Chartering a Greener Course: A review of Mature Technologies for Lowering Vessel GHG Emission

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Synopsis

In response to the escalating challenge of climate change, the International Maritime Organization (IMO) adopted a groundbreaking strategy during its 72nd Maritime Environmental Protection Committee (MEPC) session in 2018 which was revised in 2023. In line with the IMO's ambitious targets for 2050, this study tries to explore the effective deployment of mature technologies to significantly reduce greenhouse gas (GHG) emissions in maritime transport. The main aim of this research is to evaluate the effectiveness of mature emission-reducing technologies that are either ready for immediate deployment or near market readiness, and to establish a structured framework assisting maritime stakeholders in aligning their operational decisions with environmental objectives. Impact in the naval sector has also been explored. The study employs a systematic literature review, analysing sources from Google Scholar and Web of Science databases collected up to December 2023. It categorises technologies into four main groups: fossil fuel technologies, renewable energy solutions, fuel cells, and alternative fuels, assessing their maturity and implementation feasibility. The research highlights the technological potential and challenges, tries to provide a clear depiction of current trends and future directions in maritime emission reduction. Findings indicate that despite the varying maturity levels of these technologies, there is a tangible shift from traditional fossil fuel solutions towards more sustainable alternatives such as fuel cells and alternative fuels. An integrated approach involving policy support, technological advancement, and international cooperation is essential for the successful real-world application of these technologies. This approach will help overcome existing barriers to implementation, such as high costs and technical challenges, and pave the way for more sustainable maritime operations.

Keywords: GHG emission, Shipping, Propulsion system, Literature survey, Alternative fuel, Current technologies,

1. Introduction:

As the urgency of global climate challenges increases, IMO has escalated its commitments to reduce GHG emissions from maritime sources, aligning with the ambitious Paris Agreement Goals. In 2018, the IMO set a groundbreaking target to reduce GHG emissions from ships by at least 50% by 2050 compared to 2008 levels, with a strategy revised in 2023 aiming for net-zero emissions around 2050. This revised strategy also set out some indicative checkpoints for 2030 and 2040. The main indicative checkpoints are reducing total GHG emissions from international shipping by 20% (striving for 30%) by 2030 and 70% (striving for 80%) by 2040 (DNV -2023).

Amidst a backdrop of increasing shipping activities and corresponding rises in GHG emissions, which saw a 9.6% increase in 2018 compared to 2012 (IMO, 2021), the maritime industry faces the dual challenges of boosting economic growth and reducing environmental impact.

By consolidating a wide range of studies and findings from 2018 to 2023, the main rationale for this paper are two: firstly, to assess the current landscape of mature technologies that are immediately deployable or close to market readiness for reducing emissions; and secondly, to provide a structured framework that aids various maritime stakeholders in making informed decisions that align with both environmental goals and operational feasibility.

Furthermore, the introduction of "indicative checkpoints" by the IMO for 2030 and 2040 demands accelerated efforts and immediate action. This paper also tries to chart a feasible course for emission reduction by meticulously evaluating the potential of four category technology groups i) fossil fuel technologies, ii) renewable energy solutions, iii) fuel cells, and iv) alternative fuels highlighting both their advancements and the hurdles they face in contributing to the IMO's emission reduction targets with the help of "SCORE" analysis method.

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 https://doi.org/10.24868/11183

2. Methodology

2.1. Research Design

This study conducted an extensive literature review using the Google Scholar and Web of Science (WoS) databases. This approach enabled a comprehensive collection of academic literature pertinent to the research objective. The search was executed in December 2023, ensuring the relevance and recency of the data collected.

2.2. Data Sources and Selection Criteria

For Google Scholar, this study considered articles containing specific keywords in their titles, indicative of the scope of technologies targeting GHG emission reductions in shipping. Keywords included combinations such as "Ship and emission," "Ship and GHG emission," and "Ship and renewable energy," among others. The initial search yielded 390 articles, narrowed down to 127 after applying filters for publication years (2018-2023) and excluding citations. A review of the abstracts further refined this list to 53 articles for in-depth analysis.

2.2.2 Web of Science

Within the WoS database, the "Topic" search function was utilized with the keyword "Ship*" in conjunction with various terms related to emissions and energy sources, including "emission*," "GHG*," "fuel cell*," and "renewable energy*." This initial search resulted in 2,854 publications, which were filtered down to 1,054 after removing non-article publications and applying the same year-of-publication criteria as for Google Scholar. A subsequent abstract review led to the selection of 61 articles for further review.

2.3. Analysis Methodology

“SCORE” analysing technique is used for further analysing the various technologies discussed in various categories. "S" represents Strengths, highlighting the inherent capabilities. "C" stands for Challenges, identifying the obstacles. "O" emphasizes Opportunities, pointing out the trends that can be leveraged for success. "R" is for Response, detailing the actions taken to capitalize on strengths, mitigate challenges, and seize opportunities. Lastly, "E" stands for Evaluation, involving a critical assessment of the outcomes and tries to suggest future strategies.

