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# Effectiveness of Current Technology in GHG Reduction – A literature Survey

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ABSTRACT: In 2018 during the 72nd session of the Maritime Environmental Protection Committee (MEPC) IMO adopted its initial strategy for the reduction of greenhouse gas emissions (GHG) from the ships to meet the Paris Agreement Goals, 2015. This is considered as a major milestone in formulizing a clear strategy by IMO towards its objective of reducing the global GHG emissions from the ships. The strategy had two primary objectives: the first was to decrease total annual GHG emissions by at least 50% by 2050 compared to 2008 levels. The second objective was to promote the phasing out of GHG emissions entirely. In 2020, the International Maritime Organization (IMO) conducted a study which revealed that greenhouse gas (GHG) emissions from shipping had increased by 9.6%. The rise in global maritime trade was identified as the main factor behind this increase. IMO's 2020 study also concluded that reducing GHG emissions by focusing only on energy-saving technologies and ship speed reduction would not be enough to meet the IMO's 2050 GHG reduction target. Therefore, greater attention needs to be given to the use of low-carbon alternative fuels. To understand the effectiveness of currently available technologies in reducing GHG emissions from ships, a literature survey was conducted in this study. The survey examined a range of related articles published between 2018 and 2022. This study aimed to identify the current stage and the quantity of literature available on various technologies and, more importantly, serve as a decision-making support tool for selecting a technology under specific circumstances in a quantitative manner. The technologies were divided into four groups: those that utilize fossil fuels, those that use renewable energy, those that use fuel cells, and those that use low-carbon or alternative fuels. The literature survey was conducted using Web of Science (WoS) and Google Scholar. The results of this study will also help to identify clear research gaps in comparing the effectiveness of various available technologies to reduce GHG emissions. Ultimately, the aim is to develop a comprehensive strategy that can be used to reduce GHG emissions from shipping and contribute to the global fight against climate change.

## 1 INTRODUCTION

The increased concentration of greenhouse gases (GHGs) and their impact on the Earth's climate are pressing issues faced by the current generation. Urgent action to reduce GHG concentrations is long overdue. The transportation sector has been identified as a major contributor to the increased GHG concentration. The shipping industry, which accounts for 80% of global trade by volume and over 70% by value, is particularly significant. According to estimates, international shipping contributed to 1.8% of global $CO_2$ emissions in 1996, and this increased to 2.7% in 2009. Although this emission rate decreased to 2.2% in 2012 due to the global economic crisis, it is projected that $CO_2$ emissions from shipping will increase by 50% to 250% in the period up to 2050, owing to the projected growth in demand for maritime transport services (IMO, 2018). The lack of strict action by the IMO can lead to a catastrophic failure of the current global target to limit the global average temperature rise to two degrees by 2050.

During the 72nd session of the Maritime Environmental Protection Committee (MEPC) in 2018, the IMO adopted its initial strategy for reducing GHG emissions from ships to meet the goals of the 2015 Paris Agreement. This adoption is considered a significant milestone in the IMO's efforts to reduce global GHG emissions from ships. The main objective of this strategy is to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 while also pursuing efforts to completely phase out GHGs (IMO, 2018). The 72nd session of the MEPC was held at the IMO Headquarters in London, United Kingdom, and was attended by more than 100 IMO member states.

This strategy establishes a future vision, various levels of ambition in reducing GHG emissions, and guiding principles that include short-term and long-term measures with possible timelines and impacts on different member states. Additionally, the strategy lists potential difficulties in achieving the milestones and sets up various supportive measures, including capacity building, technical cooperation, and research and development. The IMO plans to revise this initial strategy by 2023.

Currently, various organizations, nations, and engine manufacturers are considering and implementing different methods and conducting research to effectively reduce GHG emissions while minimizing the cost impact on the industry. Although some of these methods and research have produced promising initial results, the full side effects and effectiveness in achieving the stringent IMO targets still need to be completely understood.

This study aims to conduct a literature survey of available articles published between 2018 and 2022 in Google Scholar and WoS to identify the effectiveness of various technologies currently available in reducing GHG emissions.

## 2 METHODOLOGY

### 2.1 *Search criteria*

For understanding the currently available technologies that target the reduction of GHG emission, a systematic review of published academic literature has been undertaken. Utilising widely used methodology (demonstrated in Wan et al -2017 and Romana; Yanz Z -2021), the Google Scholar and Web of Science (WoS) database was used for gathering the academic literature. The search for this paper was conducted in January 2023.

