

Review

A Review of LCA Studies on Marine Alternative Fuels: Fuels, Methodology, Case Studies, and Recommendations

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Abstract: Life Cycle Assessment (LCA) methodology can be used to quantitatively assess the greenhouse gas emissions of low- or zero-carbon marine alternative fuels throughout their life cycle (from well to wake) and is an important basis for ensuring a green energy transition in the shipping industry. This paper first clarifies the trends and requirements of low-carbon development in shipping and introduces the major ship emission reduction technologies and evaluation methods. Next, the characteristics of various alternative marine fuels (i.e., LNG, hydrogen, methanol, ammonia, and biofuels) are comprehensively discussed and analyzed in terms of production, storage, transportation, and ship applications. In addition, this work provides a comprehensive overview of LCA methodology, including its relevant standards and assessment tools, and establishes a framework for LCA of marine alternative fuels. On this basis, a literature review of the current research on LCA of marine alternative fuels from the perspectives of carbon emissions, pollution emissions, and economics is presented. The case review covers 64 alternative-fueled ships and 12 groups of fleets operating in different countries and waters. Finally, this paper discusses the main shortcomings that exist in the current research and provides an outlook on the future development of LCA research of marine alternative fuels.

Keywords: marine alternative fuels; life cycle assessment (LCA); green maritime transport; carbon reduction



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1. Introduction

1.1. Trends and Requirements for Low-Carbon Development in Shipping

Since the 1950s, while the global economy has experienced significant growth, the environmental challenges confronting humanity, including global warming and atmospheric pollution, have intensified. As stated in the World Meteorological Organization (WMO) report of “The State of the Global Climate 2022”, the global average temperature in 2022 was approximately 1.15 °C above the pre-industrial level [1]. Global warming has directly resulted in notable alterations to the climate system, including the occurrence of ocean heat waves, extreme high temperatures, substantial heavy precipitation, and the emergence of ecological droughts in certain regions, as well as the melting of glaciers, reduction of permafrost, and sea level rise. In order to mitigate the threat of natural disasters, the WMO and the United Nations Environment Programme (UNEP) have established the Intergovernmental Panel on Climate Change (IPCC) as early as 1988, and the Marine Environment Protection Committee (MEPC) has incorporated the issue of air pollution into their work plans. At the Rio Earth Summit in 1992, 154 countries signed the United Nations Framework Convention on Climate Change (UNFCCC) [2]. The UNFCCC was adopted

in December 1997 by 149 countries, who collectively agreed to the Kyoto Protocol [3]. On 12 December 2015, nearly 200 parties to the UNFCCC reached the Paris Agreement at the Paris Climate Change Conference [4]. The advent of these international documents and conventions signifies the emergence of a novel paradigm in global climate governance. In its report released on 9 August 2021, IPCC states that global warming will exceed 1.5 °C to 2 °C unless greenhouse gas emissions are significantly reduced in the coming decades [5].

Ship transportation plays a significant role in the global integrated transport system, with its advantages of lower costs and higher volumes. Nowadays, it is responsible for over 90% of global trade transportation [6], which has expanded the carbon footprint of the shipping industry. As evidenced by the IMO Fourth Greenhouse Gas Study 2020, global greenhouse gas emissions from shipping have reached 1076 million tons in 2018, representing 2.89% of the total global anthropogenic greenhouse gas emissions [7]. In fact, as early as 1991, the IMO adopted a resolution related to the MARPOL Convention (International Convention for the Prevention of Pollution from Ships), which called for a new draft to address the issue of reducing air pollution from ships. Subsequently, a series of discussions and planning sessions on carbon emission reduction have been conducted in MEPC meetings, and the principal outcomes are presented in Table 1. Additionally, the EU has also established policies pertaining to the development of environmentally sustainable shipping practices, as illustrated in Table 2. In summary, the establishment of Emission Control Areas (ECAs), the enactment of a global sulfur restriction (low-sulfur fuel for ships), and the implementation of the IMO's strategy on greenhouse gases in recent years have indicated an increasing international focus on the issue of reducing ship emissions. Furthermore, some companies have also begun to reduce the carbon footprint of their shipbuilding products throughout their life cycle by requesting their partners and transportation companies in the supply chain to fulfill their global social responsibility and obligation to be green and low-carbon shipping. The combined effect of international regulations, social responsibility, and customer requirements has brought green shipping to the forefront of the times. It has become an inevitable trend for the global shipping industry to move towards energy-saving, green, and low-carbon development.

Table 1. Summary of previous MEPC meetings on carbon emission reduction.

Meetings	Time	Related Content
MEPC40	1997	Put the search and review of greenhouse gas emission reduction strategies on the agenda.
MEPC42	1998	Identified the responsibility of IMO and conducted research on CO ₂ emissions from ships.
MEPC45	2000	Adopted the “IMO Report on the Study of Greenhouse Gas Emissions from Ships”.
MEPC53	2005	Adopted the “Interim Guidelines for Voluntary Trial of Ship CO ₂ Emission Index”.
MEPC56	2007	Proposed technical measures to improve ship design to control CO ₂ emissions from ships.
MEPC57	2008	Proposed for the first time the CO ₂ Design Index for newly built ships and measures to reduce CO ₂ emissions from ships in three aspects: technical standards, operations, and the market.
MEPC58	2008	Proposed the Energy Efficiency Design Index (EEDI).

Table 1. Cont.

Meetings	Time	Related Content
MEPC59	2009	Issued “Provisional Guidelines on the Calculation Method of EEDI for Newbuilding Ships”, “Guidelines for Voluntary Trial of Ship Energy Efficiency Operation Index (EEOI)”, “Guidelines for Formulation of Ship Energy Efficiency Management Program (SEEMP)”, “Guidelines for Development of Energy Efficiency Management Program (EEMP)”, “Guidelines for the Development of Ship Energy Efficiency Management Program (SEEMP)”, “Interim Guidelines for the Voluntary Validation of Energy Efficiency Design Index (EEDI)”, and other related specifications.
MEPC60	2010	Completed the text of MARPOL Annex VI substantially.
MEPC61	2010	Improved the EEDI and SEEMP, and discussed the EEDI calculation method.
MEPC62	2011	Adopted the “Ship Energy Efficiency Rules” and discussed the use of energy saving technologies and alternative fuels to reduce carbon emissions.
MEPC63	2012	Adopted the resolutions on EEDI and SEEMP, and put forward the requestion for existing ships to formulate management programs to improve energy use.
MEPC64	2012	Adopted the amendments to the Guidelines on the Methodology for Calculating the Energy Efficiency Index for New Ships 2012 (resolution MEPC.212(63)) to further improve the energy efficiency of newly built ships.
MEPC65	2013	Continued to discuss the implementation of EEDI and SEEMP, and discussed issues related to new energy technologies and carbon reduction measures, and refined the scope of the updated study on greenhouse gas emissions from international shipping.
MEPC66	2014	The implementation of EEDI and SEEMP was further promoted, and new energy technologies and greener ship designs were discussed.
MEPC67	2014	Discussed rules for GHG data collection and reporting from ships.
MEPC68	2015	Discussed issues related to oil quality standards for ships to reduce Sulphur oxide (SOx) emissions.
MEPC69	2016	Discussed the development of a global GHG strategy for ships and the adoption of cleaner technologies and fuels to reduce carbon emissions.
MEPC70	2016	Adopted the International Ship GHG Strategy, which sets targets for reducing GHG emissions from the global shipping industry and identifies a range of measures, including technological innovation, data collection, and the promotion of alternative fuels, and proposed measures and timetables for progressive emission reductions.
MEPC71	2017	Continued to discuss the details of the implementation of the International Ship GHG Strategy, including the conduction of technology assessments, the collection and assessment of carbon emissions data, and the development and promotion of technologies.
MEPC72	2018	Adopted the IMO Initial Strategy for Greenhouse Gas Emission Reductions from Ships, which sets a target to reduce greenhouse gas emissions from global shipping to half of 2008 levels by 2050 and requires ships to report fuel oil bitumen quality data.

Table 1. *Cont.*

Meetings	Time	Related Content
MEPC73	2018	Continued to promote the IMO GHG Strategy, which sets reduction targets and calls for the development of specific measures, and discussed issues related to bunker oil bitumen quality standards for ships.
MEPC74	2019	Adopted the fourth GHG study report and discussed issued such as fuel bitumen quality standards, revisions to the Ship Energy Efficiency Design Index (SEDI), and guidance for existing ship management energy efficiency programs.
MEPC75	2020	Discussed various technological and policy options to address GHG emissions, and research and development of zero-carbon fuels such as hydrogen and ammonia were encouraged. As a result of COVID-19, the implementation date for regulations on fuel bitumen quality was postponed.
MEPC76	2021	Adopted a revision of the IMO Greenhouse Gas Strategy, setting a reduction target of halving carbon emissions from the global shipping industry by 2030 compared to 2008 levels, and discussed a range of measures to promote carbon emission reductions, such as the use of alternative fuels, improvements in ship design and sailing efficiency, and carbon pricing.
MEPC79	2022	Adopted the “Invitation to Member States to promote voluntary cooperation in the port and shipping sectors to contribute to the reduction of greenhouse gas emissions from ships” and “The encouragement to Member States to develop and submit voluntary national action plans to address greenhouse gas emissions from ships”.
MEPC80	2023	Adopted the IMO Strategy for the Reduction of Greenhouse Gas (GHG) Emissions from Ships to 2023, which proposes to achieve peak GHG emissions from shipping as soon as possible and net zero emissions by 2050.

Table 2. EU Policies related to green shipping.

Time	Policy	Main content
2011	Transportation White Paper	By 2050, carbon emissions from shipping should be reduced by 40% to 50% compared to 2008 levels.
2013	MRV (Monitoring, Reporting and Verification of Greenhouse Gas Emissions from Ships) Regulation	Ships were required to monitor and calculate fuel consumption, carbon dioxide emissions, and related information during their own operations, and have the data submitted, verified by a third party, and reported within a specified timeframe.
2014	European Marine Fuel Infrastructure Directive	EU member states were required to develop infrastructure for alternative fuels, such as liquefied natural gas and electricity, to promote the use of cleaner fuels in shipping.
2015	EU MRV Regulations	Required ship operators to monitor, report, and verify the greenhouse gas emissions of their ships to improve transparency in the shipping industry and provide data to support carbon reduction targets.
2019	European Green Deal	Shipping was included into the EU Emissions Trading Scheme (EU ETS), and it was proposed to promote the development and use of zero-carbon fuels, improve energy efficiency, reduce carbon emissions from ports and shipping, and stimulate innovation in green shipping technologies.

Table 2. Cont.

Time	Policy	Main content
2021	The “Fit for 55” reform program	It aims to fully integrate shipping into the existing carbon market by 2026 and ensure that EU greenhouse gas emissions are reduced by at least 55% by 2030 compared to 1990 levels.
	EU Emissions Trading Scheme (EU ETS)	For ships of 5000 gross tons and above, ships operating exclusively within the EU will pay for all their CO ₂ emissions, while ships entering and leaving the EU will pay for 50% of their CO ₂ emissions.
	Fuel Alliance Maritime Initiative	From 2025, the EU will impose increasingly stringent limits on the greenhouse gas intensity of marine fuel use and set specific greenhouse gas reduction targets.
	Renewable Energy Directive	A target of 40% renewable energy by 2030 was set to promote renewable fuels.