2.4. Classification Framework

A total of 114 (Appendix A) publications, comprising 53 articles from Google Scholar and 61 from Web of Science, were meticulously categorized into four distinct groups:

Category 1 - Technologies Using Fossil Fuels
Category 2 - Technologies Using Renewable Energy
Category 3 - Technologies Using Fuel Cells
Category 4 - Technologies Using Low Carbon/Alternative Fuels

Figures 1 to 4 presents year-wise distribution and analysis of articles across these categories, reflecting the research community's growing interest in sustainable and innovative solutions to maritime GHG emissions.

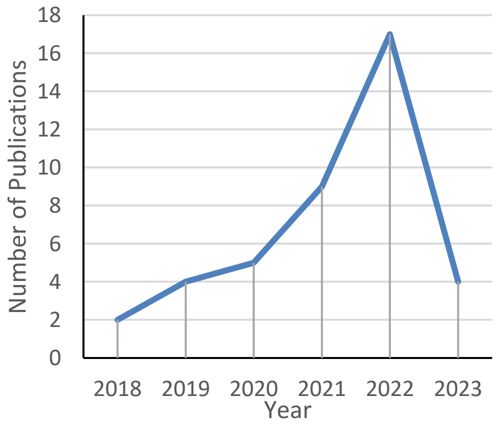

Figure 1: Year Wise Distribution Category-1

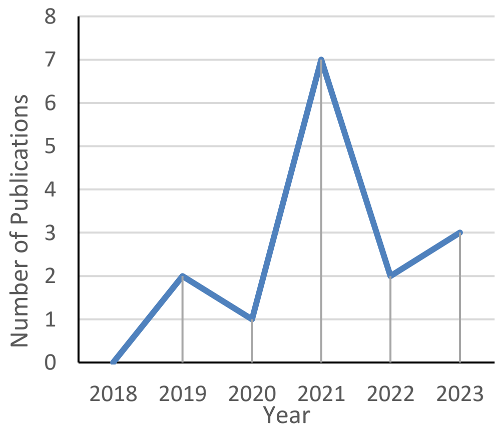

Figure 2: Year Wise Distribution Category-2

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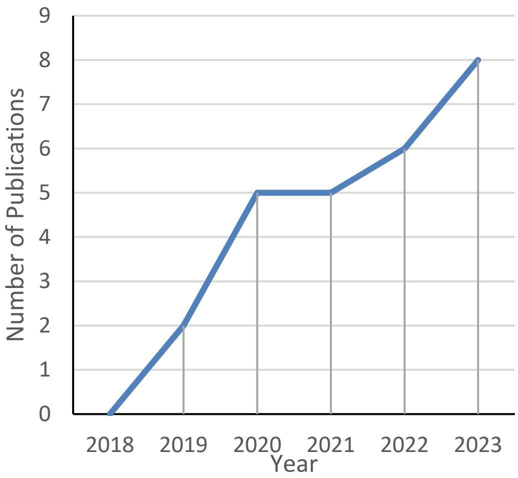

Figure 3: Year Wise Distribution Category-3

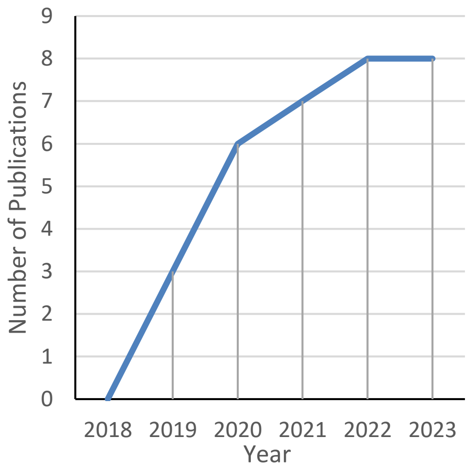

Figure 4: Year Wise Distribution Category-4

3. Review and Analysis of Selected Articles

3.1. Distribution of publication by years

3.1.1 Category 1- Technologies that uses fossil fuels.

Figure 5 shows an increasing trend in the number of publications from 2018 to 2022, starting with 2 publications in 2018 and peaking at 17 in 2022. However, there's a significant drop to 4 publications in 2023, indicating a possible shift in focus towards more sustainable technologies.

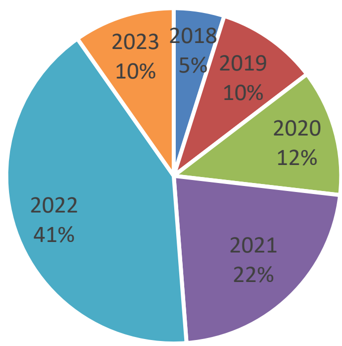

Figure 5: Distribution over Years in Category 1 (2018-2023)

3.1.2 Category 2 - Technologies Using Renewable Energy:

Figure 6 demonstrates a slow start with no publications in 2018, a slight increase to 2 in 2019, and a peak at 7 publications in 2021. The number of publications decreases in 2022 to 2 but sees a slight rise to 3 in 2023, suggesting a fluctuating but ongoing interest in renewable energy technologies for vessels.

