping, such as water and air pollution, and then explores options like methanol engines, ammonia propulsion systems, hydrogen and solar photovoltaic fuel cells, and wind-assisted propulsion technology like rotor sails. It also discusses eco-friendly antifouling methods and the feasibility of their adoption. The paper emphasizes sustainability frameworks, the economic viability of these technologies, and the funding mechanisms required for implementation. Green fuel logistics and the involvement of private stakeholders in promoting faster sustainable shipping is investigated in this study. Government programs, such as India's Harit Sagar scheme and the Green Port initiatives, are reviewed, supported by case studies by the Mormugao and Mangalore ports. Finally, the study highlights the opportunities, challenges, and future prospects for green shipping in achieving economic development and environmental conservation.

## **2. ENVIRONMENTAL IMPACT ON SHIPPING**

The shipping business world-wide contributes immensely to pollution of the environment, mainly through contamination of air, water, and noise. The industry is ranked as number six among the world's greenhouse gas emitters, ranking between Japan and Germany. Based on the world's greenhouse emissions, 2% to 3% are currently attributed to shipping, but, if left uncontrolled, emissions may increase to 17% by 2050 [Solutions, MAN Energy 2021]. The release of carbon dioxide changes the chemical structure of oceans, making them more acidic and threatening the future of shell-forming creatures and coral reefs [Dubinsky and Stambler 1996]. In addition, warming the ocean temperatures enhances storms and participates in causing sea levels to rise. Furthermore, sulphur oxide (SO<sub>x</sub>), nitrogen oxide (NO<sub>x</sub>), particulate matter (PM), and black carbon emissions account for more than 60,000 premature deaths worldwide and contribute to respiratory issues in millions of people, especially those who reside near busy ports [Dubinsky and Stambler 1996].

A maritime vessel produces about 190 decibels of sound, more than the takeoff noise level of a jet aircraft. In the ocean, sound travels much quicker, four times as fast as in air, so the noise made by a ship can radiate much farther than the expected distances, affecting huge expanses of the sea through which it travels [Wepener and Degger 2012]. Studies have shown that frequent man-made noise in aquatic ecosystems is largely caused by shipping, with both short-term and long-term adverse impacts on marine species, particularly marine mammals. The United Nations Environment Programme (UNEP) oversees a global program to safeguard the marine ecosystem against land-based activities, which includes combating issues of plastic pollution and waste [Pettipas, Bernier and Walker 2016]. Plastics, when discarded, form some of the main causes of marine pollution and thus contribute to higher water contamination by toxic bacteria and viruses, especially due to single-use plastics

[Schnurr et al. 2018]. Heavy metals have also been identified as major contributors to marine pollution [Ansari, Marr and Tariq 2004].

Studies prove that major unintentional oil spills contribute a high percentage of total oil released into the world's oceans every year. Further, ballast water release systems by ships can have a negative impact on marine life and environment. Cargo ships release different kinds of wastewater, such as bilge water, black water, and grey water, all of which can pollute the water, damage marine ecosystems, and lead to public health concerns. Ballast water, which is stored in ballast tanks when a vessel has discharged its cargo and sails away carrying little or no cargo, is then carried and dumped at the next port, where the ship loads more cargo. This dumping releases non-native organisms, such as invasive and exotic species, into the local ecosystem.

### **3. WHAT IS GREEN SHIPPING**

Green shipping is the mode of carrying out maritime transportation in a sustainable and green manner with special emphasis on the reduction of unwanted impacts on the environment as well as a reduction of greenhouse gases, air contaminants, and other shipping operations-associated forms of pollution. This includes using different modes, technology, and shipping practices to achieve efficiency in terms of energy use, minimize fuel consumption, and adopt cleaner substitute fuels. One method is to monitor the presence of molecular biomarkers in samples taken from sea water in various regions [Sarkar et al. 2006].

Green shipping encompasses practices like the use of alternative fuels (e.g., LNG, biofuels, hydrogen), adoption of energy-efficient technologies and practices, incorporation of renewable sources of energy (e.g., solar, wind), adoption of emission control technology, routing optimization and speed management, and compliance with environmental standards. The intention of green shipping is to achieve a more environmentally friendly and sustainable maritime transport industry while providing for international transport requirements and facilitating the combat against climate change as well as the preservation of marine ecosystems [Reinhold, Järvis and Prause 2019].

### **4. EMERGING GREEN PROPULSION METHODS**

The shipping industry is transforming massively towards greener propulsion technologies to comply with tighter environmental regulations and decarbonization efforts. The new approaches target alternative fuels, new-generation engines, and hybrid systems to minimize greenhouse gas emissions and enhance energy

efficiency. The following section discusses the latest advancements that are shaping the sustainable future of marine propulsion.

#### **4.1. Methanol engine – MAN B&W ME-LGIM**

Green methanol (CH<sub>3</sub>OH), produced from renewable energy resources, is a promising substitute marine fuel because of its negligible carbon emission. Green methanol-powered engines are able to offer carbon-neutral power. Sanctioning the use of methanol in the IMO's Interim Guidelines for Low Flash Point Fuels took place in November 2020. It may be used on ships as fuel for internal combustion engines or for fuel cells [Svanberg et al. 2018].

MAN has launched the 'ME-LGI' concept for high-pressure injection of low flashpoint liquid fuels, such as methanol. Methanol has been listed in the IMO's Interim Guidelines for Low Flash Point Fuels. This system runs on a relatively low fuel supply pressure, with the entire high-pressure pumping taking place within the injector itself. The injection process is controlled by a Fuel Booster Injection Valve (FBIV-M) that raises the injection pressure between 550 and 600 bar [Dubinsky and Stambler 1996]. First adopted in engines of different methanol carriers, the idea takes advantage of methanol's liquid character at ambient conditions to utilize current liquid fuel systems with minimal retrofitting. Refurbishment of existing systems for traditional marine fuels is minimal, mainly compensating for methanol's low flash point.

As a result, ship owners will pay less to convert their ships for methanol operation through small adjustments to the current two-stroke internal combustion engine. Based on the zero carbon policy, MAN has designed the world's first two-stroke dual-fuel engine, the MAN B&W ME-LGIM, which can be run on both methanol and conventional fuels. This engine is also developed to serve the maritime sector with a low-cost, scalable, and versatile solution that can be applied across a broad variety of vessel types [Dubinsky and Stambler 1996].