For Google Scholar – Articles with the words “Ship and emission”, “Ship and GHG emission”, “Ship and fuel cell”, “Ship and renewable energy” and “Ship and low carbon fuel” contained in the title were considered for the review as part of this paper.

For WoS – Within WoS, for function “Topic” word Ship* was used for “Titles” emission*, GHG*, fuel cell*, renewable energy*, and low carbon fuel* were used.

### 2.2 *Selection of articles*

Google Scholar –An initial search using the search criteria outlined in section 2.1 of this paper resulted in a total of 254 articles in Google Scholar. After excluding citations and applying the search criteria for the year of publication (2018-2022), the total number of articles was reduced to 117. Upon reviewing the abstracts of various articles, a total of 22 articles were shortlisted for further review as part of this paper.

Web of Science (WoS)- An initial search using the search criteria outlined in section 2.1 of this paper resulted in a total of 2,153 publications. After excluding publications that are not articles (such as proceedings, early access, editorial material, etc.) and applying the search criteria for the year of publication (2018-2022), the total number was reduced to 997. After a quick review of the abstracts, 46 articles were shortlisted for further review as part of this paper.

## 3 RESULTS

### 3.1 *Technologies that utilize fossil fuels*

A total of 16 articles were reviewed in this section. The shipping industry contributes significantly to global greenhouse gas (GHG) emissions, with fuel costs accounting for approximately 50-60% of the operating cost for a merchant vessel. To reduce emissions from the use of fossil fuels, two main categories of methods are considered: technical and operational. Technical methods include modifications to the hull, engine, propeller, capacity, and design of ships, while operational methods include speed optimization, loading-unloading management, trim optimization, and weather routing. Another option is the use of alternative fuels compared to the commonly used heavy fuel oil (HFO).

Technical methods mainly focus on improving the Energy Efficiency Design Index (EEDI). It is worth noting that further improvement to the EEDI is one of the IMO's key strategies in reducing GHG emissions. The EEDI is intended as a non-prescriptive, performance-based mechanism where ship designers and builders can select the most cost-efficient solution in complying with IMO regulations (Harlos, 2019). The basic simplified formula for calculating the EEDI is as follows:

EEDI = $CO_2$ emission/Transport work (Class NK-2016)

$CO_2$ emissions are calculated based on the carbon content of fuel consumption, which is determined by the power used for auxiliary and propulsion power at a defined design condition. Transport work is estimated by multiplying the ship's capacity, as defined by IMO guidelines, by the ship's reference speed at the corresponding draft. The reference speed is generally determined at 75% of the rated installed propulsion power and at 83% of the rated installed propulsion power for LNG carriers with a diesel-electric or steam turbine propulsion system (ICCT, 2020).

The current EEDI calculation and regulation focus on $CO_2$ emissions. As the EEDI currently only regulates $CO_2$, ship owners are increasingly inclined to purchase LNG-fuelled ships as it is much easier to meet the current regulations using LNG as fuel. The main reasons for using LNG are: i) LNG emits approximately 25% less $CO_2$ than conventional marine fuel providing the same amount of propulsion power (ICCT, 2020), ii) there is less sulphur content in LNG, iii) low nitrogen oxide emissions with the help of less expensive technology treating the exhaust gas, iv) with less sulphur oxide and nitrogen oxide emissions, these vessels are easy to operate in emission-controlled areas (ECA), and v) LNG is less expensive than MGO (Marine Gas Oil) and in some places even cheaper than HFO.

Operational Method - The majority of papers assessed in this section focus on the method of "slow steaming," which involves reducing the speed of ships to reduce fuel consumption and GHG emissions. One study (Ayudhia, 2019) noted that a 20-knot ship consumes 130% more fuel than a 15-knot ship with the same load, indicating that a ship's speed affects its fuel consumption and emissions. Lowering the speed of ships can result in a 40% reduction in fuel consumption, but the benefits may not always be realized if the shipping time exceeds the specified time window. For this study, emissions were calculated using a method developed by the Puget Sound Maritime Air Emission Inventory (PSMAEI) published in 2016.

Below is the summary of this study.