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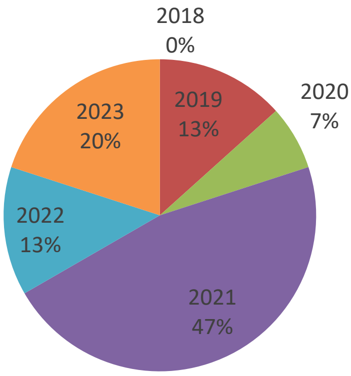

Figure 6:Distribution over Years in Category 2 (2018-2023)

3.1.3 Category 3 - Technologies Using Fuel Cells:

Similar to category 2 publications in the category 3 as shown in Fig 7 also starts with no publications in 2018 but shows a more consistent increase in the number of publications over the years. The count rises from 2 in 2019 to a peak of 8 in 2023, highlighting a growing interest and investment in fuel cell technology as a sustainable alternative for vessels.

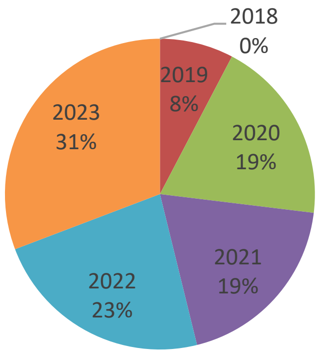

Figure 7: Distribution over Years in Category 3 (2018-2023)

3.1.4 Category 4 - Technologies Using Low Carbon/Alternative Fuels:

There were no publications in 2018, but there has been a steady increase from 3 in 2019 to 8 in both 2022 and 2023. This trend indicates a strong and sustained interest in exploring low carbon and alternative fuels for reducing vessel GHG emissions.

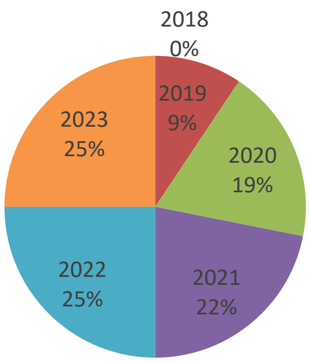

Figure 8: Distribution over Years in Category 4 (2018-2023)

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4. Results

4.1. Category 1 – Technologies that uses fossil fuels.

4.1.1 Technology Evaluation

Key technologies considered includes i) technical methods like wet scrubbing with electrolyzed seawater, and energy efficiency improvements like EEDI, SEEMP, and EEOI, and ii) operational methods like slow steaming, weather routing, trim optimization, and hull and propeller maintenance.

Technical methods, Wet scrubbing technology, particularly through electrolysed seawater, demonstrates significant promise in reducing sulphur oxides (SOx), nitrous oxide (NOx) and particulate matter (PM) emissions. Data reveal (Yang, 2018) removal efficiencies reaching up to 92% for NOx and nearly 100% for SOx, showcasing its potential to meet stringent international regulations. Study (Jimenez, 2022) highlights the potential of various energy efficiency improvement methods and the importance of accurate reporting by shipping companies to improve transparency and accountability and ultimately improving energy efficiency contribution.

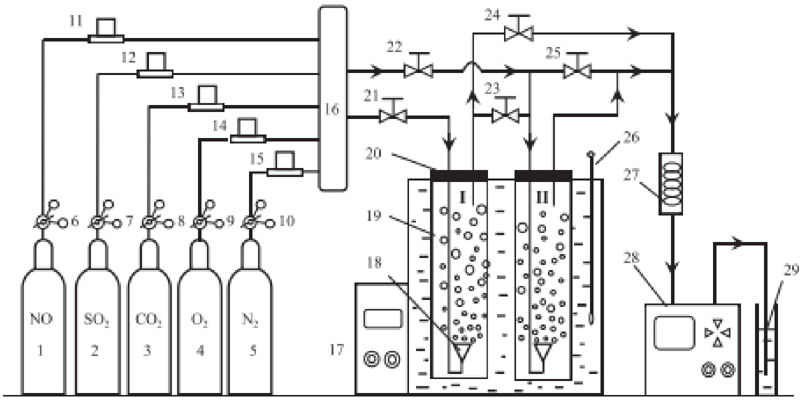

Figure 9 - (1–5) gas cylinders used for the stimulation of the flue gas emitted from ships; (6–10) reduced valves; (11–15) mass flow controllers; (16) gas mixer; (17) constant temperature water bath; (18) gas distributor; (19) bubble column; (20) rubber plug; (21–25) block valves; (26) thermometer; (27) electronic condenser.

Figure 9: Experimental Model Used in the Study by (Yang, 2018)

Operational measures involving lowering ship speed, weather routing, trim optimization, hull, and propeller condition maintenance reduces resistance and energy requirements exponentially. These techniques not only address the environmental impact but also enhance the operational efficiency and lifespan of maritime vessels (Elkafas, 2021).

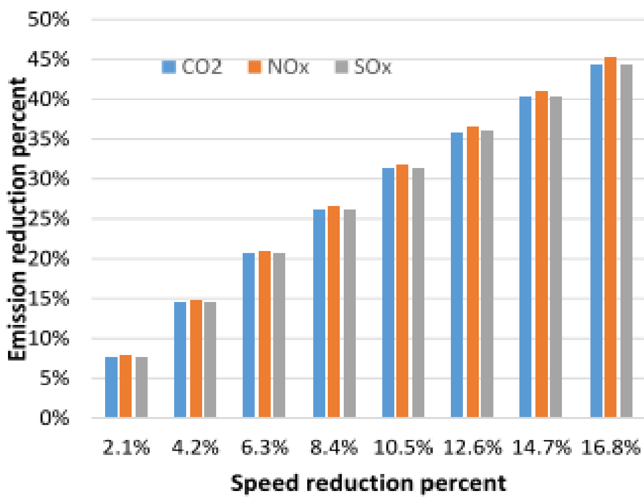

Figure 10- Results from the case study (Elkafas, 2021)

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4.2. Category 2 – Technologies that uses renewable energy.