The low-handling, storage, and bunkering cost of methanol, while having comparatively straightforward auxiliary systems and the promise of carbon neutrality, makes it an appealing solution for achieving decarbonization. The engine illustrates higher efficiency than traditional marine fuel engines, and the switch from methanol to fuel oil is smooth, resulting in uninterrupted and consistent engine use [Dierickx et al. 2018].



**Fig. 1.** MAN B&W ME-LGIM

*Source: [Solutions, MAN Energy 2021].*

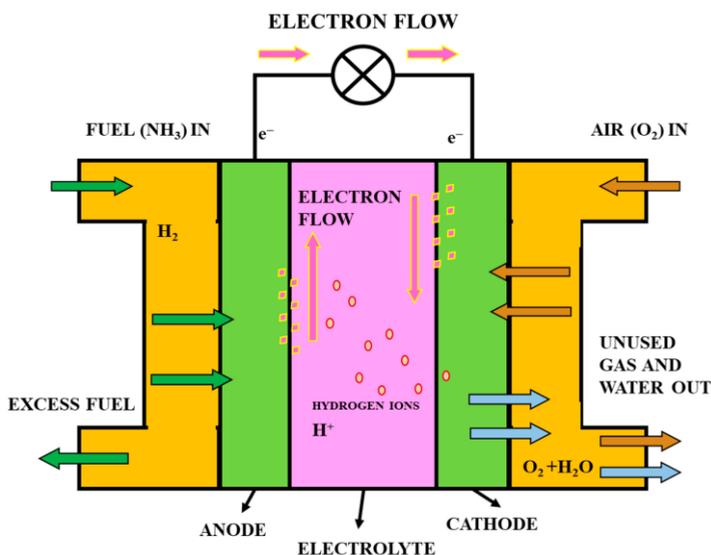
The mass scale production of green methanol is a major challenge, and many countries and companies have invested heavily in the required infrastructure. The project can potentially reduce CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, and particulate emissions significantly. Increasing production capabilities could make this green fuel cheaper, but a significant disadvantage is that the specific energy of methanol, which is 19,700 kJ/kg, and is much lower than for LNG and traditional liquid fuels. As a result, to have the same amount of energy, methanol would need about 2.54 times the volume of traditional fuels, something that needs to be considered [Wissner et al. 2023].

#### **4.2. Ammonia-based sofc propulsion systems**

Ammonia potentially aligns trajectories with IMO's decarbonization targets for 2050 as a carbon-free marine fuel. It can be stored as liquid at moderately high pressures, of around 9.9 bar at a temperature of 25°C. Combustion proves arduous due to its substantially high auto-ignition temperature alongside unusually narrow flammability limits. Ships would need larger fuel tanks owing to the low energy density of the fuel, thereby fairly significantly reducing cargo space. Man Energy Solutions and Wärtsilä ammonia propulsion models are being developed rapidly alongside other innovative AmmoniaPower sources nowadays [Kim et al. 2020].

Solid Oxide Fuel Cell (SOFC) generates power energetically by oxidizing fuel electrochemically in an energy conversion system. A Solid Oxide Fuel Cell primarily consists of anode and cathode as well as an electrolyte alongside an interconnector.

Liquid ammonia at 8.8 bar and 20°C vaporizes rather quickly and is thoroughly preheated with hot exhaust gases. The process starts at the ammonia storage tank, where ammonia flows and is pumped into the anode side of SOFC. H<sub>2</sub> is oxidized electrochemically, producing electricity and water very efficiently. Cathode air is preheated, prior reacting with the anode's H<sub>2</sub> simultaneously. Exhaust heat is recycled relatively efficiently for preheating air and producing steam, thus significantly enhancing overall thermal efficiency. SOFC's net electrical efficiency averages a rather high 57% normally. Solid Oxide Fuel Cells (SOFC) are increasingly explored for zero-emission maritime propulsion [Di Micco et al. 2024].



**Fig. 2.** Ammonia-fuelled SOFC

Source: [Di Micco et al. 2024].



Ammonia, primarily manufactured by China, India, Russia and the USA, is emerging globally and rapidly as a somewhat unconventional marine fuel nowadays. It can be utilized in dual-fuel internal combustion engines and today can reduce emissions very effectively when obtained from renewable biomass sources. It is a toxic and fairly corrosive material, but the low flammability reduces fire risks relatively significantly onboard ships, making it a safer sustainable option [Machaj et al. 2022].

### 4.3. Hydrogen fuel cell

Hydrogen fuel cells convert fuel into electricity by utilizes electrochemical reactions that occur without combustion taking place. Also known as PEM fuel cells, they use hydrogen and oxygen, and are mildly efficient for transportation, shipping, and microgrids. However, they encounter high costs and low efficiency. The study is based on literature reviews, technical studies, and case analyses from the U.S. Department of Energy, Airbus, and other institutions. It looks into how far into the market a fuel cell can be adopted, its efficiency, feasibility, and overall impact on the environment. Even though hydrogen fuel cells have their drawbacks, they bolster energy security and lead to emission reduction when paired with other sources of energy [Fichter and Werner 2022].

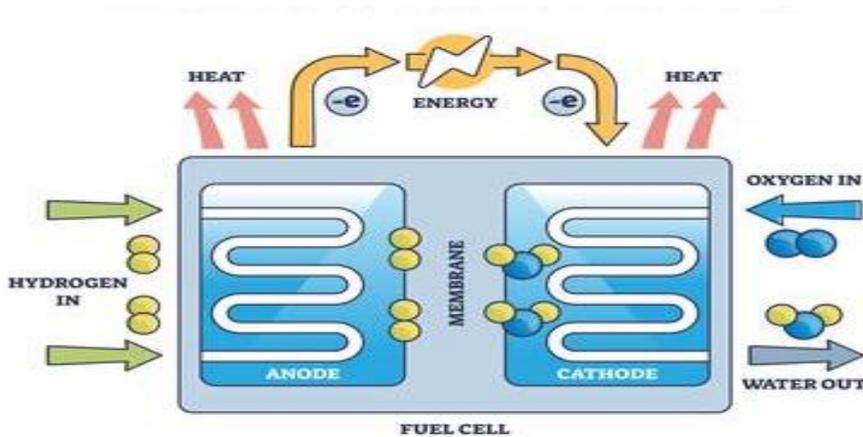


Fig. 3. Hydrogen Fuel cell

Source: [Fichter and Werner 2022].