1.2. Carbon Reduction Technologies and Evaluation Methods

Effective ship emission and carbon reduction measures can be categorized into three groups: technical measures (including the use of alternative fuels), operational measures, and market-based mitigation measures, as shown in Figure 1 [8–10].

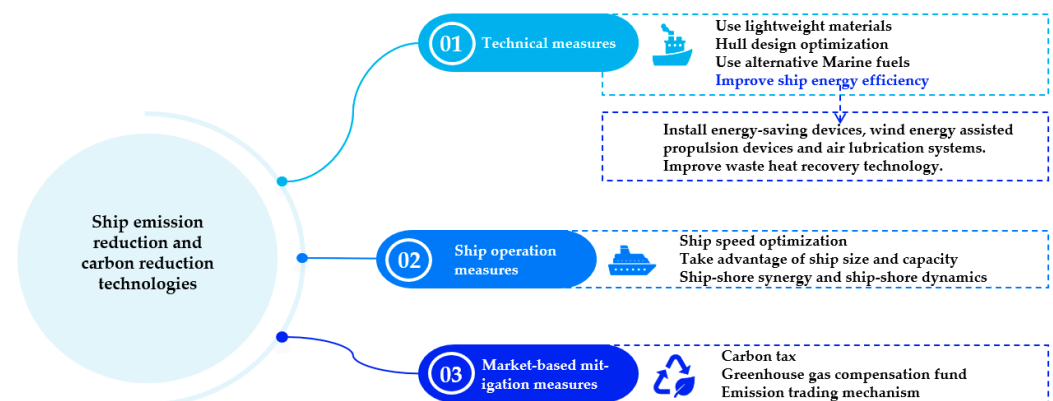


Figure 1. Ship emission reduction and carbon reduction measures.

Technical measures to reduce carbon emission of ships mainly include the use of lightweight materials, hull design optimization, the use of alternative fuels, and various energy efficiency improvement techniques (such as installing energy-saving devices, wind energy assisted propulsion devices and air lubrication systems, and improving waste heat recovery technology, etc.). According to the global ship energy efficiency management regulations, ships built since 1 January 2013 must comply with EEDI of the MARPOL convention, which requires the ship CO₂ emission reduction to reach 10% in 2015–2020, 20% in 2020–2025, and 30% by 2025–2030. Without considering the mutual influence of various technical carbon reduction measures, researchers estimated the CO₂ reduction potential of several major technical measures, of which the use of lightweight materials can reach about 0–10%, ship line optimization about 10–15%, propulsion improvement devices about 1–25%, hull peripheral flow field optimization (addition of bulbous-nose ship) about 2–7%, air lubrication and hull surface drag reduction about 2–9%, and waste heat recovery from exhaust gases about 0–4% [11–13]. Furthermore, the energy saving potential of different technical measures is affected by the weather, ship operating conditions, ship type, and engine operating conditions.

The main operational measures include ship speed optimization, ship size and capacity utilization, ship-shore synergy and ship-shore power. Without considering the mutual influence of various operational measures, researchers estimated the CO₂ reduction potentials of several major measures, among which optimizing ship speed can reach about 0–60%, improving ship size and capacity utilization about 0–30%, ship-shore synergy about 0–1%, and on-shore power facilities about 0–3% [14–16]. Therefore, CO₂ emissions from ships can be reduced through speed reduction, larger ships, optimized ship-to-shore synergies, and onshore power supply. Market-based mitigation measures include the establishment of greenhouse gas compensation funds, the provision of carbon taxes, and the establishment of emissions trading mechanisms. The measures themselves cannot reduce greenhouse gas emissions, but they have played a certain role in promoting the market's enthusiasm for reducing emissions.

As can be seen from above, the market-based mitigation and operational measures possess limited potential in ship carbon reduction. In the report “Catalyzing the Fourth Power Revolution”, the International Chamber of Shipping (ICS) introduced low-carbon and zero-carbon alternative fuel technologies, including hydrogen, ammonia, batteries, and others [17]. The report emphasized that the fourth power revolution is a crucial step in decarbonizing ships and that the rise of alternative fuels for ships is an inevitable trend for the shipping industry to achieve green development. At present, alternative fuels for maritime applications encompass liquefied natural gas (LNG), methanol, biofuels, hydrogen fuel, and ammonia fuel. In comparison to traditional fossil fuels, LNG has a greater abundance of reserves, a lower cost and a cleaner combustion process [18]. The technology associated with methanol fuel is relatively mature, and the combustion products are cleaner and more renewable [19]. Biodiesel has low volatility and high low-temperature start-up performance and safety [20]. Hydrogen fuel does not produce greenhouse gas emissions, and the hydrogen fuel cells are more efficient than the traditional diesel engine [21]. A substantial body of research has demonstrated that alternative fuel technologies can effectively mitigate CO₂ emissions of ships. In the context of long-term carbon reduction strategies for green and low-carbon shipping, it is of paramount importance to develop and utilize low-carbon or even zero-carbon alternative fuels for maritime transportation.

The mechanisms of action and efficacy of disparate ship carbon reduction technologies vary considerably. In order to ascertain the extent of carbon reduction achieved by different technologies or measures, it is essential to first establish the carbon footprint of ships and then evaluate the level of carbon emissions using appropriate methods. Carbon emission evaluation methods mainly include direct measurement method, database method, and life cycle assessment (LCA) evaluation method [22]. The direct measurement method is the most accurate, but it requires researchers to invest a lot of time and energy and is more suitable for measuring a certain product or a specific activity. The database method is less laborious than the direct measurement method, but it needs to rely on the existing database of carbon emission factors and combine with the different levels of activity. The LCA method can trace back the source of a product and measure the carbon emissions generated by the whole life process of production, application, and disposal. This approach is more appropriate for the quantification and comparison of the carbon footprints of different technologies and measures. It is regarded as the most effective approach for assessing and analyzing carbon reduction in shipping [23–27].

1.3. Contents and Features of This Article

Shipping carries more than 80% of the total global transportation volume, but its carbon emissions only account for 6.1% of the total emissions of the transportation industry [28]. Therefore, under the general trend of energy conservation and emission reduction,

shipping will surely play a more important role in the field of transportation. The core competition in the shipping industry has gradually shifted from cost, service, and safety to the ability to reduce carbon emissions. In the medium to long term, the use of low-carbon/zero-carbon alternative fuels is the most effective way to realize carbon emission reduction in shipping. However, it is important to note that, while the use of alternative fuels in ship propulsion can significantly reduce emissions, upstream emissions generated during the fuel production process still need to be accounted for. To determine whether alternative fuels for ships can create better environmental benefits over the full life cycle process, there is an urgent need for a more comprehensive scientific analysis.

By using the LCA method, it is possible to fully understand the potential environmental consequences and resource use associated with different marine alternative fuels from cradle to grave (including raw material development, fuel production, transportation, application, disposal, and recycling). This enables a comprehensive understanding of their environmental footprints to be gained, the potential areas of improvement to be highlighted, and a valuable tool to be provided for use by policy makers, shipping companies, and consumers for the purpose of comparing and assessing the environmental performance of different marine alternative fuels. The application of this methodology can serve to advance the sustainability of low-carbon green shipping.

In summary, this paper firstly discusses and summarizes the features of various alternative ship fuels (i.e., LNG, hydrogen, methanol, ammonia, and biofuel) from the aspects of production, storage, transportation, and ship application. Then, the LCA method is introduced thoroughly, including relevant standards, implementation steps, database software, and the basic framework used for the evaluation of carbon emissions from ships. On this basis, a literature review of the current research on LCA of alternative ship fuels is conducted from the perspectives of environmental impact and economy. Finally, this paper discusses the main problems in the current LCA studies of alternative ship fuels and puts forward the prospects for the future LCA development of alternative marine fuels.

2. Alternative Fuels for Ships

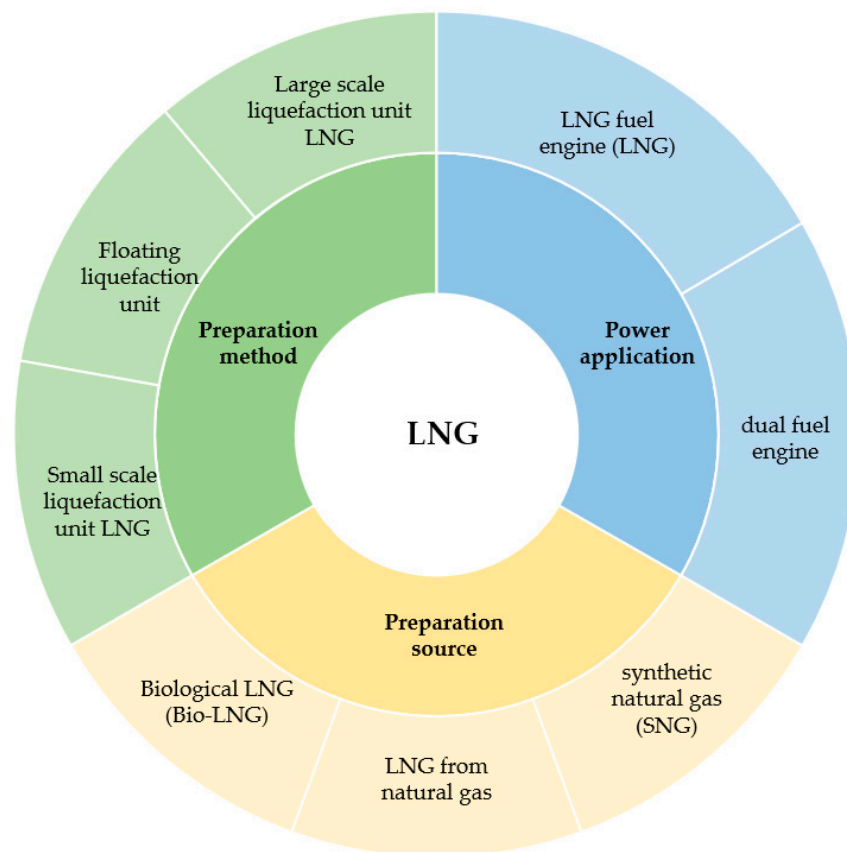
In recent years, with the development of green shipping, how to reduce carbon emissions from ships has received unprecedented attention from the shipping industry. IMO has advocated the research and development of alternative fuels in its initial strategy for reducing greenhouse gas emissions from ships, and more and more countries and organizations are planning to replace traditional fossil fuels with low-carbon and zero-carbon fuels to solve the current energy and environmental problems. At present, the alternative fuels available for maritime applications are primarily liquefied natural gas (LNG), methanol, ammonia, hydrogen, and biofuels. The principal property parameters and performance indexes for these fuels are presented in Table 3. Notably, e-fuel is a kind of green synthetic fuel prepared based on sustainable energy and various energy conversion processes, including e-methanol, e-hydrogen, e-ammonia, etc. For example, e-methanol is synthesized by carbon dioxide and the hydrogen produced by renewable energy electrolysis of water, in which the carbon dioxide is derived primarily from carbon capture and storage projects. In theory, e-fuel can be seen as a photovoltaic enrichment product, and the production process is also known as Power-to-X, which can achieve net zero carbon emissions in principle. However, e-fuels are still in the early stage of development, and there are few case studies concerning the lifecycle carbon emission of e-fuels. This review will not introduce them separately, but include them in the corresponding fuel types. In this part, an overview of the production, storage, and transportation processes, as well as ship power applications of various alternative fuels are presented.