4.2.1 Technology Evaluation

Solar Power and Photovoltaic Systems: Operational benefits of these systems include powering onboard systems, thereby reducing diesel generator loads and contributing to fuel savings and GHG emission reductions. A case study on cruise ship (Ghenai, 2019) demonstrate a reduction of 9.84 % GHG emission compared to the baseline using Diesel Engine. Figure 11 shops a typical power distribution arrangement using solar power system.

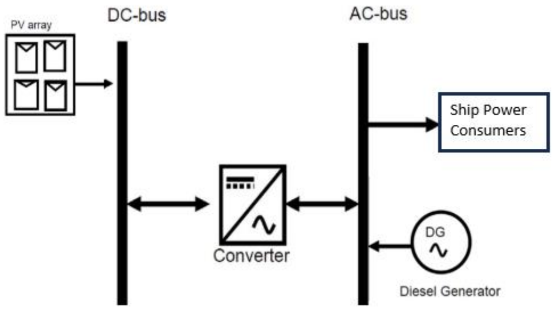

Figure 11: A typical solar power distribution system.

Wind-Assisted Propulsion Systems (WASP): Innovations like flettner rotors, towing kites, wing sails, and soft sails have reintroduced wind power as a feasible and efficient source of propulsion thus reducing reliance on fossil fuels. Vessels equipped with these systems report (Wang, 2022) emission reduction and fuel savings up to 20%, showcasing the potential of wind power in enhancing maritime fuel efficiency and sustainability.

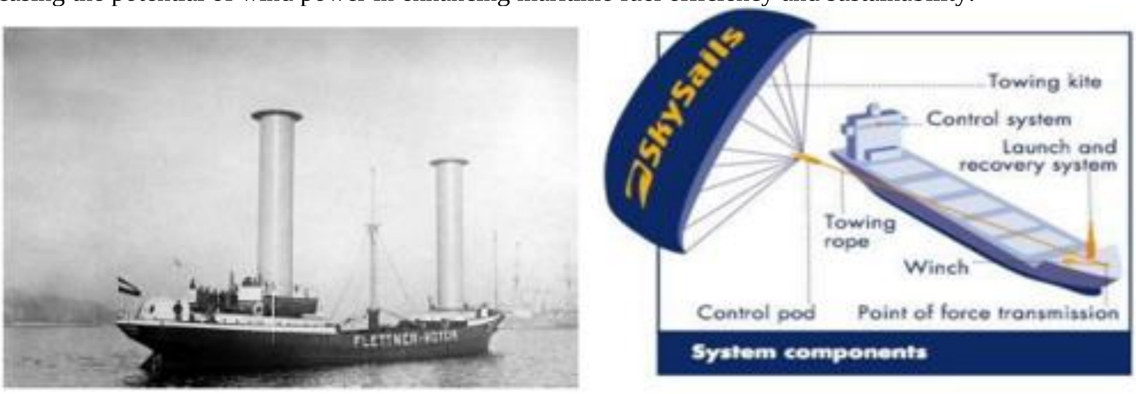

Figure 12 -Representation from Wang, 2022

Hybrid Power Systems: Hybrid systems blend renewable energy with traditional power sources to create efficient, sustainable solutions for ships. Advanced energy management maximizes renewable use and minimizes emissions. Numerous case studies affirm the role of hybrid systems in the future of green shipping (Setiawan-2021, Huang-2021, Gabbar-2021, Stamatakis-2021, Cheng-2022, Dolatabadi-2023).

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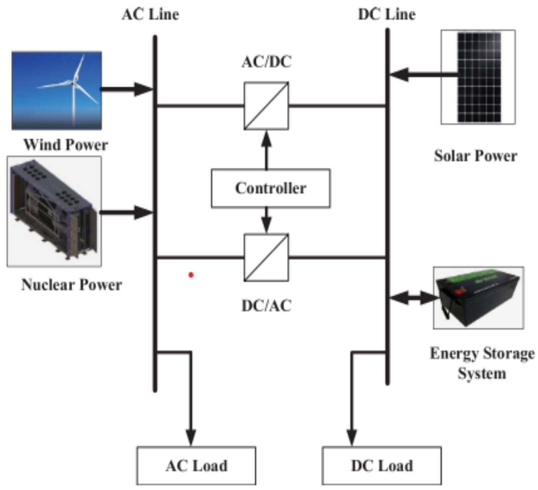

Figure 13: Typical Hybrid Arrangement (Gabbar - 2021)

4.3. Category 3 – Technologies that uses Fuel Cells

4.3.1 Technology Evaluation

The evaluation of Proton Exchange Membrane (PEM) and Solid Oxide Fuel Cells (SOFCs) in maritime applications shows significant progress toward zero-emission transport. Each technology has distinct advantages: PEM Fuel Cells offer efficiency, rapid start-up, low operating temperatures, and high-power density, reducing fuel consumption by 9% and CO2 emissions by 5.5% in auxiliary power applications (Matulić, 2018). PEM fuel cells, with their operational advantages and environmental benefits, are closer to mainstream adoption, evidenced by various pilot projects and case studies (Matulic -2018, Cavo – 2021 and Saloniemi -2022). SOFCs boast high efficiency and fuel flexibility, operating on various fuels and reducing GHG emissions by 34% (Baldi, 2020). However, high operating temperatures and cost barriers challenge SOFCs' widespread adoption.