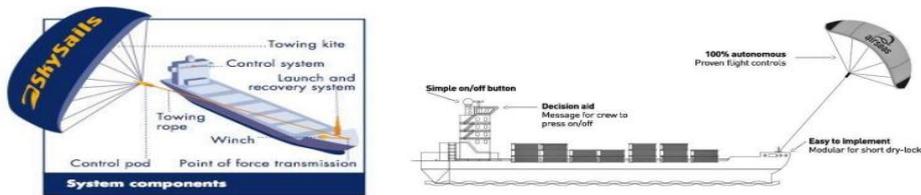
He also notes the challenges in the hydrogen storage system for fuel cell vehicles boundaries, identifying it as an obstruction to the commercial appeal of hydrogen-powered transport. There is progress occurring in fuel cell technology, but the problem of safe, efficient, and lightweight hydrogen storage remains unsolved. This paper looks into diverse storage approaches, such as liquid hydrogen, high-pressure hydrogen, metal hydrides, chemical hydrides, and physisorption on porous materials. Heavy transition metal hydride systems are best studied, while lighter sodium alanates and lithium amides are burdened with issues of thermal stability and slow kinetics.

Physisorption on materials like carbon nanotubes and MOFs shows promise at low temperatures but is currently impractical at ambient conditions. The study concludes that meeting the U.S. Department of Energy targets (e.g., 6% hydrogen

by mass, rapid refuelling) will require significant breakthroughs in materials science, especially in developing lighter, more stable, and recyclable storage systems [Xuan et al. 2022].

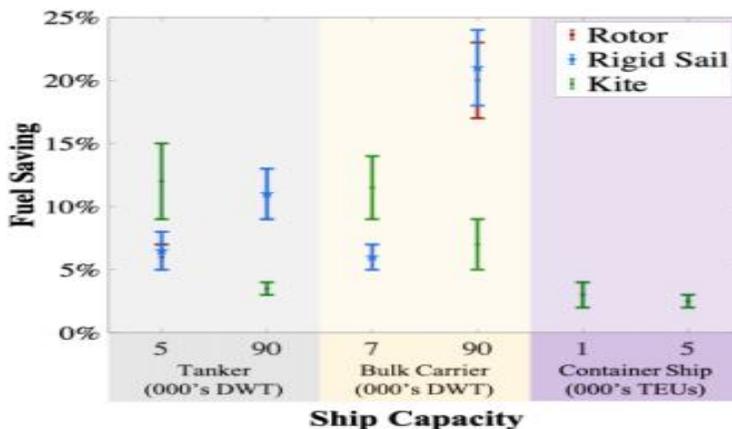
#### 4.4. Wind assisted propulsion system

Wind propulsion is strongly thought to be amongst the most efficient means of decarbonizing shipping. Wind propulsion machinery, like Flettner rotors, suction wings, and kite sails, generates additional thrust, resulting in substantial fuel savings. The technology takes advantage of aerodynamic forces that act effectively over long distances with a consistent wind [Wang 2022].



**Fig. 4.** Examples of wind propulsion technologies deployed in commercial shipping

Source: [Wang. 2022].



**Fig. 5.** Vessel fuel saving

Source: [Khan et al. 2021].

Existing ship designs now incorporate wind propulsion technologies into their propulsion systems, as opposed to adding them as retrofits on current vessels.

The reduction in fuel consumption brought about by these innovations is between 5% and 25%, depending on the size of the vessel, the wind patterns, and the route of navigation [Khan et al. 2021].

Other fuels, like ammonia, hydrogen, methanol, and LNG, are also being considered alongside wind power. Ammonia is a zero-carbon fuel source, although issues related to safety and toxicity remain. Short-sea and port vessels are increasingly turning to hybrid propulsion systems that combine electric motors with diesel engines and alternate fuels [Zhang et al. 2024].

#### 4.5. Hybrid photovoltaic/diesel propulsion

The sea transport sector's transition towards greener business models has fuelled innovative opportunities – hybrid propulsion systems with PV panels, diesel engines, SOx scrubbers, and other pollution abatement technologies being just some of them. This article examines the progress and environmental effects of these technologies in the context of green shipping.

Hybrid PV/diesel propulsion systems minimize fuel consumption and exhaust emissions with the assistance of onboard photovoltaic panels that collect solar energy. Current research shows that even the incorporation of minimal PV systems is likely to achieve sizeable savings and reductions in emissions [Kumar 2025]. The systems typically work very effectively in sunny climates and under daytime operation [Lee et al. 2013].

Some studies suggest that through modelling and simulation analyses, the integration of PV power would lower fuel oil consumption by a maximum of 20% for some ship types, relative to the size of solar panels and batteries. A robust energy management system with real-time monitoring is critical for these strategies, system performance optimization, and achieving the desired outcomes [Lau et al. 2010].

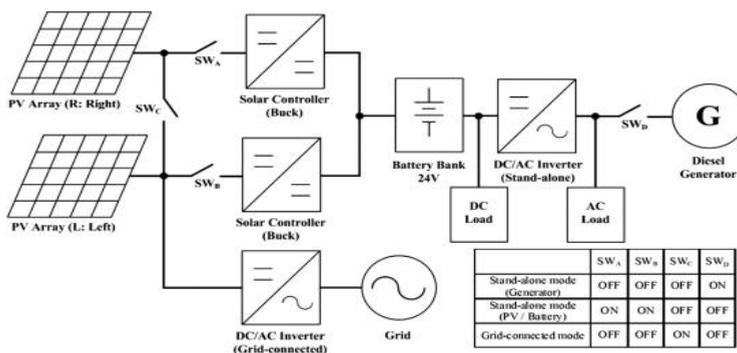
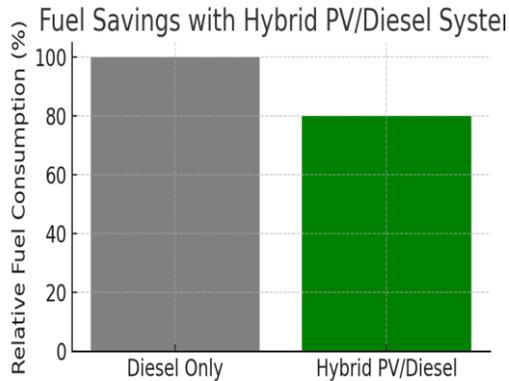


Fig. 6. Hybrid photovoltaic/diesel propulsion

Source: [Tsuanyo et al. 2015].