Table 1. Vessel Details (Ayudhia, 2019 – Table 1)

| Name of ship | M.V. Meratus Malino |
|---|---|
| **Dimension (Loa; B; H; D)** | 149.6 m; 23.1 m; 12.8 m; 8.8 m |
| **Service speed** | 15.6 knots |
| **M/E (unit, type, power, SFOC, year)** | MAN B & W (1), 7S 50 - MC, 13610 HP, 167, 1995 |
| **GT** | 11964 |
| **Routes** | Surabaya (SUB) - Belawan (BLW), Indonesia |

Table 2. Total Emission with each speed scenario (Ayudhia, 2019 - Table 7)

| Speed (knots) | LF | Energy (kWh) | $NO_X$ (ton) | $CO_2$ (ton) | $SO_2$ (ton) | $PM_{2.5}$ (ton) | CO (ton) |
|---|---|---|---|---|---|---|---|
| **12** | 0.46 | 196033 | 3.1 | 109.7 | 0.003 | 0.01 | 0.3 |
| **12.2** | 0.48 | 213357 | 3.4 | 119.4 | 0.003 | 0.01 | 0.3 |
| **12.4** | 0.50 | 232031 | 3.7 | 129.8 | 0.003 | 0.01 | 0.3 |
| **12.6** | 0.53 | 252039 | 4.0 | 141.0 | 0.004 | 0.01 | 0.4 |
| **12.8** | 0.55 | 273556 | 4.4 | 153.1 | 0.004 | 0.01 | 0.4 |
| **13** | 0.58 | 296783 | 4.7 | 166.1 | 0.004 | 0.01 | 0.4 |
| **13.2** | 0.61 | 321598 | 5.1 | 180.0 | 0.005 | 0.01 | 0.5 |
| **13.4** | 0.63 | 348323 | 5.6 | 194.9 | 0.005 | 0.02 | 0.5 |
| **13.6** | 0.66 | 377074 | 6.0 | 211.0 | 0.005 | 0.02 | 0.5 |
| **13.8** | 0.69 | 407975 | 6.5 | 228.3 | 0.006 | 0.02 | 0.6 |
| **14** | 0.72 | 441011 | 7.0 | 246.8 | 0.006 | 0.02 | 0.6 |
| **14.2** | 0.75 | 476585 | 7.6 | 266.7 | 0.007 | 0.02 | 0.7 |
| **14.4** | 0.79 | 514849 | 8.2 | 288.1 | 0.007 | 0.02 | 0.7 |
| **14.6** | 0.82 | 555809 | 8.9 | 311.0 | 0.008 | 0.03 | 0.8 |
| **14.8** | 0.85 | 599610 | 9.6 | 335.5 | 0.008 | 0.03 | 0.8 |
| **15** | 0.89 | 646743 | 10.3 | 361.9 | 0.009 | 0.03 | 0.9 |
| **15.2** | 0.93 | 697055 | 11.1 | 390.0 | 0.010 | 0.03 | 1.0 |
| **15.4** | 0.96 | 751257 | 12.0 | 420.4 | 0.011 | 0.03 | 1.1 |
| **15.6** | 1.00 | 809204 | 12.9 | 452.8 | 0.011 | 0.04 | 1.1 |

Alternative fossil fuels - The next majority of studies related to the use of fossil fuels compare the economic feasibility and $CO_2$ emission reduction from LNG-fuelled ships. It can be summarized that, although LNG reduces GHG emissions, its use is economically feasible only under certain conditions such as round-trip, ship size, oil bunker price, and LNG bunker price discount. The optimal ship size depends on bunker prices and $CO_2$ emission reduction. These studies provide valuable insights into the trade-offs between the economic feasibility and environmental sustainability of LNG-fueled shipping.

One study (Peng Cheng, 2021) aimed to reduce greenhouse gas emissions in the marine transportation sector by using hybrid electric propulsion systems (HEPS) with natural gas (NG) engines. The results showed that the use of LNG fuel and the optimization of the hybrid electric propulsion system reduced fuel consumption and GHG emissions. The switch from diesel to NG-diesel dual-fuel engines reduced fuel costs by 74%, but GHG emissions decreased by only 7.24%. The optimal hybrid electric powertrain with NG fuel reduced GHG emissions by 38.67%. The simultaneous design and control optimization of the NG engine was crucial in reducing emissions, as the engine operating within a low-emission zone led to reduced GHG emission.