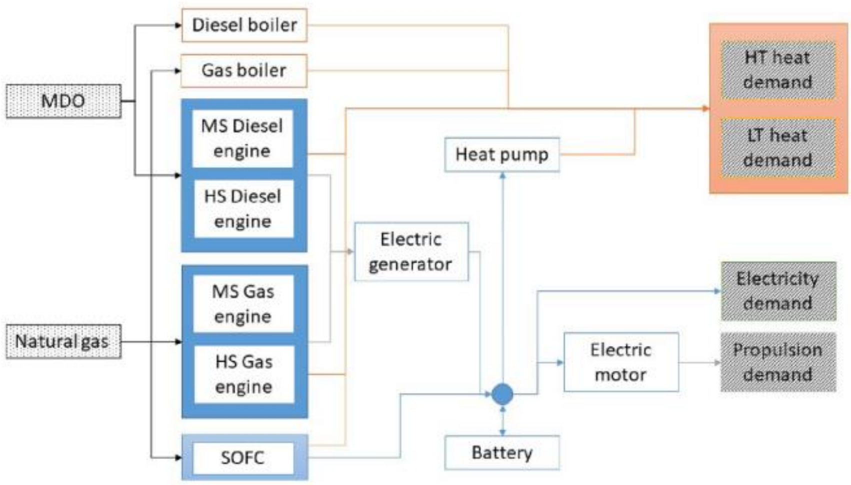

Figure 14- Proposed SOFC ship energy system (Baldi, 2020)

4.4. Category 4 – Technologies that uses Low Carbon/Alternative Fuels

4.4.1 Technology Evaluation

Fuels such as LNG, methanol, ethanol, biofuels, hydrogen, and ammonia have shown a CO_2 reduction range from 20% to 100%, with the specific potential varying based on the type of fuel (Xing, 2021).

 https://doi.org/10.24868/11183

LNG, compared to HFO, typically delivers a modest 10% reduction in GHGs. It is considered the most practical short-term option for cutting CO2 emissions due to its cost-effectiveness and the existing infrastructure (Balcombe, 2019).

Biofuels are highlighted for their compatibility with existing marine engines and potential to lower emissions of GHGs and pollutants. While presenting a renewable alternative, concerns around feedstock sustainability, environmental impact, and the need for technological integration persist.

Methanol and Ethanol offer cleaner burning options and does not contain sulphur.

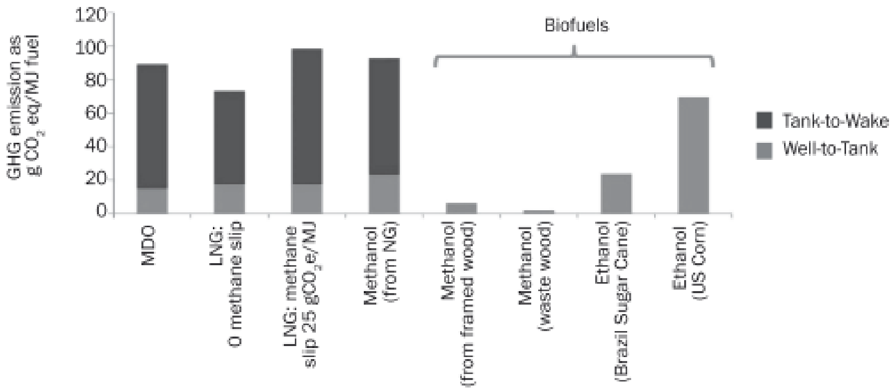

Figure 15: GHG emission from a case study (Radonja, 2019)

Ammonia is commonly produced in a commercial amount using the Haber-Bosch (H-B) process. A simplified block diagram is shown in Figure 16 (Al-Aboosi, 2021) on H-B process. Its economic and efficiency advantages, alongside significant environmental benefits, position it as a viable alternative for maritime fuel. However, challenges related to toxicity, storage, and the development of efficient propulsion technologies must be addressed.