**Fig. 7.** Fuel savings

Source: [Lee et al. 2013].

#### 4.6. Solar and wind assisted propulsion

Apart from hybrid photovoltaic/diesel, there is continued innovation of wind and solar renewable sources in marine applications. Rotor sails, kites, and fixed wing sails are emerging technologies for wind-assisted propulsion to reduce the use of fossil fuel. Research shows a decrease in fuel consumption by 5-20% due to wind-assisted rotor sails [Rutkowski 2016].

Apart from application in hybrid model systems, solar power is also being studied for application in auxiliary shipboard systems run on batteries. There have been prototypes of entirely solar-powered ships designed for shorter routes and for research purposes, highlighting the need to enhance current systems [Nyanya et al. 2021].

The use of solar energy for powering static applications, such as heating, small appliances, and battery charging, is now being expanded to the more mobile form of locomotion over land, sea, and air. Transportation that is powered solely by the sun may be on the fringe of realization at the moment, solar powered vehicles like golf carts, cars, ferries, and even aircraft are proof that innovation is underway towards decreasing fossil fuel dependency, leading to financial and ecological improvements. In one of his works, George Marsh explains that the advancements in solar technology will soon enable the reduced usage of conventional fuels in transport vehicles [Marsh 2001].

For comprehensive details pertaining to emerging green propulsion methods, see Table 1.

## **5. ENVIRONMENT FRIENDLY ANTI-FOULING COATING**

### **5.1. Hydrogel based anti-fouling coatings**

These give reduced substantially with green antifouling coatings maintaining high performance relatively effectively under diverse operational conditions. They form hydrophilic non-stick surfaces that relatively effectively resist attachment of various marine organisms to them. Semiconductor coatings containing TiO<sub>2</sub> and ZnO produce reactive oxygen species under light, which degrades organic matter and thwarts biofouling relatively effectively. Micro/nano-textured coatings disrupt bioadhesion points on natural surfaces, thereby inhibiting the settlement of fouling organisms relatively effectively underwater. Recent advancements focus heavily on bolstering mechanical robustness, thereby quietly ensuring a decidedly longer service life. Biomimetic strategies spawn novel innovations backed by nanotechnology, offering substantially efficient broad-spectrum non-toxic solutions for sustainable marine antifouling applications [Liu et al. 2023].

### **5.2. Zwitterionic anti-fouling coatings**

These provide eco-friendly solutions for marine biofouling prevention, largely without significantly harming marine life or the environment. Coatings function by luring a robust hydration layer that makes the coated surface appear eerily like water to fouling organisms, thereby thwarting settlement. Zwitterionic coatings offer a markedly safer option for protracted ecological well-being, unlike traditional antifouling methods steeped in biocide usage. They are practically effective for real-world applications and easily applied using conventional spray techniques [Fore 2020].

### **5.3. Polyurethane-based anti-fouling coatings**

These nowadays provide, relatively effectively, a sustainable practical ecofriendly solution against marine biofouling organisms on submerged surfaces. Polyurethane serves as a self-renewing layer gradually degrading in seawater and releasing antifoulants steadily over relatively long periods while maintaining surface cleanliness. Butenolide derived from marine bacteria effectively prevents barnacle and algae attachment on ship hulls reducing the biofouling risk quite significantly underwater. Environmentally conscious approaches ensure robust protection lasting at least three months, making it suitable for myriad short-term applications. Polyurethane coatings emerge as substantially promising alternatives, owing largely to the unique blend of controlled degradation and natural antifoulants supplanting traditional toxic antifouling paints [Ma et al. 2017].

## 6. SOX SCRUBBER SYSTEMS FOR EMISSION ABATEMENT

SOx scrubber systems are fitted on ships to assist in the elimination of sulphur oxides from the exhausts of ship diesel engines, assisting ships in meeting SOx emissions regulations stipulated by the marine pollutant convention (IMO2020) guidelines. Scrubber systems utilize seawater or freshwater in open-loop, closed-loop, or hybrid configurations. Scrubber systems have removal efficiencies up to 98% SOx [Boscarato et al. 2015].

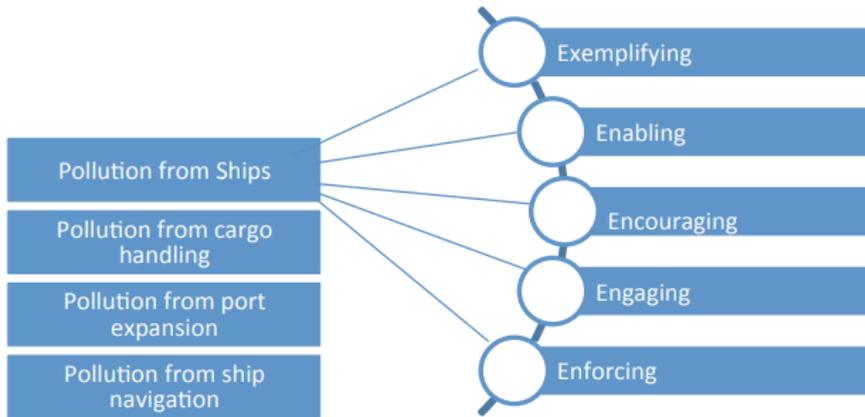
The International Maritime Organization (IMO) imposed a restriction on the sulphur-content within marine fuels during the 70th Marine Environmental Protection Committee meeting. In light of this compliance, ship owners have been provided with the following options: (1) the use of low-sulphur fuels, (2) the adoption of LNG as a marine fuel or (3) the use of SOx reduction devices, commonly referred to as scrubber systems. The use of LSFO enables remaining marine diesel engines to maintain SOx emissions within acceptably lower ranges without scrubber units. However, LSFO does incur 50% higher costs in the refining phase, and the catalyst fines for LSFO equipped engines are also elevated, considerably reducing the economical advantages compared to the scrubber systems. The measures will undoubtedly drive operating costs higher, but integrating SOx scrubbers into the design would provide the benefit of reduced fuel expenditures since they would primarily utilize high sulphur oil instead of the current low-sulphur oil used in vessels [Jee 2022].

These systems are likely to provide the highest capture efficiency; however, capital investment costs are usually high. External considerations, such as ease of maintenance, wash water discharge regulations, and so forth, can create issues [Tran 2017].