## 3.2 *Technologies that utilise renewable energy*

Only six papers/articles were identified that were published on technologies that utilize renewable energy for the propulsion of vessels. While renewable energy sources (RESs) are free from GHG emissions and play a vital role in sustainable development by reducing GHG emissions from ocean-going marine ships, their advantages are overridden by the large amount of reliable energy needed to support the propulsive load demand, resulting in space constraints. RESs are intermittent, and a large amount of energy cannot be stored economically by available energy storage techniques. Additionally, the penetration of RESs in a marine ship is limited by the available area and total weight carrying capacity of the marine ship (Gabbar, 2021).

Due to the limitations of dependability on renewable energy sources alone, all the papers reviewed presented a study on the optimization of the hybrid power system. The aim is to reduce marine environmental pollution and greenhouse gas emissions by using renewable energy technologies along with conventional energy sources. Some of the systems addressed were wind-diesel-storage hybrid power systems, solar-diesel-storage hybrid power systems, and nuclear-renewable hybrid power systems. A typical arrangement of such a system is shown in figure 1 below (Gabbar, 2021).

The results from these studies show that the hybrid systems like one mentioned above are helpful in reducing GHG emissions. However, the main challenges that need to be overcome are storage issues with renewable energy sources, weight, maintenance costs, and less overall value for money.

Another system considered in one of the articles (Yunlong -2022) is wind-assisted ship propulsion (WASP). The International Maritime Organization has established measures to reduce emissions, and re-searchers have been exploring WASP technology as a means to achieve this goal. WASP technologies, such as rotor sails and towing kites, have been developed and tested, and have shown promise in reducing fuel consumption and emissions. However, the widespread adoption of WASP technology is limited by factors such as cost, maintenance, deck space requirements, and safety concerns. The authors of this paper suggest that further research should be conducted to assess the techno-economic feasibility of WASP technologies and address safety concerns to promote their adoption in the shipping industry.

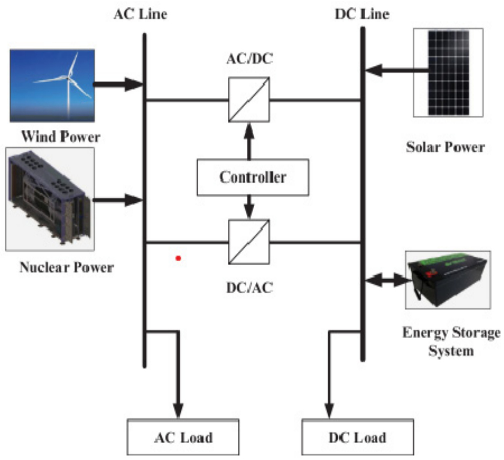


Figure 1. Typical Hybrid Arrangement (Gabbar, 2021 – Figure 5)

3.3 *Technology that utilise fuel cells*

In a fuel cell, hydrogen combines with oxygen to release electrons and generate electric power. This electrochemical reaction can be represented by the below equation.

$$Anode: H_2 + O^{2-} \rightarrow H_2O + 2e^-$$
$$Cathode: \tfrac{1}{2}O_2 + 2e^- \rightarrow O_2^-$$
$$Overall: H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$

Fuel cells do not use all of the supplied fuel, leaving residual fuel that needs to be collected and burned for safety reasons. This results in a large amount of heat energy being produced, including from the electrochemical reaction and combustion of residual fuel. Onshore power plants can utilize this thermal energy to provide not only electricity but also heating to surrounding areas through combined heat and power (CHP) systems. However, ships at sea do not require as much heating, so alternative uses for this thermal energy must be considered in fuel-cell ships.

A total of 22 articles were reviewed in this section. One study (Ref D.-S. C. Donghyun Oh, Dae-Seung Cho -2022) proposes a hybrid propulsion system for ships, combining electric and thermal energy from fuel cells to generate mechanical driving force as shown in below figure 4. The system consists of an electric motor and a steam turbine, and the rotational powers from both are combined at the propeller shaft. The study analyses the efficiency of the system through numerical simulations and finds it to be 49%. The results show that the proposed system can decrease fuel consumption and reduce the size of the fuel cell compared to conventional systems, but further optimization is needed to increase efficiency.