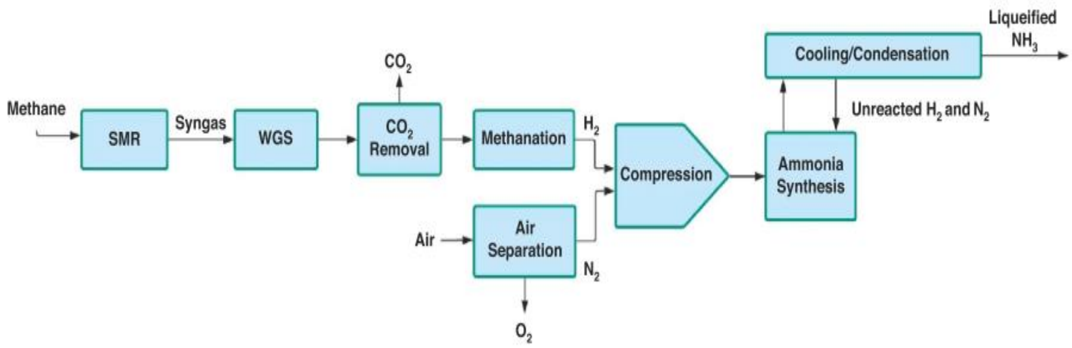

Figure 16: Simplified NH_3 production process using H-B process (Al-Aboosi, 2021).

Innovative Propulsion Technologies, such as green hydrogen and nuclear energy, represent cutting-edge approaches. Nuclear power, with its high energy density and operational efficiency, could drastically cut emissions if safety, regulatory, and public acceptance challenges can be surmounted.

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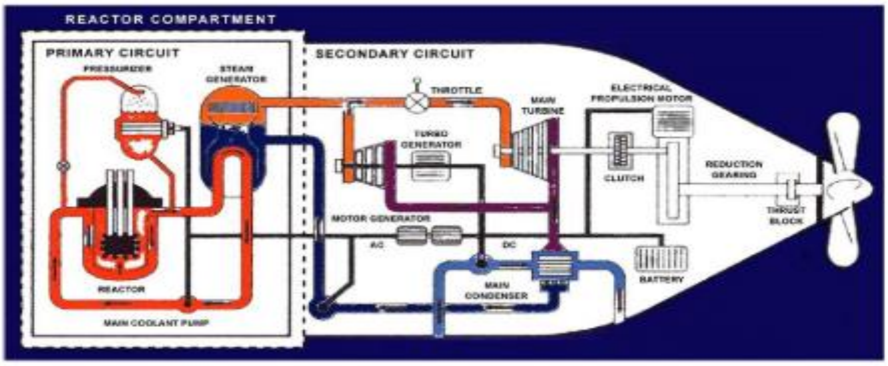

Figure 17: Pressurised Water Reactor based Nuclear Marine Propulsion (C. D. Kunze-2022)

5. Discussion

5.1. Category 1 – Technologies that uses fossil fuels.

Strength	<u>*Electrolysed Seawater Wet Scrubbing:*</u> *High Removal Efficiency:* Study (Yang, 2018) shows that this technology stands out for its ability to remove up to 92% of NOx emissions and nearly 100% of SOx emissions, showcasing remarkable efficiency in purifying ship exhaust gases.
	<u>*Energy Efficiency Methods:*</u> Optimizing structural design and propulsion systems with EEDI, SEEMP, and EEOI leads to significant fuel savings and reduced GHG emissions, supporting global climate change mitigation efforts.
	<u>*Operational Methods:*</u> Implementing effective operational methods decreases water resistance and selection of fuel-efficient paths thus drastically cutting fuel consumption, lowering GHG emissions and extending engine lifespan.

Challenges	<u>*Regulatory Complexities:*</u> The maritime industry operates globally under diverse regulations. Compliance with international, regional, and local standards, particularly in emission control areas (ECAs), requires extensive regulatory knowledge and operational flexibility.
	<u>*Technological and Operational Adaptability:*</u> *Integration with Existing Systems:* Advanced emission control technologies require not only physical space but also compatibility with existing propulsion and operational frameworks, which may not be designed for such integration. *Dynamic Maritime Environment:* The effectiveness of emission reduction operational methods are highly dependent on external conditions like weather, sea states, and port regulations. Adapting while maintaining efficiency and compliance adds complexity.

Opportunities	<u>*Innovations in Scrubbing Technologies*</u>: The development of wet scrubbing technology using electrolyzed seawater shows promise for reducing SOx and particulate matter emissions.
	<u>*Digitalization and AI in Operations*</u>*:* Integrating AI and big data into maritime operations allows real-time optimization of routes, speed, and fuel efficiency. These technologies can predict energy-efficient paths by considering weather, currents, and vessel specifics, leading to substantial emissions reductions.

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Response	<u>*Collaborative Efforts for Sustainable Practices:*</u> The maritime industry increasingly values collaboration among shipbuilders, engine manufacturers, operators, regulators, and environmental advocates.
	<u>*Adaptation to Regulatory and Environmental Changes*</u>: In response to stricter regulations, ship operators are retrofitting vessels with emission control technologies and opting for environmentally sustainable new ships along with adopting digital technologies like AI and big data analytics for optimal route planning to reduce fuel consumption and emissions.

Evaluation	<u>*Operational and Economic Benefits*</u>: Beyond environmental benefits, these initiatives offer operational advantages, including fuel savings, enhanced engine lifespan, and reduced maintenance costs.
	<u>*Challenges and Adaptability:*</u> While commendable strides have been made, the articles highlight challenges of high initial costs, regulatory complexity, and the need for adaptability in technology and operations.