Table 3. Property parameters and indicators of marine alternative fuels.

	LNG	Hydrogen	Methanol	Ammonia	Biodiesel	Bioethanol	MGO
Boiling temperature at 0.1 MPa (°C)	−161	−252.87	65	−33.34	100–350	100–350	175–650
Density (kg/m ³)	450	70.85	796	682	800–950	800–950	<900
Energy Density (MJ/L)	23.4	8.5	15.8	12.7	35–37	20–25	35.9
Dynamic Viscosity at 40 °C (cSt)	-	0.07	0.6	-	2–10	2–10	3.5
Net Calorific Value (MJ/kg)	50	120.0	19.9	18.6	37.8	20–25	43
Storage Temperature (°C)	−162	−253	20	−34/20	-	-	20
TCC (°C)	−175	−253	12	-	50	12	>60
Auto ignition temperature (°C)	540	-	464	651	-	-	250–500
Flammability Limit	5–15	4–75	6–36	15–28	-	-	0.3–10
SFC (g/kWh)	171.58	57	327.2	547.6	187	187	-

2.1. LNG

LNG is primarily composed of methane, with minor constituents of light hydrocarbon gases such as ethane, propane, and butane. Marine LNG fuels can be categorized according to different sources, preparation methods, and power applications, as shown in Figure 2.

**Figure 2.** Classification diagram of marine LNG fuel.

LNG can be categorized into fossil LNG, biological LNG, and synthetic LNG according to their source. At present, large-scale marine LNG fuel is fossil LNG, and its production process mainly includes natural gas extraction, pre-treatment, compression, cooling, and separation, as shown in Figure 3 [29–32]. Bio-LNG is produced by anaerobic fermentation and purification of various types of organic waste, such as agricultural and forestry residues, and it has the advantages of being green and renewable. Synthetic LNG, also known as e-LNG, is manufactured through a renewable power-to-gas process. In the medium to long term, fossil LNG will be unable to meet the requirements for deep decarbonization of

shipping. Therefore, there is a growing interest in biological LNG and e-LNG. LNG fuel can be transported to ports or terminals in several ways, including LNG carriers, tanker trucks, rail tanks, and pipeline delivery. Given that LNG is an extremely low-temperature and flammable liquid, ensuring the safety of the marine LNG filling and storage system is of paramount importance. Marine LNG is typically stored in double-walled adiabatic LNG storage tanks to maintain its low temperature [33–36]. The primary forms of LNG ship power include steam turbine power, single LNG-fueled engines, and dual-fueled engines. LNG carriers commonly utilize a single LNG fuel as the primary energy source, whereas most other merchant ships employ dual-fueled engines. By the conclusion of 2023, 1070 of the total 1760 alternative-fueled vessels in existence worldwide were powered by LNG, with approximately 550 of these being LNG-fueled LNG carriers. Moreover, 273 ports worldwide have already been equipped with LNG bunkering facilities [37].

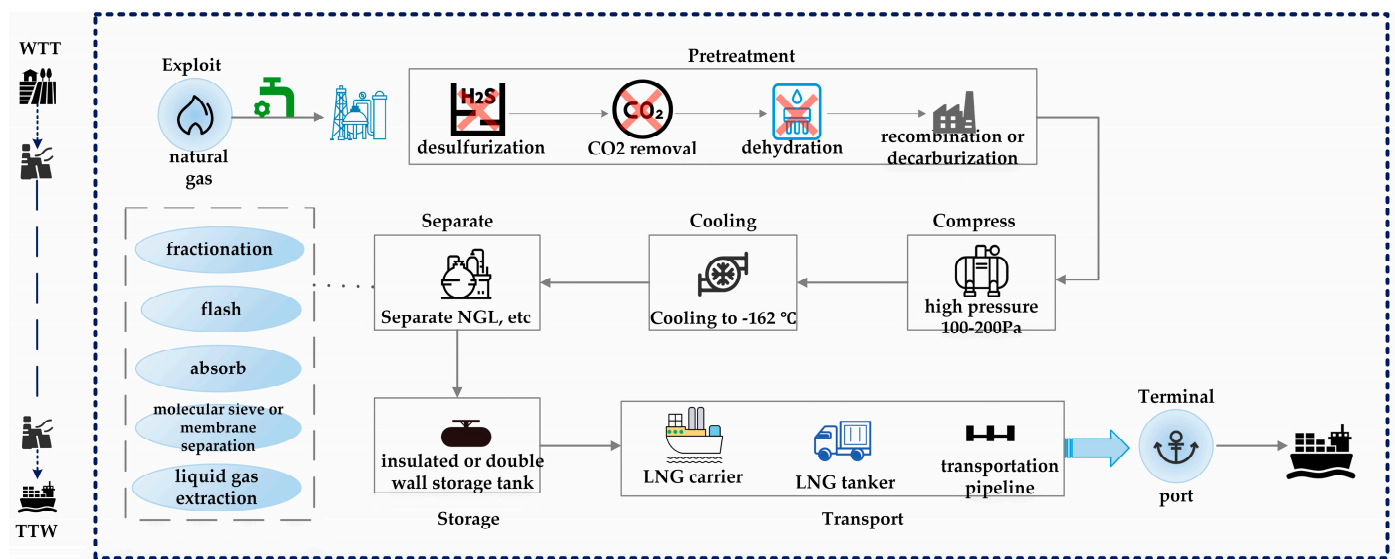


Figure 3. Production, storage and transportation flow chart of marine LNG fuel.

In general, marine LNG possesses the following advantages. The combustion of LNG produces lower CO_2 , NO_x , and particulate emissions than conventional marine fuels, and it does not produce SO_x emissions, thereby addressing climate issues. LNG's high energy density makes it suitable for long voyages and reduces the number of refuelings. In comparison to petroleum products such as diesel, LNG is less volatile, and natural gas resources are widely distributed, which makes it relatively easy to supply. Furthermore, LNG power technology is mature and highly compatible, which allow it to be used on different ships and in conjunction with conventional fuel powertrains. While marine LNG fueling offers numerous advantages, it also presents certain challenges, including the construction of LNG supply chain and the investment in storage and refueling facilities. Furthermore, particular attention regarding the issue of methane escape is required, given the strong thermal effect of methane. This is evidenced by its 100-year and 20-year global warming potential (GWP), which is approximately 28 and 82 times that of carbon dioxide, respectively [38]. Currently, due to the high technical maturity, stable fuel supply, and reasonable market price of marine LNG, it is considered the best transitional energy source for shipping.

2.2. Hydrogen

Hydrogen can be utilized as a marine fuel in gaseous or liquid form, with the property parameters contingent upon its physical state. Marine hydrogen fuels can also be cate-

gorized according to their source, preparation methods, and ship power applications, as shown in Figure 4 [39].

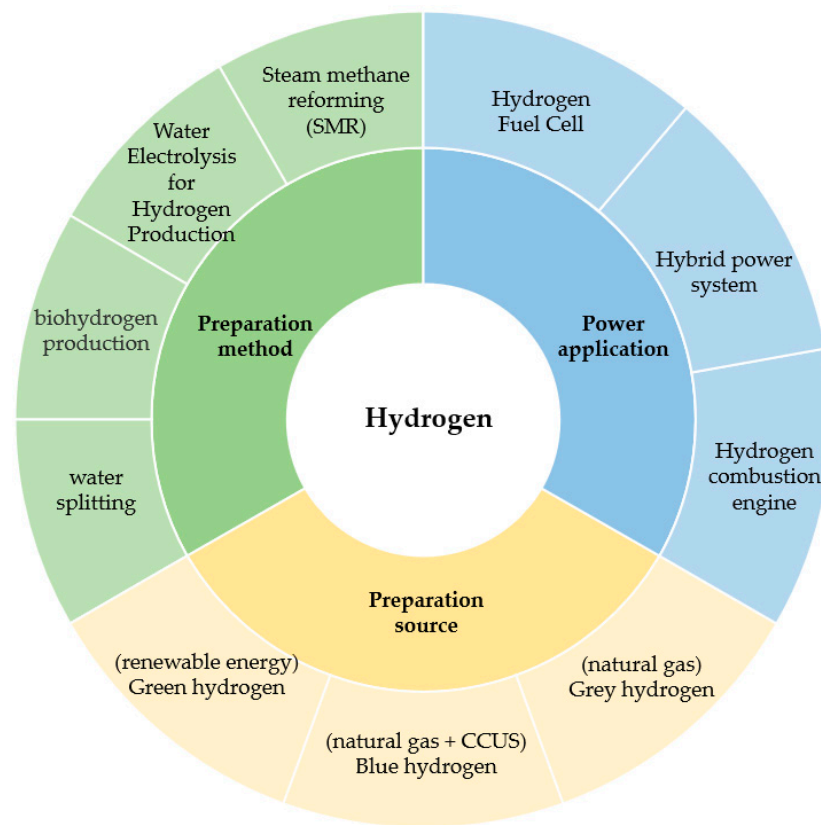


Figure 4. Classification diagram of marine hydrogen fuel.

The production of marine hydrogen fuel employs a variety of techniques, including steam methane reforming (SMR), electrolysis of water, biological hydrogen production, photolysis of water, and pyrolysis of water. SMR is currently the most common method of hydrogen production [40–42]. The process uses methane (natural gas) and water vapor as feedstock, and produces hydrogen and some carbon dioxide through a high-temperature reaction. In order to reduce CO₂ emissions, gray hydrogen can be converted to blue hydrogen through the use of carbon capture storage (CCS) technology. However, the deployment of CCS technology entails not only increased capital expenditures but also the necessity of additional equipment for carbon dioxide storage, which in turn gives rise to elevated production costs [43–45]. Biological hydrogen production, photolysis of water, and thermal water splitting are regarded as green and sustainable methods of hydrogen production, but they have not been widely used due to the high requirements on resources, technology, and equipment [46–52]. In the context of global carbon reduction, the traditional gray and blue hydrogen production methods are gradually being supplanted by green hydrogen production methods based on renewable energy (RSE).

The transportation of hydrogen to ports is facilitated by high-pressure gas pipelines, high-pressure gas-hydrogen long-tube trailers, or low-temperature liquid hydrogen tankers. Hydrogen refueling stations or exchange tanks are utilized to ensure a continuous supply of hydrogen for hydrogen-powered ships. Most existing hydrogen-powered ships utilize high-pressure gaseous hydrogen storage. With the objective of enhancing energy storage density, there is a growing interest in liquid hydrogen storage and solid hydrogen storage [53–56]. For example, the design schemes of “Topeka” ro-ro ship and “AQUA” yacht claim to adopt low-temperature liquid hydrogen storage [57]. Hydrogen ships can be powered

by fuel cells, hydrogen combustion engines, or hybrids. At present, most hydrogen-powered demonstration ships, such as the Water-Go-Round ferry in the United States and the Three Gorges Hydrogen Boat No. 1 in China, use fuel cell power systems [58,59]. The process of marine hydrogen fuel production, storage, and transportation is shown in Figure 5. Due to the enhanced power output and reduced cost associated with the hydrogen internal combustion engine, it possesses a considerable potential for integration in maritime applications.