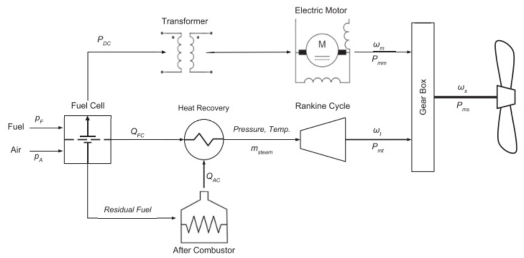


Figure 2. Hybrid System (Donghyun , 2022 Figure 3)

Most of the articles reviewed in this paper discuss the use of hydrogen fuel cells in ships and the potential risks associated with hydrogen leakage. While fuel cells have been promoted as a zero-emission alternative energy source for ships, safety concerns have also been raised. Three papers primarily focus on the impact of hydrogen leakage from fuel cells, valves, and connectors on a fuel cell-powered ship and evaluate the effectiveness of existing ventilation systems.

One article (Lijian Chen – 2021) uses a fuel cell-powered and tried to calculates the release rate of hydrogen leakage from a typical vessel. It also considers the safety principles of the fuel cell space, such as "single failure safety" and "explosion prevention." The results show that optimizing the fuel cell space design, ventilation, and module design can significantly reduce the scope of the explosive gas environment created by hydrogen leakage and improve the safety of the ship. However, further research is needed to extend these measures to passenger ships and address the uncertainties in risk assessment.

Another study (Xiaobing - 2021) investigates the safety of hydrogen fuel cell systems (HFCS) in ships by simulating the diffusion and explosion behaviour of hydrogen in different compartments after a leakage. The simulations were conducted using the ANSYS Fluent software and the Realize k-ε turbulence model, taking into account the boundary conditions and possible ignition sources. The results showed that the position of the explosion centre affects the overpressure damage, and hydrogen concentration affects the high-temperature damage. The fuel cell compartment had the most severe overpressure damage, followed by the control compartment, while the passenger compartment had the least overpressure damage but posed the greatest danger to the crew in case of an explosion.

Another article (M. Cavo – 2021) discusses a research project aimed at developing and testing a zero-emission ship powered by PEMFC (Proton Exchange Membrane Fuel Cells) and Li-ion batteries. The ship is designed to store hydrogen using metal hydrides and will use a PI controller to regulate the thermal coupling between the fuel cells and metal hydrides. The system components involved in thermal control include heat exchangers, blenders, control valves, and variable-speed pumps. The mathematical modelling of these components is described using equations. The simulations are conducted using real operating conditions and a 7-hour journey duration. The fuel cell energy system sustains the electrical demand, with the metal hydrides absorbing residual heat. The hydrogen consumption in the system increases with the load on the cells, decreasing the internal pressure of the metal hydrides, which results in a higher hydrogen flow. The water temperature at the metal hydrides inlet is controlled by adjusting the flow rate of the heat exchanger system.

### 3.4 *Technologies that use low-carbon or alternative fuels*

A total of 24 articles were reviewed in this section. Most of the papers aimed to explore the potential use of ammonia as an energy storage solution for renewable energy. They proposed ammonia as a solution due to its high energy density and feasibility of production. Other advantages of ammonia are that it does not contain carbon and when burnt completely, it only produces water and nitrogen without other polluting gases.

The use of hydrogen as a promoter for ammonia engines has been extensively studied due to ammonia's low specific energy, high auto-ignition temperatures, and narrow flammability limits. Hydrogen has the lowest ignition energy, highest combustion velocity, and widest flammability range, making it effective in speeding up combustion when added in small amounts to the air-ammonia mixture. Ammonia-hydrogen mixtures can be used in both compression ignition (CI) and spark ignition (SI) internal combustion engines, with the CI having a trade-off between a high compression ratio to promote ammonia combustion and a limited compression ratio to prevent hydrogen from ringing.

Research by K. Kim, G. Roh, W. Kim, and K. Chun (2020) has investigated the use of ammonia in SI engines, resulting in a reduction in harmful emissions compared to CI engines. Studies varied the excess air ratio and the ammonia-to-hydrogen ratio to determine the proper air-ammonia-hydrogen mixture composition for actual operating conditions. An onboard reformer could be used to crack a proportion of the ammonia into hydrogen to support combustion, but further research is required to calibrate the rate of hydrogen cracking to support stable combustion conditions at variable engine loads and speeds.