5.2. Category 2 – Technologies that uses renewable energy.

Strength	<u>*Innovative Renewable Energy Technologies:*</u> Modern solar panels are highly efficient, lightweight, and durable, designed for marine conditions. Wind-assisted propulsion systems, like flettner rotors, kites, wing sails, and soft sails, harness wind energy. Hybrid systems combining renewable and conventional power optimize energy use, reduce emissions, and provide versatile operational solutions.
	<u>*Economic Advantages:*</u> By reducing reliance on volatile fossil fuel markets, companies can achieve more predictable operational costs and long-term savings.

Challenge	<u>*Technical and Logistical Challenges:*</u> *Integration into Existing Designs:* Retrofitting ships with solar panels, wind-assisted propulsion, or hybrid power is complex, requiring extensive structural modifications and sophisticated new electrical systems. *Intermittent Nature of Renewable Energy:* Wind and solar energy are variable and intermittent, making it challenging to maintain a stable and reliable onboard power supply.
	<u>*Economic Considerations:*</u> *Long Payback Periods*: High initial investment costs and long payback periods may deter companies from adopting green technologies.

Opportunities	<u>*Innovative Wind Propulsion Mechanisms:*</u> Optimized rotor sails, automated kites, and advanced wing sails enhance performance and adapt to varying wind conditions.
	<u>*High-Capacity, Lightweight Battery Systems:*</u> Advanced battery technologies like solid-state batteries and supercapacitors offer higher energy density, faster charging, and improved safety, essential for storing renewable energy and ensuring a stable power supply during voyages.
	<u>*Integration of Digital Technologies:*</u> AI and machine learning can optimize energy usage based on load demand, weather, and battery status.

Response	<u>*Policy Development and Regulatory Support:*</u> Governments and international organizations are offering incentives and subsidies to offset the high initial costs of renewable energy adoption, encouraging shipping companies to transition.

Evaluation	Integrating new technologies into existing fleets poses technical and logistical challenges, along with significant economic investment. Advances in renewable energy, energy storage, and digitized energy management can help overcome these barriers. Achieving sustainable maritime practices with renewable energy requires ongoing innovation, supportive policies, and global cooperation.

5.3. *Category 3 – Technologies that uses Fuel Cells*

Strength	*PEM* Fuel Cells offer rapid start-up times and high-power density, crucial for maritime vessels' dynamic power needs. A 2018 study by Matulić showed significant environmental benefits, reducing diesel fuel consumption by 9% and CO2 emissions by 5.5% in a one-hour voyage simulation.
	SOFC's efficiency levels often exceeding 60% and potentially reaching over 85% in combined heat and power (CHP) systems, mark a significant stride towards reducing fuel consumption and operational costs (Micoli, 2021).

Challenges	*Hydrogen Infrastructure:* The widespread adoption of hydrogen fuel cells faces challenges in hydrogen production, storage, safety, and bunkering facilities.
	Regulatory and Safety Standards: *Regulatory Framework:* Comprehensive regulations for the unique challenges and safety of hydrogen fuel cells in maritime applications are not yet fully developed. *Safety Considerations:* Hydrogen, the primary fuel for many fuel cell systems, is highly flammable and difficult to detect leaks, posing significant safety challenges.

Opportunities	*Technological Innovations:* Advancements in materials science and system design are essential for improving fuel cell performance and integration into maritime vessels, making them more appealing to shipowners and operators
	Regulatory Momentum: Through incentives, subsidies, and regulations supporting clean energy adoption boosts the attractiveness of fuel cell solutions for maritime use, fostering investment and innovation.

Response	*Enhanced Research and Development Initiatives:* Effective integration of fuel cell systems into vessel designs requires collaboration between shipbuilders, fuel cell manufacturers, regulators, and maritime operators
	Educational and Training Programs: Adopting fuel cells widely necessitates training ship crews on their operation, maintenance, and hydrogen fuel safety protocols.

Evaluation	*Technological Maturity and Infrastructure Development:* Advancements in fuel cell design, materials science, and system integration, along with hydrogen production, storage, and distribution networks, are essential for the technology's feasibility and success.
	Regulatory Frameworks and Safety Standards: A crucial part of the evaluation process is creating regulatory frameworks and safety standards for fuel cell technology. These regulations must balance safety and innovation, ensuring fuel cell adoption does not compromise maritime safety.

5.4. *Category 4 – Technologies that uses Low Carbon/Alternative Fuels*

Strength	*Economic and Efficiency Advantages:* Adopting alternative fuels in propulsion technologies can improve maritime operations' efficiency. Using biofuels and green hydrogen in engines and fuel cells enhances energy efficiency, reducing fuel consumption and operational costs.
	Environmental Benefits: By switching to alternatives like ammonia, biofuels, methanol, and green hydrogen, the maritime industry can significantly lower its CO_2, SOx, and NOx emissions.

Challenge	*Storage and Handling:* Ammonia, ethanol, and methanol pose significant storage and handling challenges.
	Economic Barriers: Transitioning to alternative fuels requires significant costs for building new ships or retrofitting existing ones.
	Regulatory and Infrastructure Readiness: *Lack of Global Regulatory Framework:* The maritime sector lacks a comprehensive regulatory framework for alternative fuels, causing uncertainty for shipowners about future compliance and investments. *Infrastructure Development:* Widescale adoption of alternative fuels requires significant development in fuelling infrastructure, which is currently insufficient.