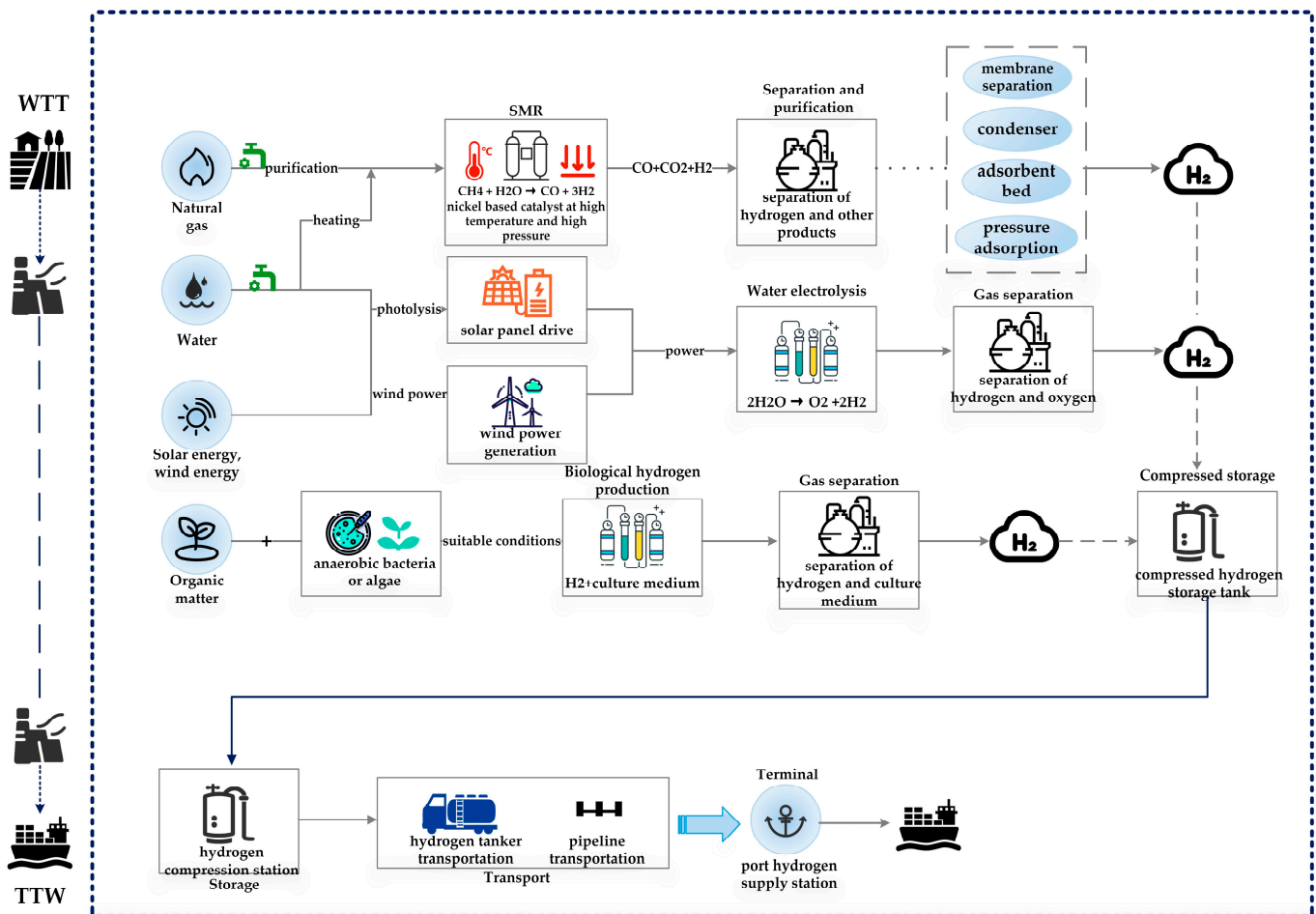


Figure 5. Production, storage, and transportation flow chart of marine hydrogen fuel.

There are many advantages of marine hydrogen fuel [57,59,60]. The primary product of hydrogen power is water vapor, which does not contain carbon dioxide or other harmful gases and particles, and contributes to the carbon emission reduction of shipping. In comparison with battery charging, the speed of hydrogen refueling is faster, which enhances the operational efficiency of the ship. Hydrogen fuel cell is capable of directly converting the chemical energy of the fuel into electricity, which is distinguished by high energy conversion efficiency, low noise, and a reduced reliance on auxiliary equipment. Additionally, it is more flexible and can be utilized in a range of ship types and power systems. However, marine hydrogen fuel is still confronted with many challenges, such as low technology maturity (i.e., high-power fuel cell technology, marine hydrogen internal combustion engine technology, high energy density hydrogen storage technology), low power rating of hydrogen fuel cells, lack of safety regulations and emergency measures, and insufficient supporting infrastructure [58,59,61]. Nevertheless, marine hydrogen fuel is still considered

a potential clean energy source that can reduce the environmental impact of ship operations and promote sustainable maritime transportation in the future.

2.3. Methanol

The methodology employed in the production and utilization of marine methanol fuel is illustrated in Figure 6.

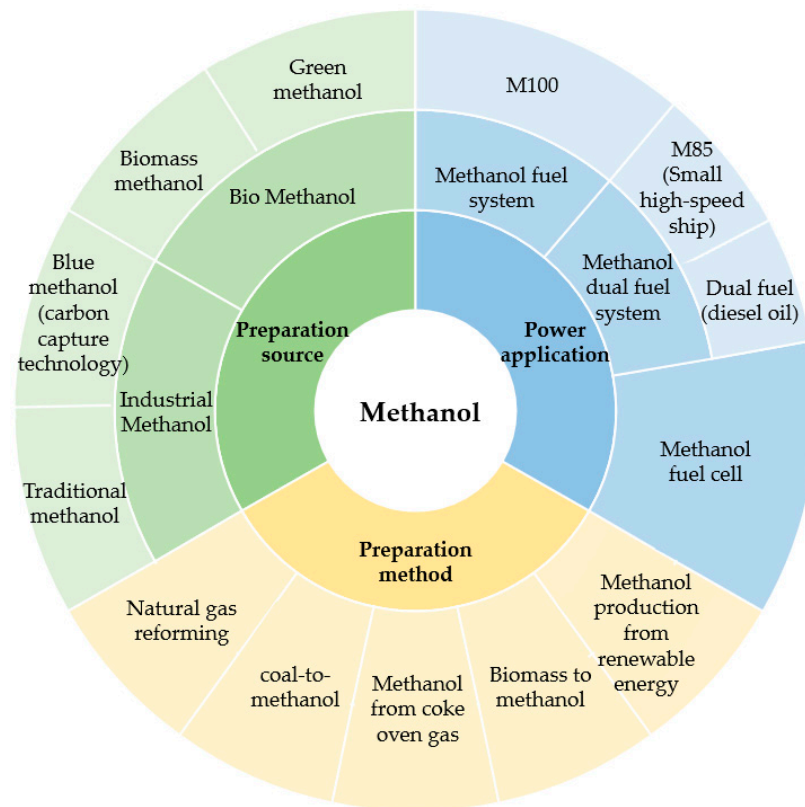


Figure 6. Classification diagram of marine methanol fuel.

Depending on the production method, marine methanol fuels are usually grouped into industrial synthetic methanol and green methanol. The most common production method for industrial methanol is the reforming reaction using natural gas as feedstock [19]. However, according to the specific resource distribution characteristic, 78% of methanol in China is produced through the coal-to-methanol process [62]. Blue methanol method refers to the process of using CCS in the production of traditional industrial methanol to reduce CO₂ footprint [63]. Green methanol fuel mainly includes two types, namely biomass methanol and e-methanol. Biomass methanol is produced from biomass derived from agricultural and wood waste, as well as municipal waste [64]. E-methanol is synthesized by carbon dioxide and the hydrogen produced by renewable energy electrolysis of water, in which the carbon dioxide is derived primarily from carbon capture and storage projects. It seems probable that the use of green methanol will continue to grow in the future, as environmental regulations become more stringent and the demand for sustainable energy resources increases.

The mode of methanol fuel delivery is typically contingent upon several factors, including the location of the supply base, the scale of production, the volume of demand, and the distance of transportation. The specific mode of delivery may also be influenced by the type of container used, with options including liquid containers, tanker trucks (for short-distance or urban deliveries), pipelines (for long-distance transportation), tankers (for long-distance international transportation), and so on [65]. Methanol fuel can be loaded

onto ships in two ways [66–68]: by shore-based bunkering or ship-to-ship refueling. Given its corrosive nature, the storage of marine methanol fuel is typically conducted using specialized storage systems, as can be seen in Figure 7. The power forms of methanol fuel are typically classified into three main categories: dual-fuel engines, single-fuel engines, and methanol fuel cells. Dual-fuel engines represent the predominant type [66,67]. Compared with other alternative fuels, methanol-fueled ship propulsion technology has basically matured. According to Clarkson data, as of the end of March 2024, there were 31 methanol-powered ships operating worldwide [69].

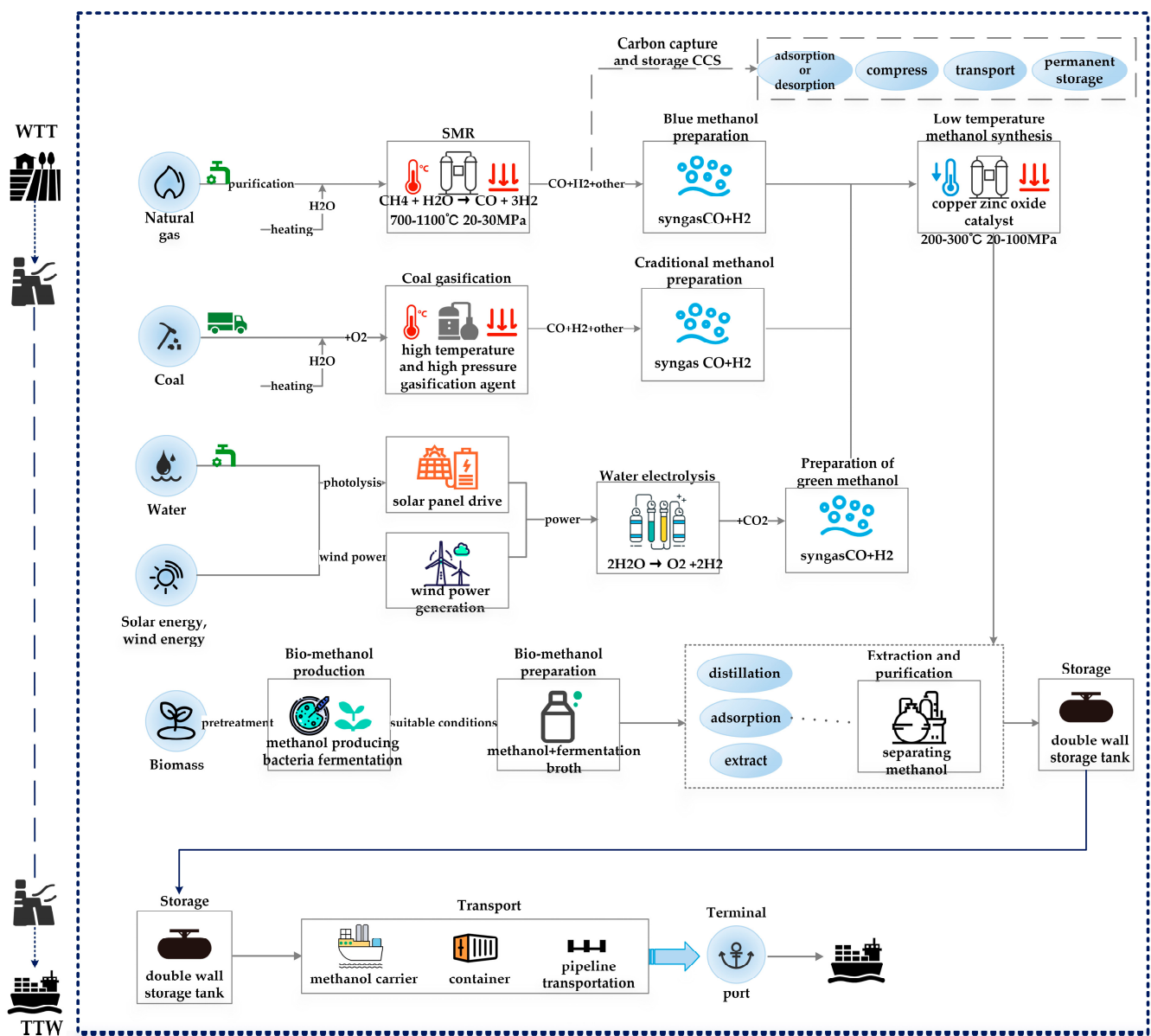


Figure 7. Production, storage, and transportation flow chart of marine methanol fuel.