A case study by Francesco Baldi (2019) investigated the use of excess renewable energy from a 200 MW offshore wind farm to propel a car ferry. The energy was stored and transported in three forms: batteries, hydrogen, and ammonia. The electric way stored excess energy in batteries, the hydrogen way used excess energy in the electrolysis to generate hydrogen, which was stored in either compressed or liquid form, and the ammonia way used excess energy to generate hydrogen from water in an electrolyser and nitrogen from air in a cryogenic air separation unit. Hydrogen and nitrogen were then used in an ammonia synthesis plant (assumed to be based on the Haber-Bosch technology) that converted them to ammonia, which was stored in liquid format at low temperature. The study found that using batteries alone was the least convenient option due to high investment costs, while liquid hydrogen was more competitive compared to compressed hydrogen.

A total of nine articles discusses the use of low-carbon fuels as an alternative to fossil fuels to reduce $CO_2$ emissions in the maritime industry. Technologies such as liquefied petroleum gas (LPG), methanol, and biodiesel are being studied as potential alternative fuels. These fuels have advantages such as lower emissions of $CO_2$ and sulphur dioxide, easy availability, and convenient storage and transportation. However, they also have drawbacks such as a limited ability to reduce $CO_2$ emissions, strong corrosiveness, and limited improvement in thermal efficiency. Research is ongoing to find the best solution to reduce emissions in the maritime industry, with a focus on improving the performance of these alternative fuels.

## 4 CONCLUSIONS

This study conducted a systematic review of academic literature to understand the currently available technologies that target the reduction of GHG emissions in the shipping industry. The researchers used Google Scholar and Web of Science databases to gather academic literature and shortlisted a total of 22 articles from Google Scholar and 46 articles from WoS for further review. Among the 68 articles reviewed as part of this literature review, the least number of articles were identified in the technology that utilizes renewable energy, followed by technologies that utilize fossil fuels, then technology that uses fuel cells, and the highest number of articles were identified on technologies that utilize low carbon or alternative fuels.

Technologies that use renewable energy - The use of renewable energy sources for the propulsion of marine vessels has been limited due to challenges such as intermittency, energy storage limitations, weight, and maintenance costs. However, research has been conducted on the optimization of hybrid power systems that combine renewable energy sources with conventional energy sources to reduce greenhouse gas emissions. Additionally, wind-assisted ship propulsion (WASP) technologies have been developed and tested as a means to reduce fuel consumption and emissions. Still, their widespread adoption is limited by factors such as cost, maintenance, deck space requirements, and safety concerns. Further research is needed to address these challenges and promote the adoption of renewable energy technologies in the shipping industry.

Technology that uses fossil fuels – Articles identified in this section discuss technical and operational methods, as well as the use of alternative fuels such as LNG. The Energy Efficiency Design Index (EEDI) has been identified as a key strategy for reducing emissions, and the use of LNG has been found to be a promising alternative to traditional marine fuels due to its lower emissions and cost. Slow steaming has also been suggested as an effective method for reducing fuel consumption and emissions, although the benefits may not always be realized if the shipping time exceeds the specified time window. Overall, the studies reviewed provide valuable insights into the trade-offs between economic feasibility and environmental sustainability in the shipping industry and offer useful strategies for reducing emissions and mitigating the industry's impact on the environment.

Technologies that use fuel cells – Although the use of hydrogen fuel cells addresses most of the issues surrounding GHG emissions, there are serious concerns regarding the safety of hydrogen fuel cells in ships, particularly related to hydrogen leakage and explosion risks. Several studies have investigated the impact of hydrogen leakage on the safety of fuel cell-powered ships and found that optimization of the fuel cell space design, ventilation, and module design can significantly reduce the scope of the explosive gas environment created by hydrogen leakage and improve the safety of the ship. Overall, these studies suggest that the use of hybrid propulsion systems and hydrogen fuel cells in ships can provide a promising zero-emission alternative energy source. Still, further research is needed to address safety concerns and optimize system efficiency.

Technologies that use alternative or low-carbon fuel: Most of the articles reviewed as part of this literature review were published in the field of technologies that use alternative or low-carbon fuel. Among these fuels, ammonia is considered the preferred option due to the lack of carbon, higher energy density, and feasibility in production, but further research is needed to optimize its use and ensure safety. The use of low-carbon fuels such as LPG, methanol, and biodiesel is also being explored in various studies, but these fuels have both advantages and drawbacks that need to be carefully considered.

## 5 FUTURE WORK

From the initial search result of 2209 articles (from both google scholar and WoS), only 68 articles were reviewed in this study due to schedule constraints. It is assumed that more articles could also be included in this literature review after further assessment of the content of these articles. This has the potential of identifying new technologies that are not listed in this study.

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