## 7. INITIATIVES TAKEN WORLDWIDE

Ports need robust written policies to build environmental controls for sustainable ports. Ports need to have an Environment Management Plan while an Environment Cell must be appointed to serve as the overall Environmental Management and to expedite and promote environment issues. Ports should implement Continuous Ambient Air Quality Monitoring Stations (CAAQMS) to monitor air quality, and Continuous Marine Water Quality Monitoring Stations (CMWQMS) to monitor the health of marine ecosystems, documenting measurements over time and reporting abnormalities. It is critical for ports to have an Online Continuous Effluent Monitoring System (OCEMS) to observe what is discharged and to assess compliance with environmental regulations in real time [Lalla-Ruiz, Heilig and Voß 2019].

Ports should also have a solid protocol in place for responding to oil spills by following the National Oil Spill Disaster Contingency Plan (NOS-DCP). Wider adoption of these measures by ports can enhance environmental performance and limit ecological disruption [Pavlic et al. 2014].



**Fig. 8.** Tree Diagram

Source: [Bin Yahya 2019].

### **7.1. Harit shrey scheme**

This is a significant initiative promoting sustainability in India’s ports, by implementing green practices and technologies. With growing concerns about port operations contributing to environmental challenges, the scheme aims to enhance ecological performance. Several initiatives will be developed under this scheme, such as tree plantation drives to boost green cover around ports, measures for better waste management in order to reduce pollution and to promote the recycling of wastes, as well as a commitment to renewable energy sources to encourage ports to use solar and wind to generate their own power [Ranade 2002].

The Harit Shrey Scheme reflects commitment to sustainability and will not only reduce the eco-footprint of marine operations, but will also align globally with climate change objectives. It is a focused initiative for other ports in the world to use to achieve a sustainable approach to generate awareness for environmental responsibility with port stakeholders. The Harit Shrey Scheme will accomplish this broadly and through various aims which impact a sustainable future to oceans and thus protect natural resources for future generations. This initiative represents India’s commitment to economic development and environmental stewardship in the Maritime sector [Venkatesh and Sriraman 2020].

## **7.2. The Global Industry Alliance (GIA) to Support Low Carbon Shipping**

The Global Industry Alliance to Support Low Carbon Shipping (GIA) is an initiative created by the International Maritime Organization to support a transition towards a low-carbon maritime sector. The GIA brings together government, industry and academia to take collaborative action to develop and implement innovative technologies and practices to reduce greenhouse gas emissions while promoting sustainable shipping practices and improving the environmental performance of the maritime sector with respect to global climate objectives [Aregall, Bergqvist and Monios 2018].

## **7.3. The Global Maritime Technology Network (GMN) project**

The Global Maritime Technology Network (GMN) project, is focused on encouraging innovation and collaboration within the maritime sector, addressing sustainability issues with low carbon technology solutions. The aim is to ultimately connect stakeholders, including those from the maritime industry and academia, so that they can share knowledge and implement green technology. The GMN enables and supports the development of sustainable maritime strategies that optimize operational efficiency and minimize environmental impacts [Lam and Li 2019].

## **7.4. GreenVoyage-2050 project**

The GreenVoyage-2050 project led by the International Maritime Organization (IMO) illustrates the need for clarity in the need for the maritime industry to examine sustainable development and the goal of cutting greenhouse gas emissions drastically by 2050. The GreenVoyage-2050 project uses its key intentions to foster international collaboration aimed at ensuring the transfer of knowledge for the shipping industry, whereby the shipping industry leaders, reforming governments, and members of the research community cooperatively engage with one another [Louizou 2024].

The GreenVoyage-2050 project is also a means to develop capacity in developing countries to implement sustainable development solutions for sustainable shipping and the possibility of all countries engaging as stakeholders in the goal to reduce maritime emissions. It supports international climate agendas, such as the Paris Agreement conceptual framework for climate change and global commitments to sustaining low carbon economies. Ultimately, it represents an important project intended to find innovation pathways to the challenges in the maritime sector while ensuring innovation for environmental responsibility and sustainability [Mahmud, Chowdhury and Shaheen 2024].



**Fig. 9.** Scheme Logo

Source: [Kumar 2025].

## **8. ADVANCEMENTS IN GREEN FUEL RESEARCH**

The researchers compared hydrogen and LNG green fuels for maritime shipping with heavy fuel oil to study emissions, including the regulatory requirements for emission reductions by the IMO. Shim evaluates the feasibility of green hydrogen, ammonia, and LNG as alternatives and emissions benchmarks. Experimental modelling along with a case study analysis evaluates other emulated benchmarks of fuel economy, storage difficulties, and economic factors. Findings indicate the reliance on the type of infrastructure available and market acceptance for adoption, with the conclusion that green fuels, specifically hydrogen, greatly aid the reduction of CO<sub>2</sub> emissions alongside the practical use of LNG for long-distance travel [Rizou 2023].

Under this study, a clean energy technologies selection model is proposed, using the Rough Set (RS) methodology with the TOPSIS approach for green ships. The model evaluates seven options, including LNG, LPG, methanol, HVO, battery, hydrogen fuel cell, ammonia fuel cell, and a few more, focusing on economic, technical, environmental, and security attributes. The RS helps with assessment of the attribute importance. As for the RS, it ranks the alternatives based on a chosen ideal solution and takes the one with the closer proximity as the optimal. As a result of the study, large coastal ships rely on the greater efficiency of LNG, while small inland vessels are better off with battery power. The approach minimizes subjectivity, enhancing the ship owners' decision-making under uncertain conditions [Ampah et al. 2021].

This study investigates a hybrid renewable energy system (HRES) for a remote island in India using HOMER software. The methodology involves simulating various configurations of solar, wind, diesel, and battery systems to determine the most cost-effective and environmentally friendly solution. The system's performance is assessed based on a cost of energy (COE), net present cost (NPC), and emissions [Ross 2006]. The results show that integrating renewables with storage significantly reduces COE and emissions compared to diesel-only setups.

## 9. FINANCING GREEN DEVELOPMENT

The finance function has a contribution toward green shipping, alongside the financial constraints toward decarbonization. The discussed efforts at the EU level included Taxonomy Regulation and EIB's Green Shipping Guarantee Programme and Poseidon Principles supporting sustainable investment. The study analyses the regulation and the available market based financing tools, such as green bonds and sustainability-linked loans, through doctrinal analysis to measure impact. It identifies high expenses, lack of transparency, and short-sightedness as some of the challenges in shipping finance. It argues for international classification frameworks coupled with targeted financial incentives aimed at green investment to promote enhanced investments [Hessevik 2022].