Opportunities	*Regulatory Frameworks and Incentives:* The development and implementation of comprehensive regulatory frameworks and incentives play a vital role in accelerating the transition to alternative fuels.
	Infrastructure Development and Global Standards: Establishing the necessary fuelling infrastructure for new fuels at major ports around the world is essential for their widespread adoption.

Responses	*Industry-Wide Collaboration and Partnerships:* Forming joint ventures between maritime companies, engine manufacturers, and research institutions to speed up technological advancements and commercialize new fuel systems.
	Financial Mechanisms and Incentives: Implementing government subsidies and grants for research into alternative fuels and for retrofitting existing vessels with new propulsion systems.

Evaluation	*Technological Readiness and Innovation:* Scaling new low-carbon or alternative fuel technologies and integrating them into existing fleets pose significant challenges.
	Economic Viability: While alternative fuels offer long-term environmental and regulatory benefits, their short-term economic impact is a considerable challenge for many operators.
	Regulatory and Policy Frameworks: A harmonized international regulatory approach would facilitate a smoother transition and enable a more level playing field.

6. Impact on Naval Sector

Among the 115 articles shortlisted for this study, only 9 were relevant to the naval sector. This limited number of relevant papers can be attributed to the niche and specialized nature of naval operations, which necessitate unique technological adaptations, stringent regulatory and safety compliance, rendering general studies on marine technologies not always directly applicable or sufficient for naval needs. The assessed papers mainly focused on the use of nuclear fuel, hybrid systems, and fuel cells for power generation.

Nuclear fuel offers the advantage of providing high energy density and continuous power output for long-duration missions without generating GHG emissions. However, it poses significant challenges in terms of safety, radioactive waste management, and high initial investment costs. A study by Balcombe in 2019 estimated that in 2016, there were 166 operational naval reactors: 85 owned by the US, 48 by Russia, and 33 spread across other countries. At the same time, only four commercial nuclear vessels have existed, with only one active at 2019 (Balcombie, 2019).

Hybrid systems can significantly reduce GHG emissions by optimizing fuel consumption and enhancing energy efficiency. However, they present disadvantages, such as the complexity of integration, space margins higher maintenance requirements, and the need for sophisticated energy management systems to balance power loads effectively (Gaber, 2021).

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Fuel cells are another promising technology for reducing GHG emissions in naval operations. They offer high efficiency, low noise, and almost no GHG emissions. From a naval perspective, other advantages of fuel cells include their scalability for different vessel sizes, silent propulsion, low thermal and acoustic signatures, low maintenance requirements, and the possibility of air independence. However, fuel cells face disadvantages such as high costs, limited hydrogen infrastructure, and challenges related to hydrogen storage and handling (van Rheenen, 2022).

7. Conclusion

Across all categories, the industry faces common challenges, including high initial costs, regulatory complexities, and the need for global collaboration for widespread implementation. Transitioning to sustainable maritime operations involves not only choosing the right technologies but also fostering an ecosystem that supports innovation, infrastructure development, and regulatory flexibility.

Fossil fuel technologies align with the 2030 IMO checkpoints, but broader adoption and further innovation are needed to meet the 2040 goals. Despite their ability to reduce environmental impact, economic and regulatory hurdles could slow their implementation without significant advancements.

Renewable energy technologies, like solar and wind propulsion systems, are emerging as feasible alternatives that could transform maritime operations and meet both the 2030 and 2040 IMO emission reduction targets. However, integration challenges, intermittent energy supplies, and high initial costs remain barriers.

Fuel cells, particularly PEM fuel cells, show significant potential for reducing maritime emissions, with several pilot projects indicating a move towards mainstream adoption. By 2040, advancements in PEM and SOFC technologies could enable broader application across various vessel types. However, technological maturity, cost issues, and the need for a global hydrogen infrastructure are critical factors affecting adoption.

Alternative fuels such as ammonia, biofuels, methanol, and ethanol are progressing towards commercial viability and could align with the IMO's short-term emission goals. The medium to long-term potential of these fuels, along with green hydrogen and nuclear propulsion, depends on overcoming substantial technological and infrastructural challenges.

In comparing various technologies, three main challenges/benefits are noted as below:

i) Environmental Impact: Renewable energy and fuel cells offer significant emission reductions. Fossil fuel technologies, while beneficial, involve trade-offs like operational changes and potential environmental risks.

ii) Economic and Operational Benefits: All technologies promise long-term savings, but renewable energy and alternative fuels face high upfront costs. Fossil fuel technologies offer more immediate economic benefits due to their maturity and existing infrastructure.

iii) Regulatory and Adoption Challenges: Fuel cells and alternative fuels face substantial barriers in regulatory acceptance and necessary infrastructure development. Fossil fuel and renewable energy technologies have more straightforward paths to integration despite facing some regulatory hurdles.

8. Future Work

To further accelerate the adoption of these technologies, future research should focus on:

Enhancing the efficiency and integration of renewable energy systems within maritime vessels to address the challenges of energy intermittency and storage.

Scaling up the production and infrastructure for fuel cells to better meet the operational demands of larger vessels.

Interdisciplinary studies that integrate technological advancements with economic, policy, and environmental considerations to facilitate a smoother transition to greener technologies.

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