Marine methanol fuel is a highly potential competitor in the green development of shipping. The combustion of methanol produces virtually no sulfur oxides or particulate emissions, as well as low carbon and nitrogen oxide emissions, which makes it a good clean energy source. As a liquid fuel, methanol has a higher energy density, which helps to reduce the need for fuel storage space. Compared to hydrogen fuel, methanol is liquid at room temperature and does not require extremely low temperatures or high pressures, so it is easier to store and handle. In addition, methanol fuel has relatively low toxicity and

flammability, which greatly improves the storage life on board. Furthermore, methanol fuel-based dual-fuel power technology has reached a relatively advanced stage of development, offering ships a high degree of flexibility and adaptability. With the increasing demand for cleaner shipping, marine methanol is gaining more attention and research as a sustainable marine fuel option. However, most methanol fuels are currently produced using natural gas, and the global green methanol preparation and supply system needs to be improved to meet the operational needs of methanol-fueled ships.

2.4. Ammonia

The preparation method and power form of marine ammonia fuel are shown in Figure 8.

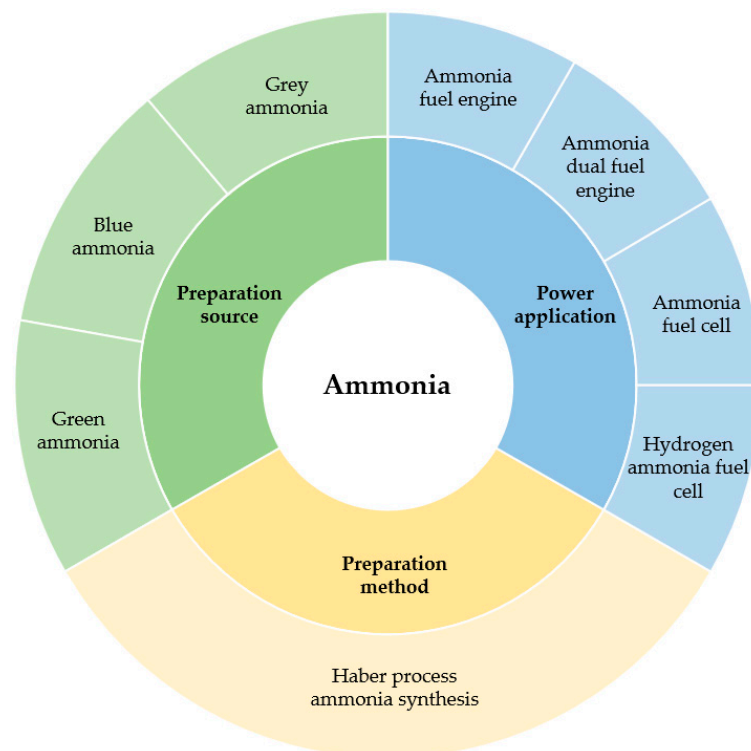


Figure 8. Classification diagram of marine ammonia fuel.

The majority of marine ammonia fuels are synthesized via the Haber–Bosch (HB) process, in which the hydrogen (H_2) and nitrogen (N_2) react on the surface of an iron-based catalyst at pressures between 10 to 25 MPa and temperatures between 350 °C to 550 °C [70]. According to the source of hydrogen, ammonia fuel can be classified into three categories: gray ammonia, blue ammonia, and green ammonia. In the conventional HB process, the hydrogen is derived primarily from SMR technology and water electrolysis, while the nitrogen is supplied by an air separation unit. The enhanced HB process employs renewable energy resources, including wind, solar, and tidal power, to generate electricity for water electrolysis to provide hydrogen as the feedstock gas. The resulting ammonia is designated as green ammonia. It is noteworthy that the enhanced HB process does not result in the emission of CO_2 , and it employs commercially available electrolyzers with size ranging from kilowatts to megawatts [71–73].

Since the liquefaction conditions of ammonia are relatively simple (1 bar, 240 K or 8.6 bar, 293 K), marine ammonia fuel is generally stored and transported through liquefaction tanks, as shown in Figure 9 [74]. Marine ammonia fuel power technology is comprised of two primary categories: the ammonia–diesel dual-fuel main engine and the

ammonia fuel cell [75,76]. At present, two prominent ship engine manufacturers, MAN and WinGD, are actively engaged in the advancement of research and development, as well as the implementation of ammonia-fueled engines. However, there are still significant technical challenges to be addressed, including the presence of unburned ammonia, high nitrous oxide (N₂O) emissions, and limited thermal efficiency, which are inherent to the combustion characteristics of ammonia fuel. Ammonia fuel cell has the advantages of high thermal efficiency, low noise, and low air pollutant emission, etc. Ammonia fuel cells can be classified into two categories: ammonia fuel cells and hydrogen-ammonia fuel cells, depending on the method of ammonia fuel supply [77,78]. Among these, solid oxide fuel cells are regarded as having considerable potential for maritime applications, largely due to their high fuel flexibility. At present, more than 200 vessels powered by ammonia are under construction globally. The ABS white paper on ammonia fuels anticipates that ammonia will represent more than 30% of marine fuel use by 2050 [79].

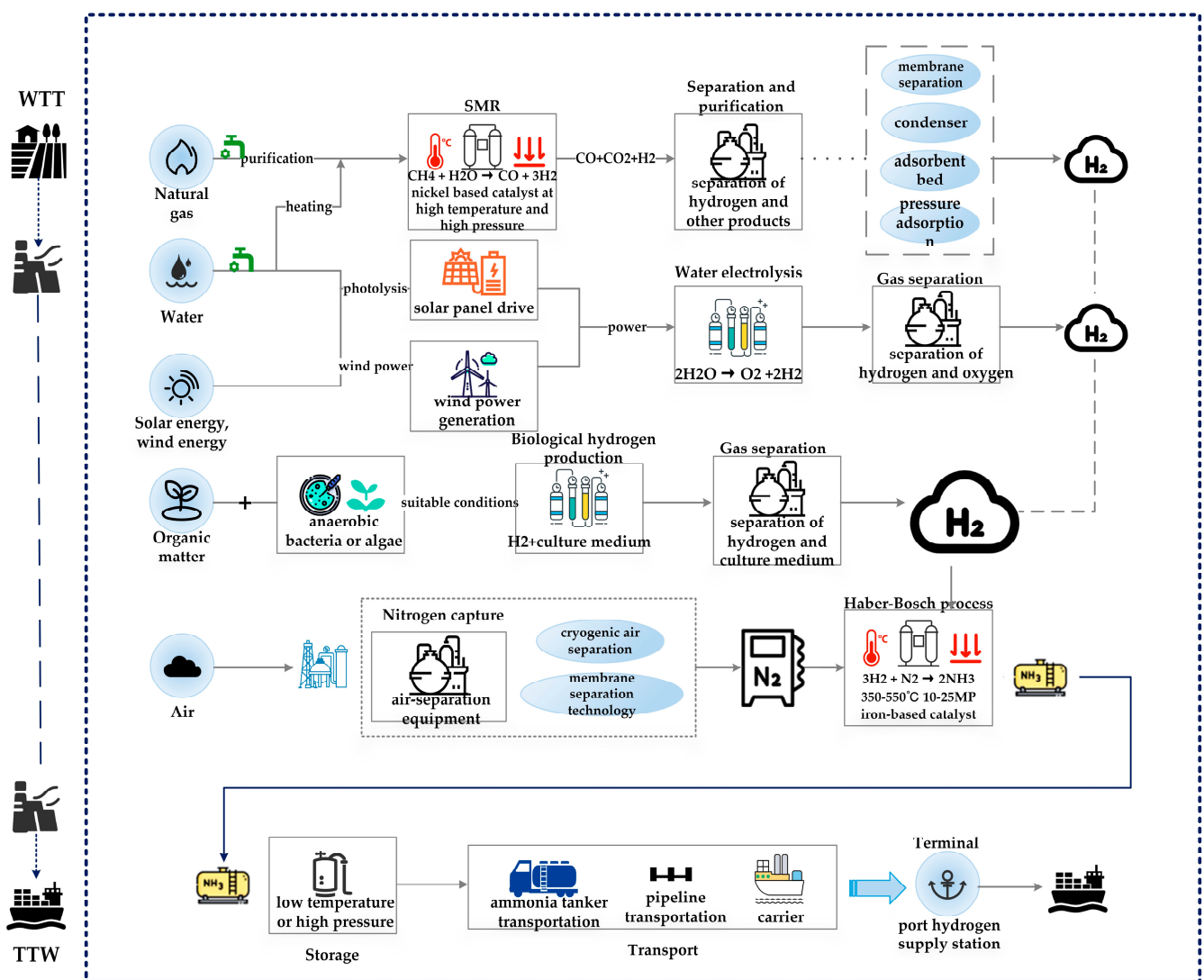


Figure 9. Production, storage, and transportation flow chart of marine ammonia fuel.

In general, ammonia fuel offers several advantages for green shipping [80–83]. The ease of liquefaction, high energy density, and high hydrogen content of liquid ammonia make it an ideal energy carrier for storage and power applications. Additionally, ammonia has a long history of industrial use, with well-developed production, transportation, and trading markets, which provides a foundation for its application in ships. The carbon-

generate hydrogen as a fuel source. It is noteworthy that biofuel can be used directly in the ship's primary engine and boiler without modifications to the existing engine and other power equipment. This alternative fuel for ocean-going vessels is regarded as the most "technologically ready" and is consequently designated as a "drop-in" green fuel. Although some scholars believe that the direct use of traditional fuel engines is prone to problems such as clogging of the fuel system, corrosion, or performance degradation because the chemical and combustion characteristics of biofuels are different from those of traditional fossil fuels, the use of biofuel oils is still an attractive option for ships that can only use traditional fuels or have the option to do so [93–95].