Industries are spending on market-based measures (MBMs) targeting investment in green shipping technologies like wind-assisted ship propulsion (WASP). It also analyses the effect of carbon pricing on investment decisions for the greening of maritime transport or the benchmarks for the direct buying of technologies against innovative financing strategies, such as shared savings. To assess the risks and opportunities associated with MBMs, the Fuzzy Pay-Off Method (FPOM) is used. The study, through literature review, sensitivity analysis, and financial modelling, concludes that ships under market-based measures increase the attractiveness of the investment, so even in the absence of enforceable carbon pricing, the investment is cost-effective [Wu, Zhang and Luo 2019].

## 10. FEASIBILITY OF GREEN SHIPPING

Part of the research examines how shipping networks impact the decarbonization strategies of offshore shipping companies in Norway. They conduct a qualitative multiple case study where they map emission control strategies from 2008 to 2020, evaluating the impact of network affiliation on the strategy. Process tracing is used to highlight key drivers, such as those from within the organization, legislation, and market forces. The study concludes that networks typically apply incremental guidance rather than substantial strategic direction, providing informational support and funding for changes. Still, assistance from networks can reduce the time needed to achieve substantive technological change by controlling the knowledge flow and financial resources for these transitions [Perna et al. 2023].

But is there a difference between green shipping and Sustainability? Based on the deep roots of the topic, along with gaps from the previous discussions, the study theoretically analyses the differences between sustainable and green shipping. It collects information using a structured literature review, which focuses on the definitions, objectives, and consequences provided in the academic literature. For such concepts as sustainable development and green development, content

analysis is used to document the focus so that it can demonstrate that, to be sustainable, civilization should be geo-centred rather than anthropocentric [Clean Energy Group]. The paper proposes that green shipping, following nature-first principles, is more effective in achieving long-term sustainability than sustainable shipping, which focuses on human needs. The findings emphasize ecosystem conservation as essential for sustainable maritime policies and future research [Metzger 2021].

## **11. THE LOGISTICS OF GREEN FUEL**

An extensive network of green fuels is necessary for sustainable fuels to be accessible to ships in ports to allow for the shipping sector to shift to cleaner operations. As the discussion papers indicated, most prominently in Green Logistics: The Carbon Agenda, the carbon emissions from energy sources has a direct influence on the overall greenhouse gas emissions from logistics, including shipping transport [McKinnon 2010].

The construction of a green fuelling infrastructure includes the installation of equipment employed in facilitating alternative marine fuel bunkering, storage, and distribution of marine fuels, such as hydrogen, ammonia, biofuels, and LNG. The availability must be consistent in all the ports so it does not suffer from any downtime for operations as well as to facilitate easy uptake.

Moreover, logistics decarbonization is also concerned with energy efficiency and modal change, in the port context referring to the integration of green energy sources into ports and logistics supply chains. Infrastructure and transport fuel innovation are also identified by the Green Logistics – Measures for Reducing CO<sub>2</sub> report as important, with regulatory frameworks and investment incentives identified as needed for these green changes. Ensuring green fuels are readily accessible at ports not only supports shipping in compliance with global standards of emissions but also assists in reinforcing broader decarbonization initiatives across global supply chains [Antoni, Perić and Čišić 2015].

## **12. ADOPTION OF GREEN SHIPPING PRACTICES**

The increasing global emphasis on environmental sustainability has prompted the maritime industry to adopt green shipping practices aimed at reducing ecological footprints. The following are the required parameters:

## **12.1. Policy and governance in maritime sustainability**

Policy frameworks represent the structural foundation that supports sustainable maritime operations. Both new and existing vessels must achieve progressive emissions reductions under the IMO's Energy Efficiency Design Index (EEDI) and Carbon Intensity Indicator (CII) requirements. The rapid adoption of low-sulphur fuels and scrubber technologies is driven by MARPOL Annex VI's strict NOx and SOx emission limits [Lister 2015].

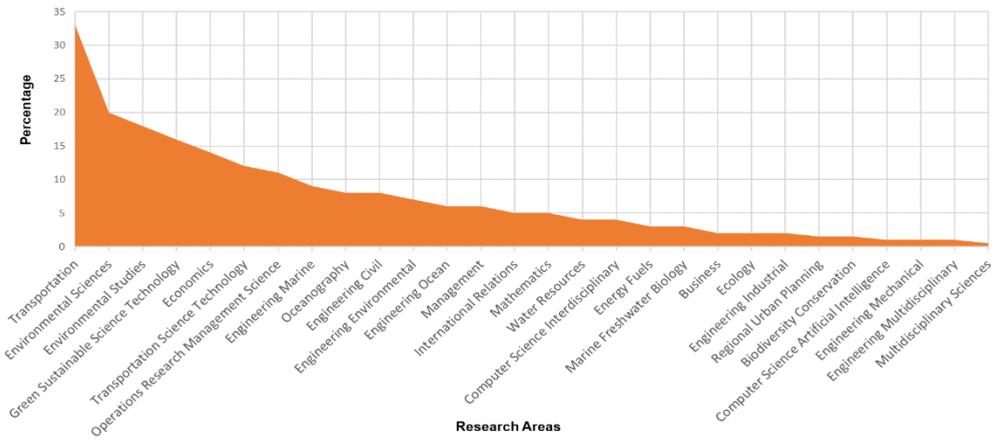
Through its Emissions Trading System (ETS), the EU has brought maritime transport into its regional regulatory framework to establish financial incentives that promote reduced emissions. Ports have implemented green port charges that offer financial incentives to ships that have cleaner operating standards and improve the economic rationale for environmental compliance. The International Maritime Organization's Data Collection System requires ships over 5,000 gross tonnage to submit an annual fuel consumption and voyage data report [Felício, Rodrigues and Caldeirinha 2021]. National governments have embraced flag-state incentives, such as reduced tonnage tax and favourable berthing terms, to promote the creation of green fleets. Financial arrangements are also made to offer grant capital to retrofit existing ships or to build zero-emission ships in the fields of green technology accelerators or innovation programs [Wuisan, van Leeuwen and van Koppen 2012].

The majority of the developing world is either underdeveloped in terms of infrastructure or lacks financial capital to match the standards in the world, thereby establishing an uneven competitive landscape. As a result, global institutions have viewed technical cooperation and capacity building as core tools for bridging policy gaps among various global regions [Mi et al. 2024].

## **12.2. Technological innovations and smart shipping**

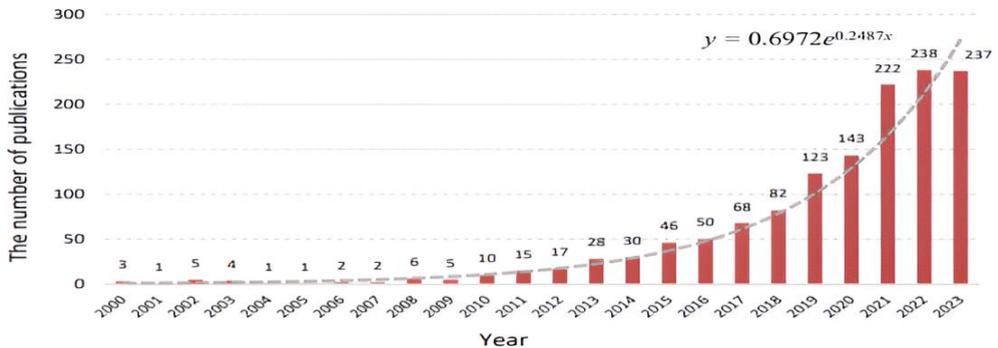
Maritime logistics activities have been made more efficient by technological progress. Real-time sensors and digital twin technology on intelligent ships make predictive maintenance possible, optimize routes, and promote energy-efficient journeys. These systems reduce fuel usage, emissions, and downtime [Petković et al. 2021].

Use of predictive analytics for supporting engine diagnosis and hull care allows proactive avoidance of failure and, consequently, a decrease in emergency fuel burn and reduced emissions. The systems utilize weather-routing software combined with satellite tracking for dynamic voyage planning, thus optimizing economic efficiency and environmental performance [Mi et al. 2024].



**Fig. 10a.** Smart shipping architecture integrating AI and IoT for performance monitoring

Source: [Mi et al. 2024].



**Fig. 10b.** Predictive maintenance models using sensor fusion for machinery health tracking

Source: [Mi et al. 2024].

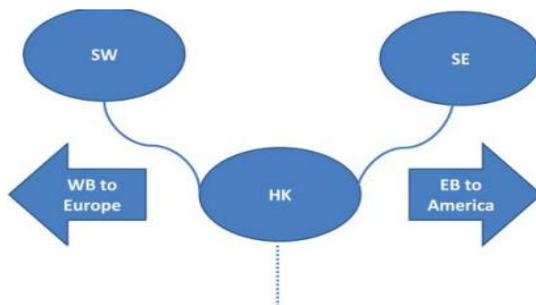
### 12.3. Green shipping networks and collaboration

Collaborative networks help in marketing green shipping programs. Port alliances, regional-level policy coordination, and green shipping corridors are critical mechanisms for promoting sustainable development. Aligning the environmental goals with collective infrastructure makes the partnerships effective in avoiding wasteful duplication and augmenting the implementation of sustainable technology in the industry [Petković et al. 2021].

The cooperative harbour operations of the PRD ports are a paradigm of the best cooperative port management. PRD ports utilize coordinated scheduling, combined

with fuel standard alignment and the utilization of common digital systems, to minimize emissions while maximizing throughput efficiency [Lun, Lai and Cheng 2013].

Public-private partnership offers ancillary assistance in the form of demonstration projects and financing for low-emission infrastructure. These networks facilitate experimentation and validation of new fuels, retrofitting techniques, and AI-based monitoring systems in real operating conditions [Lun 2013].



**Fig. 11.** Pearl River Delta regional port map demonstrating collaborative logistics planning

Source: [Lun 2013].

## 13. KEY CHALLENGES

### 13.1. High upfront costs

Green technologies such as alternative fuel engines, fuel cells, and wind-assisted systems have high initial capital costs and expenditure. They are typically prohibitively costly to small and medium-sized shipping companies with limited budgets. Moreover, the economics and further financial obstacles regarding scalability of such technologies also need to be considered. Retrofitting of the current ships to address environmental needs is also financially burdensome. Such high costs pose a risk of a poor return on investment (ROI), to the investors involved. Also, green technologies do not show immediate profits or cost savings, leading to a longer payback periods.

### 13.2. Infrastructure limitations

Ports and coastal terminals in the majority of places have no infrastructure facilities necessary for environmentally sustainable bunkering, distribution, and fuel storage [Lee, Kwon and Ruan 2019]. Fuel supply chains and networks may suffer blocks

and bottlenecks, interrupting the efficient logistics of green fuels, which is further amplified by global port disparities and the lack of relevant infrastructure. They also do not have standardized mechanisms for energy distributions, such as for ammonia and hydrogen fuels, which raise the challenges. Unavailability confines the use of green ships at scale.

### **13.3. Technology maturity**

There exist various green shipping technologies in the early stages of development or introduction. Such technologies as hydrogen fuel cells and ammonia engines are technically immature and require proof and optimization. Shipowners do not want to invest since no reported long-term performance exists. Technologies which are new need to be certified and a smooth transfer needs to be made from old technologies. Also, the concerned technologies and their reliability to work as required under stress conditions need to be tested.

### **13.4. Operational constraints**

The incorporation of green technologies imposes new operational requirements, such as greater maintenance and crew training. Alternative fuels may demand special handling and safety practices, affecting voyage planning and vessel design. Fuel compatibility issues may arise due to dependence on older fuels and technologies. Moreover, emergency response protocols for handling alternative fuel technologies need to be established and implemented. These constraints adversely affect overall operational efficiency and performance.

### **13.5. Range and performance**

Green fuels possess less energy density than traditional marine fuels, and therefore produce lower ship range and the capability to perform. This indicates a reduced energy-to-weight ratio. It renders them less than appropriate for deep-sea or distant shipping in the absence of extensive design modifications, which in turn affects the energy conversion efficiency. Fuel efficiency, directly contributing to endurance limitations at sea, and storage capacity are both fundamental issues here.

### **13.6. Transition period**

Green shipping transition is a gradual process involving the long-term coexistence between the old and the new systems. New systems, such as dual fuel systems, bring a level of complexity which needs to be smoothly transitioned, instead of a series of sudden changes. These new systems and fuels also need to be addressed regarding

flag state and port state policies, both of which need to be complied with. Uncertainty regarding regulation and the absence of global harmonization in such a stage could cause difficulties in compliance. The transition into new technologies also brings a risk of stranded old assets concerned with use of older fuels. The uncertainty of future fuel availability and policy trends also impact planning in the long term [Petrychenko et al. 2024].