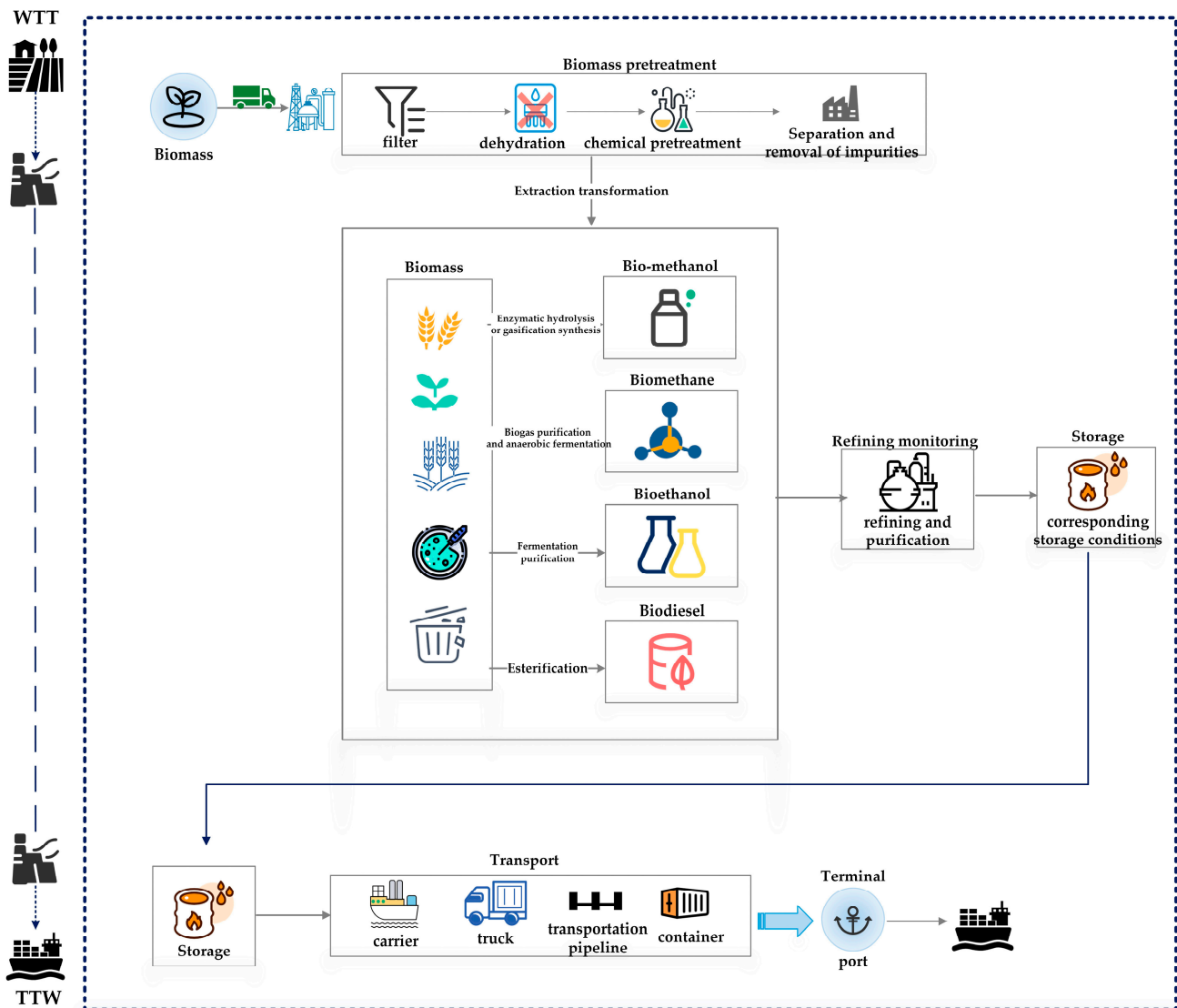


Figure 11. Production, storage, and transportation flow chart of marine biofuels.

The utilization of biofuels as energy carriers for maritime applications is expected to offer several advantages [94,96]. The source of marine biofuels is relatively sufficient and can be continuously regenerated, which effectively reduces the dependence on fossil fuels. Additionally, the low-nitrogen and low-sulfur characteristics of biofuels result in lower emissions of nitrogen oxides (NO_x) and sulfur oxides (SO_x), making them more environmentally friendly than traditional fossil fuels. Biofuels produced from biological waste derived from agriculture and forestry departments can achieve significant carbon reduction rates and play an important role in achieving carbon reduction and decarboniza-

tion goals. In the medium to long term, biodiesel may become an ideal fuel for ocean-going vessels. However, the production and application of biofuels still faces several challenges, the main factors of which are fuel availability and investment costs. If large-scale commercialization of biofuels is to be achieved, it is necessary to establish a solid biofuel supply system by using waste and low-quality feedstocks, enhancing process design, and adopting an integrated strategy to promote the widespread use of biofuels in the shipping industry [92,97,98]. Furthermore, in order to achieve zero-emission shipping, it is essential to develop biofuel-adapted engines that can accommodate changes in the energy supply structure.

3. LCA Method and Framework for Marine Fuel

3.1. LCA Development and Introduction

Life cycle assessment, as an effective evaluation method, can analyze the resource and environmental problems caused by human production and consumption activities in order to improve the product or technology [99]. The life cycle mentioned in the LCA method refers to the whole process of product production and consumption activities: i.e., starting from the extraction of various resources required, the whole process of obtaining complete products after processing various intermediate raw materials and energy, and then putting them into use and finally disposing of them. Conceptually, LCA is a quantitative analysis method that can analyze and assess the potential resource and environmental impacts of various products and technologies in the whole life cycle process, thus providing methodological and data support for the continuous improvement of the products and technologies.

In 1990, the International Society of Environmental Toxicology and Chemistry (ISETAC) formally proposed the concept of LCA at the SETAC conference [100]. Subsequently, SETAC issued the inaugural methodological guide to Life Cycle Theory in 1993, which defined the fundamental framework and methodology for LCA assessment [100,101]. With the promotion of ISETAC, the LCA theory has developed rapidly, which has led to the formulation of the ISO14000 series of standards by the International Organization for Standardization (ISO) [95,102–105]. As depicted in Figure 12, the LCA framework is divided into four parts, which are goal and scope definition, life cycle inventory analysis, life cycle impact assessment (LCIA), and life cycle interpretation (LCI). LCI has a wide range of applications, including the evaluation of various technical and management improvement measures, as well as the development of policy and market systems [106].

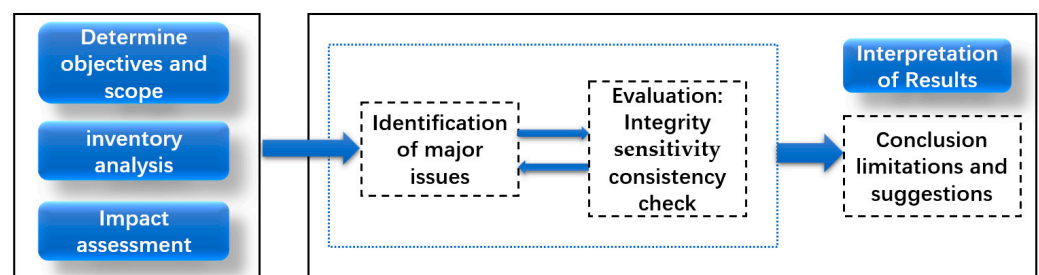


Figure 12. Four elements of LCA method.

Driven by the requirement of carbon emission reduction in shipping, the evaluation of carbon emission in the whole life cycle of the shipping industry has received wide attention. In 2018, the IMO proposed to integrate the development of guidelines for GHG intensity of marine fuels into the initial strategy for GHG emission reduction in shipping [107]. Subsequently, in 2023, the MEPC adopted the Guidelines for Full Life Cycle Greenhouse Gas Intensity of Marine Fuels, which will serve as a reference for evaluating

carbon emissions in the shipping sector [108]. Therefore, it is imperative to conduct life cycle assessment of carbon emission in shipping.

3.2. Life Cycle Assessment Tools

Data collection represents a crucial phase of the life cycle assessment process, which requires significant time and resources. Consequently, the development of an LCA database is a crucial step. Researchers may utilize assessment tools to reasonably and accurately screen various emission factors and address associated uncertainties through scenario analysis. Currently, the most applied LCA assessment tools include Simapro, Boustead, GaBi, TEAM, GREET, ELCD, NREL, Eco-Invent, and CLCD database. Table 4 demonstrates the developers and applicability of some LCA databases and commercial software [109].

Table 4. Summary of LCA assessment tools.

LCA Assessment Tools	Developer	Content and Applicability
NREL	National Renewable Energy Laboratory, USA	Represents the state of the art of U.S. indigenous technology for the technical, economic, and feasibility assessment of renewable energy; provides tool models such as HOMER, SAM, etc.
Ecoinvent	Developed by the Ecoinvent Center, Switzerland	Covers chemical, construction, agriculture, transportation, and energy sectors; applicable to life cycle and other sustainability environmental impact assessment processes.
ELCD	European Union Directorate-General for Research (JRC) in collaboration with European industry associations	Applicable to the EU; covers manufacturing, transportation, waste management, construction, agriculture, and energy production.
GREET	Argonne National Laboratory of the US Department of Energy (DOE)	Software focusing on LCA in the transportation sector (including aviation, road, rail, and maritime) with options for WTT and WTW analysis phases.
CLCD	Sichuan University and Ecoinvent	Supports full LCA analysis and evaluation indicators for energy saving and emission reduction, including Chinese localization parameters.
GaBi	IKP Institute, University of Stuttgart, Germany	Capable of modular presentation and Excel report generation by nesting different scenarios, suitable for in-house product evaluation or improvement design.
SimaPro	Center for Environmental Sciences (CML), Leiden University, The Netherlands	Provides complex product data sets, functional analysis, and custom visualization; applicable to supply chain management, product design, and environmental policy formulation.
TEAM	French Environment and Energy Management Agency (ADEME) and French energy giant EDF Development	Supports sensitivity analysis and includes information on 10 data categories: paper, petrochemicals and plastics, inorganic chemicals, steel, aluminum, other metals, glass, energy conversion, transportation, and waste management.
OpenLCA	GreenDelta Corporation	Open source software with comprehensive databases of Life Cycle Inventory (LCI) and Life Cycle Assessment (LCIA) data; capable of quantifying carbon footprint, water footprint, resource use, and many other environmental impact categories.

Table 4. Cont.

LCA Assessment Tools	Developer	Content and Applicability
Boustead	Boustead Consulting & Associates	Includes data from various countries such as USA, China, Japan, etc.; suitable for LCA analysis in the fields of industrial ecology, environmental engineering, and sustainability, and is widely used in the automotive industry.

3.3. LCA Framework for Marine Fuels

An alternative marine fuel will not qualify as a viable option for shipping if it requires a significant input of resources during production, involves the use of higher-emission equipment in its storage and transportation, or fails to reduce carbon emissions at the source and merely transfers pollutants. It is evident that to ascertain whether a specific marine fuel can be utilized as an alternative green energy source, it is imperative to consider not only economic, technological, and social factors, but also to conduct a full LCA of its emissions. The life cycle of marine fuels can be divided into three stages: Well-to-Tank (WTT), Tank-to-Wake (TTW), and Well-to-Wake (WTW), as shown in Figure 13 [110]. The WTT stage considers the whole processes of transporting marine fuel from collection points such as oil wells and mines to the ship's fuel tanks, refinement, processing, transportation and distribution of raw materials. TTW stage focuses on the process of burning fuel and generating carbon emissions in the actual operation of the ship, including the use of fuel storage on board the ship and the carbon emissions generated by the operation of the ship, which are related to the fuel efficiency, speed, load and other factors of the ship's performance and operation. The WTW phase integrates the entire life cycle of marine fuels. It considers carbon emissions from raw energy capture to ship tailing, and is a more integrated perspective that contributes to a comprehensive understanding of the environmental impacts of marine fuels.

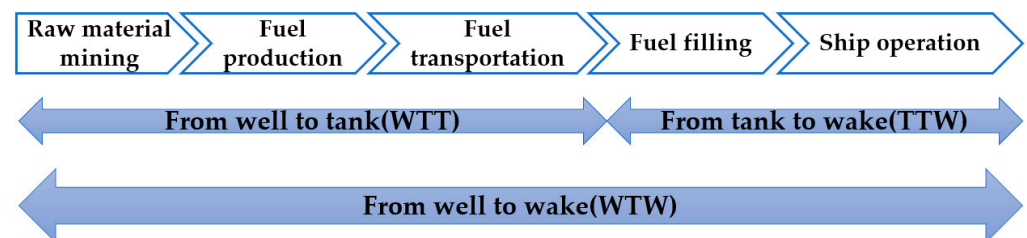


Figure 13. Life cycle processes of marine fuels.

In order to conduct a scientific evaluation of carbon emissions from marine fuels using the LCA methodology, it is necessary to first establish a systematic LCA framework, as shown in Figure 14. This framework must assess the level of carbon emissions over the entire life cycle of the fuel, from the point of collection or production, through transportation, ship application, and finally to disposal.

The first step is the definition of objectives and scope, including ship parameters, fuel type, fuel life chain, and functional units [111]. Worth noting, in the carbon emission evaluation of ship fuels, functional units are usually used to represent a particular capacity or distance of cargo transportation in order to compare the carbon emission performance of different fuel types or different ship transportation systems. The selection of functional units is closely related to the type and function of the ship. Common functional units include cargo transportation capacity per ton-kilometer (comparing the carbon emission of different fuel types for each unit of cargo transportation capacity), distance per ton of cargo (comparing the carbon emission of different ship fuel types at different transportation

distances), energy output per unit (comparing the carbon emission of different fuel types in energy production and use), carbon emission per unit of ship load (comparing the carbon emission of different ship fuel types in energy production and use), unit ship load (comparison of carbon emissions of different ship types or sizes), carbon emissions per voyage (assessment of specific routes or voyages), time per unit of cargo (assessment of emergency cargo transportation), etc.

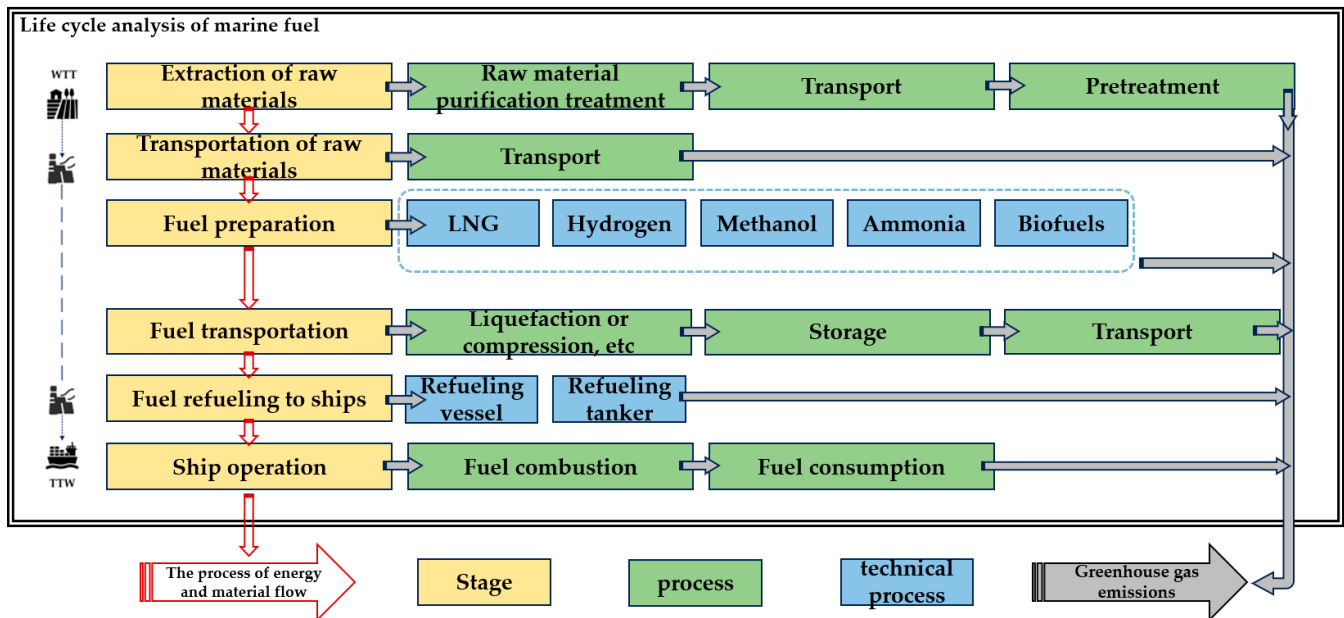


Figure 14. LCA framework of marine alternative fuel.

The next step is the construction of life cycle inventory (LCI), which involves the collection and organization of carbon emission data related to the life cycle of marine fuels. This is achieved through industry databases, producer databases, or literature research [112]. The data collected include information on the raw materials used, the production of fuels, their transportation and distribution, and their use and disposal. The collection of raw materials for marine fuels may include carbon emission data generated during the extraction or cultivation stages of oil, natural gas, biomass, etc. The production process involves refining and processing, and requires the collection of carbon emission data related to energy use and chemical processes. The transportation and distribution require the assessment of carbon emissions generated by the transportation of fuels from the location of production to the location of ship use. The parameters to be considered include the distance of transportation, the type of transportation (pipeline, ship, road), and the carbon emissions resulting from the combustion or conversion of ship fuels to electricity at the point of use, including both direct and indirect emissions. Finally, the treatment and disposal of waste fuels from ships must be considered, including the carbon emissions resulting from the incineration, recycling, and landfilling of waste fuels.

On this basis, life cycle impact assessment (LCIA) can be conducted. An LCA calculation model is established for marine fuels, and LCI data are used to obtain the carbon emissions at each stage. A unified carbon emission unit, such as carbon equivalent, is suggested by using the carbon footprint and other carbon emission indicators [113].

Finally, the relative contribution of each stage of the life cycle to carbon emissions is determined through interpretation and analysis. Based on the findings of the life cycle assessment, recommendations for improvement are proposed with the objective of effectively reducing fuel-related carbon emissions, including the utilization of cleaner fuels, enhance-

ments to the production process, optimization of transportation modes, and improvements to ship efficiency.

4. Case Review

This part systematically compiles the literature related to the LCA analysis of marine alternative fuels, which involves 64 alternative-fueled ships and 12 groups of fleets operating in different countries and waters. Most of the literature can be dated to the years between 2021 and 2024. The distribution of these works by country and ship type are illustrated in Figure 15.

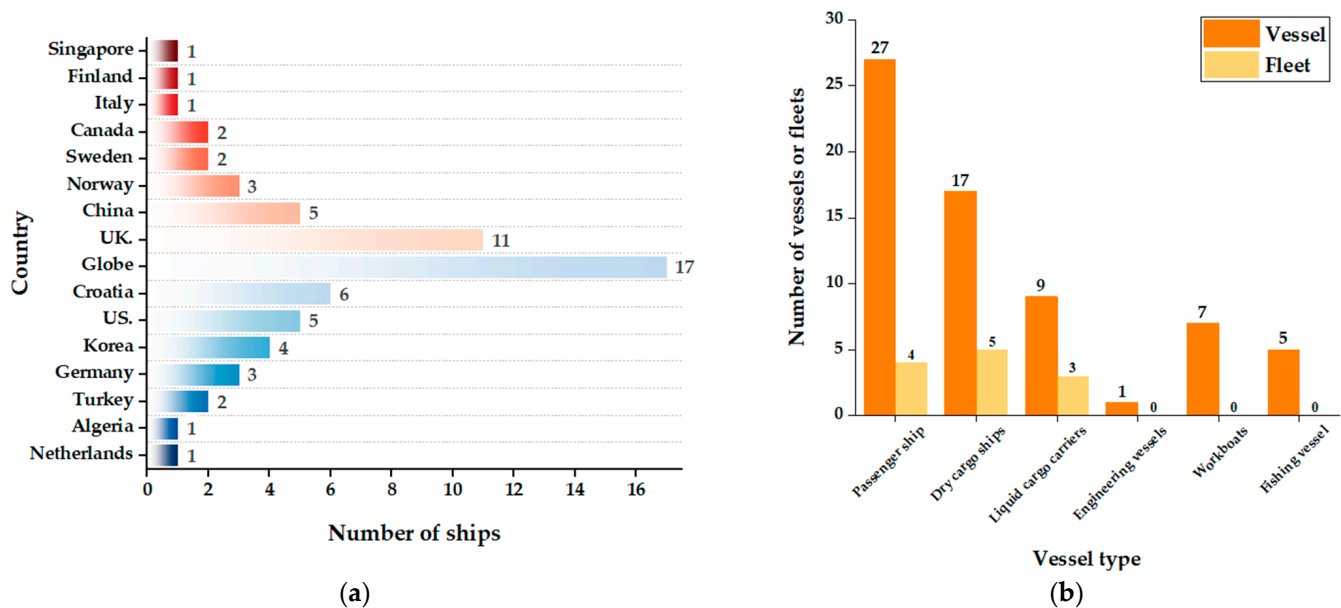


Figure 15. Distribution of LCA research papers on marine fuel by country and ship type. (a) Distribution by country; (b) Distribution according to ship type.

4.1. LCA Research on Marine LNG Fuel

This section covers 34 studies on the full life cycle carbon emission evaluation of marine LNG fuels, accounting for 55% of the total number of studies on LCA of marine alternative fuels. The carbon emission profile of LNG fuel is generally categorized into two phases, WTT and TTW, for comparative studies. In the WTT stage, the GHG emissions mainly come from the feedstock extraction and natural gas liquefaction process [114–120]. Hwang et al. [114] showed that every 1 t of natural gas production emitted 67.6 kg of CO₂, and the liquefaction process to get 1 t of LNG produced 228 kg of CO₂. Manouchehrinia et al. [119] obtained that CO₂ emissions from natural gas extraction and liquefaction processes accounted for 87% of the total emissions at the WTT stage by setting the average emission factor of the liquefaction process to 5.35–8.2 gCO₂e/MJ. In fact, the energy source in the LNG fuel preparation process has an important impact on total carbon emissions, and some studies have explored the energy distribution, but a specific analysis is missing [115–117].