### **13.7. Supply chain complexity**

The widespread adoption of green fuels, like ammonia, hydrogen, and bio-LNG, is slowed by limited production and uneven global distribution, due to a non uniform spread of supply networks globally. The relevant infrastructure is often concentrated in specific regions, reducing operational flexibility and convenience. Maintaining coordination between fuel suppliers, ports, and shipbuilders is complex and still developing, which can delay large-scale adoption.

### **13.8. Hidden and indirect costs**

Green technologies bring hidden costs, which include insurance premiums, which are costlier than regular options, certification costs for these new improved fuels, and also downtime expenses. These costs are sometimes underestimated during the planning stage and may lead to the budget being extended.

### **13.9. Training requirements and skill gap**

To transition to low and zero emission fuels, seafarers, engineers and port workers need to acquire new skills and undergo new training methods. Improved and relevant infrastructure is also required for related training and skill acquisition. Thus, a continuous process of skill development and training would have to be maintained.

### **13.10. Resource scarcity and raw material dependence**

The installation, implementation and usage of new green technologies are most dependent on the availability of raw materials, such as rare earth metals for batteries and fuel cells. Availability is also affected by geopolitical conditions and relations, which may also have an effect on pricing. The procurement of a few selected critical components for said technologies may also result in dependence on certain countries and regions. The implementation of green technologies may, unintentionally, cause environmental impacts as a result of raw material extraction methods.

## 14. CONSOLIDATED TABLES

**Table 1.** Emerging green propulsion methods

S. No.	Topics	Title	Technique Used	Marine Application	References
1	Methanol propulsion	The methanol-fuelled MAN B&W LGIM engine	ME-LGIM engine invention Retrofit possibilities	Dual-fuel engine MARPOL Tier III Compliance	Svanberg et al. 2018
2		Strategies for introducing methanol as an alternative fuel for shipping	Methanol infrastructure readiness Reduced emissions	Scalable adoption	Dierickx et al. 2018
3		Renewable methanol as a fuel for the shipping industry	Methanol types: black, blue, green, grey Renewable methanol supply chains	Effective supply chain Methanol benefits	Solutions, MAN Energy 2021
4		Methanol as a marine fuel	Methanol production Bunkering infrastructure	Higher safety standards	Wissner et al. 2023
5	Ammonia propulsion	A Preliminary Study on an Alternative Ship Propulsion System Fuelled by Ammonia: Environmental and Economic Issues	SOFC-based system 92.1% GHG reduction	Ammonia-fuelled system	Kim et al. 2020
6		Ammonia as a potential marine fuel: A review	High upfront costs and design changes	Ship redesign needed	Machaj et al. 2022
7		Ammonia-powered ships: Concept design and feasibility assessment of powertrain systems for a sustainable approach	Modular powertrain configuration 57% net efficiency	Hybrid ammonia propulsion	Di Micco et al. 2024
8	Hydrogen propulsion	Green Fuels in Maritime Shipping Heating, electric power supply and ship propulsion with hydrogen and LNG fuels	Dual-fuel engines (LNG & Hydrogen) Cryogenic hydrogen storage	Hybrid hydrogen propulsion	Fichter and Werner 2022
9		Hydrogen storage: The major technological barrier to the development of hydrogen fuel	High-pressure hydrogen storage	Hydrogen storage solutions	Machaj et al. 2022
10		Green shipping networks as drivers of decarbonization in offshore shipping	Fuel cells & ammonia retrofits	Offshore decarbonization	Hessevik 2022
11		Hydrogen fuel cells by clean energy group	Hydrogen fuel cells operation	Hydrogen fuel cells	Clean Energy Group, n.d.
12	Wind assisted propulsion	Wind Assisted Ship Propulsion Technologies – Can they Help in Emissions Reduction?	LNG, hydrogen, hybrid engines	Emission reduction	Petković et al. 2021
13		A review of wind-assisted ship propulsion for sustainable commercial shipping: latest developments and future stakes	Kite sails, rigid sails	Fuel reduction	Khan et al. 2021
14		Analysis on the Development of Wind-assisted Ship Propulsion Technology and Contribution to Emission Reduction	Flettner Rotors (Rotor Sails)	Fuel & emission reduction Use on VLCCs, bulk carriers	Wang 2022

cont. Table 1

15	Hybrid Photovoltaic/ Diesel Propulsion	Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions	Technology analysis Economic analysis	Fuel consumption reduction Carbon emissions decrease	Lau et al. 2010
16		Hybrid photovoltaic/diesel green ship operating in the standalone and grid-connected mode– Experimental investigation	Hybrid energy system	Hybrid Propulsion System	Lee et al. 2013
17		Modelling and optimization of batteryless hybrid PV (photovoltaic)/Diesel systems for off-grid applications	Optimize hybrid systems Minimize LCOE	Maintenance Reduction	Tsuanyo et al. 2015
18	Solar and Wind Assisted Propulsion	Harnessing the sun for energy.	Reducing fossil fuel.	Solar for remote tasks	Marsh 2001
19		Study of Green Shipping Technologies-Harnessing Wind, Waves and Solar Power in New Generation Marine Propulsion Systems	Renewable energy integration	Photovoltaic solar system	Rutkowski 2016
20		Wind and solar assisted ship propulsion optimization and its application to a ship.	Deck Space Allocation: 75% wind, 25% solar energy	Combined wind & solar systems	Nyanya et al. 2021
21		Solar energy: revolutionizing shipping industry towards sustainability and environmental stewardship	Solar energy applications Retrofit feasibility	Electrified Ports Solar-Powered Vessels	Petrychenko et al. 2024

## 15. CONCLUSIONS

The project on green shipping and environmental sustainability for marine engineering underscores the imperative for transformative action within the maritime industry. Through the integration of innovative technologies, rigorous regulatory compliance, and collaborative efforts, significant strides have been made towards mitigating the environmental impact of marine transportation. However, the journey towards a truly sustainable maritime sector is ongoing and requires continued dedication from all stakeholders. Marine engineers, as key agents of change, are poised to lead this evolution, leveraging their expertise to drive innovation, optimize operations, and safeguard our oceans for future generations. By embracing the principles of green shipping, we can forge a path towards a cleaner, more resilient maritime future, where economic prosperity aligns harmoniously with environmental stewardship.

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