In the TTW phase, most of the researches have focused on the reduction of emissions from engine systems and re-liquefaction equipment utilized in LNG ships [110,114–116,118–137]. For example, Balcombe et al. [138] found that engine choice has a significant impact on GHG emissions. They determined that high-pressure dual fuel 2-stroke (HDPDF) and low-pressure dual-fuel 2-stroke engines (LPDF) can reduce GHG emissions by 28% and 18%, respectively, compared to common heavy fuel oil (HFO) marine engines. Conversely, lean-burn spark ignited (LBSI) and low-pressure dual-fuel 4-stroke (LPDF 4-stroke) engines have

poor climate benefits due to excessive methane emissions. Seithe's study found that LNG fuel is more suitable for tankers and cruise ships where cargo capacity remains constant, and only outperforms HFO in two-stroke engines [134]. Zhou et al. [132] focused on three dual-fuel engine types and analyzed data from more than 7000 ships in a comprehensive manner through the PT-LCA method. The findings indicated that all engine types fueled by LNG were effective in reducing environmental potential in short voyage situations. However, in long voyage situations, the sole option for reducing GWP was the use of LS-HPDF gas engines. Lee et al. [139] proposed that the constrained carbon reduction capability of LNG could be enhanced by incorporating green hydrogen into the fuel, namely hydrogen-enriched LNG. On this basis, the TTW emissions of six hydrogen-enriched LNG engine systems with different ratios were analyzed. Their findings indicated that, in comparison with pure LNG, the hydrogen-enriched LNG with the hydrogen enrichment exceeding 50% demonstrated a pronounced carbon abatement effect, with a reduction of at least 17.2%. Moreover, Zhou's team evaluated the environmental impact of LNG carriers utilizing five distinct LNG partial re-liquefaction system configurations [123]. Their findings indicated that the LNG re-liquefaction systems comprising the PRS+SMR (Partial Re-liquefaction System and Single Mixed Refrigerant) and PRS+MRS (Methane Refrigerant System) combinations exhibited superior environmental performance and energy efficiency compared to conventional systems, such as SMR and MRS. Therefore, the authors encouraged the shipping market to introduce PRS re-liquefaction systems to reduce carbon emissions from LNG fuel during transportation.

It is worth noting that for LNG-powered ships, methane leakage cannot be ignored. Some studies have discussed the impact of methane escape from marine LNG fuel, which mainly involves three processes: extraction and processing, engine refueling, and fuel combustion [115,119,121,125,134,137,140]. At the extraction and processing stage, in addition to directly quoting market GHG emission data [125,134], Manouchehrinia et al. [119] interviewed specific natural gas companies in their case study and indicated that methane escape during extraction and processing of natural gas leads to a 4% increase in upstream emissions. Methane losses during the fuel refueling phase were generally referenced to the leakage data from ground-based LNG filling stations [125,134]. For instance, Guo, H. et al. [141] set the amount of refueling loss to be 0.0361% of the weight of the refueling. Furthermore, engine combustion also results in methane leakage, with the quantity of leakage dependent on the engine type. Sharafian et al. [142] calculated the leakage as 6.9 gCH₄/kWh, and Tripathi et al. [137] set the methane slip as the best, standard, and worst case scenarios at 0.3 g/kWh, 2 g/kWh, and 4 g/kWh, respectively. Researchers in Centre for Marine Sustainability discussed engine methane leakage and indicated that the total GWP of LNG fuel was 5.4% higher than diesel due to its impact, and that LNG can reduce emissions by 20–25% in WTW if methane leakage was not taken into account [140]. Tagliaferri et al. [143] estimated that, if methane leakage in the LNG supply chain accounted for 1% of total natural gas, the GWP would increase by 15%. Therefore, in order to reduce CO₂ emissions from LNG ships, it is necessary to reduce CH₄ escape through technologies and operations, such as reducing pipeline transportation distances and leakage, shortening LNG storage time, and recovering fugitive losses.

In addition, 62% of the LCA studies on marine LNG fuel addressed emissions of other pollutants [110,114–116,119–131]. For example, in a 12,577 kW LNG-fueled ferry studied by Hua et al. [129], nearly 35–42% of the total SO₂ arose during the extraction phase, and nearly 50% of particulate matter (PM) arose during the production phase. Overall, compared with heavy fuel oil, emissions of CO (42–43%) and NO_x (38–39%) were substantially reduced in the WTW stage, and the emission reductions of PM (up to 97.5%) and SO_x (up to 99.8%) were even more dramatic.

A total of 23% of the articles analyzed the economics of LNG fuel for ships [116,125,126,130,135,143,144]. A study by Fan et al. [144] showed that the inland diesel-powered ships could have a 42% reduction in full-life cycle costs if an LNG option was used. Butarbutar et al. [135] conducted a case study for a 600 TEU container ship, and the results showed that the cost required to retrofit existing engines was 53% of the newbuild costs for dual-fuel ships and 61% of the newbuild costs for MGO-fueled ships. In general, the initial investment cost is higher because LNG fuel requires cryogenic equipment during its storage and transportation. However, the LNG-fuel-adapted engines only need to be retrofitted on existing diesel engine equipment, and the price of LNG fuel is generally lower than that of traditional fossil fuels at this stage, which can effectively reduce the operating costs and neutralize the overall fuel economy, making the total life cycle cost competitive [145].

4.2. LCA Research on Marine Hydrogen Fuel

Among the LCA studies on carbon emissions from alternative marine fuels, those involving marine hydrogen fuel occupied 30%. Given that the hydrogen-fueled ship power units (including hydrogen fuel cells and hydrogen internal combustion engines) produce only water and do not emit any pollutant gases during the TTW stage, studies on carbon emissions from hydrogen-fueled ships have primarily focused on the WTT stage (mainly the fuel preparation stage) and the WTW stage.

The whole life cycle carbon emission of marine hydrogen fuel is closely related to its preparation method and energy source [121,140,146–148]. The principal methods of hydrogen preparation include coal gasification, steam methane reforming (SMR), wind energy electrolysis (AEL), and methanol cracking. Lee et al. [115] demonstrated that hydrogen production by SMR required a significant amount of electricity input and resulted in substantial CO₂ emissions, accounting for approximately 71% of the GWP value in the WTT stage. Gilbert et al. [146] examined the emission profile of hydrogen production by SMR, and observed that the GWP and sulfur oxide emissions were 63.93% and 26.86% higher than those of diesel fuel, respectively. Therefore, it is necessary to exploit the full environmental potential of SMR by CCS technology. Zhou et al. [147] conducted a comparative analysis of the GWP values associated with four hydrogen production methods, namely coal gasification, steam methane reforming, wind energy electrolysis, and methanol cracking. Their findings revealed that, for a 5000 kW class ship, the full life cycle CO₂ equivalent emission from hydrogen production by coal gasification was approximately 1.8 times higher than those from SMR, and 22.5 times higher than those from electrolysis. While the GWP emissions from cracked hydrogen do not perform as well as electrolytic hydrogen, SO₂ emissions are only half of those from electrolytic hydrogen. E-hydrogen obtained from wind power electrolysis and methanol cracking is the path-optimal choice. Similarly, Hwang et al. [121] put forth the proposition that green hydrogen produced by water cracking with renewable or nuclear energy as the energy supply can be utilized as an alternative fuel for zero-emission ships. Wang et al. [148] conducted a trial involving three hypothetical hybrid grids, each with a distinct scenario of fossil fuel-based power generation, a transition to cleaner power generation, and an entirely clean power generation. Their findings suggested that with the green transformation of power grid, the GHG emissions associated with hydrogen production will experience a notable reduction.

Due to the limitation of the low energy density of hydrogen fuel, researches on the application of hydrogen fuel in ships were mainly focused on inland cargo ships, small cruise ships, sightseeing barges, fishing vessels, and tugboats at this stage [124,136,140,145,148–150]. The study of Kori et al. [145] on the emissions of fishing vessels found that the GWP level of using fossil-based hydrogen fuel was 10% higher than

diesel, but the emission levels of AP, EP, and POCP were lower. Wang et al. [151] showed that the inland freighters using green hydrogen were able to achieve a GWP reduction of 79.71% compared to MGO, and more than 91% for large ferries. Fernández-Ríos et al. [149] compared the life cycle emissions of three power technologies for a small tourist ship, which were a conventional internal combustion engine, a hydrogen internal combustion engine, and a hydrogen polymerized electrolyte membrane fuel cell. The results indicated that the hydrogen internal combustion engine was able to reduce GWP and ADP by 45% to 72% compared to fossil fuels. Chen et al. [150] found that a green hydrogen-powered tugboat can reduce CO₂ equivalent emissions by 4.86×10^7 kg, mitigating global warming impacts by 83.9–85%. In addition, hydrogen fuel cells can be used as the main load for short-distance ferries, with inland power and solar photovoltaic cells to power other loads. Zhou et al. [146] has shown that this solution can reduce greenhouse gas emissions by 74.3% compared to diesel. Overall, from a WTW perspective, the contribution of fossil fuel-based hydrogen to carbon reduction in shipping is very limited, and e-hydrogen based on sustainable energy sources is an important means of realizing low/zero carbon emissions from ships.

40% of the case studies involved emissions of other pollutants, and the differences were mainly related to hydrogen production methods. For example, in the case study of a 5000 kW power class ship, Jang et al. [147] found that the hydrogen fuel produced by pyrolysis generated 80,000 kg SO₂ equivalent, which was about 1/2 of electrolytic hydrogen and 1/4 of hydrogen produced by SMR. The coal gasification value is much higher than that of the first three preparation methods. As far as EP is concerned, hydrogen production from pyrolysis is slightly lower than that from water electrolysis, which is 1/5 of that from SMR. In general, coal gasification-based hydrogen has the highest environment impacts, while cracked hydrogen and electrolytic hydrogen performed relatively well [115,122,130,150–152].

Furthermore, 44% of the articles discussed the economics of hydrogen-fueled vessels [116,122,130,145,148,151,153]. Kori et al. [145] considered the costs of investment, storage, maintenance, and fuel for a hydrogen-powered fishing vessel. The results demonstrated that the fuel cost of hydrogen was approximately twice that of the diesel power. If hydrogen fuel cell power was used, Perčić et al. [116,122] suggested that ships use hydrogen with other energy sources as an auxiliary power system to reduce the investment in large batteries and charging power consumption. The disadvantage of hydrogen fuel is that when the more environmentally friendly green hydrogen is adopted, the technical requirements and investment cost will become higher, and the economy will deteriorate. In addition, hydrogen needs to be stored and transported under high pressure and low temperature, which further increases the investment in infrastructure equipment [153]. With the expansion of hydrogen production scale and the development of green hydrogen technology, the total cost of hydrogen-fueled ships is expected to decrease rapidly in the future, facilitating their large-scale application in the marine sector.

4.3. LCA Research on Marine Methanol Fuel

LCA studies on the carbon emissions of methanol-fueled ships account for approximately 30% of all LCA studies on alternative fuels for marine vessels. Similar to LNG fuel, the carbon emissions of marine methanol fuel can be analyzed in two stages: WTT and TTW.

At the WTT stage, researchers mainly discussed the impact of methanol preparation methods (including coal methanol [117], natural gas [98,127,128,131,140], biomass sources [98,127,131,140,154], electro-methanol [155,156]) on carbon emissions. The impact of coal-to-methanol and natural gas-to-methanol on the full life cycle GHG emissions of

ships is not promising. Huang et al. [117] found that coal-to-methanol process produced approximately 10 times more carbon emissions than diesel, while natural gas-to-methanol process produced approximately 3 times more carbon emissions than diesel. In the case of a 310,000 DWT VLCC oil tanker, Wang et al. [140] found that natural gas methanol produced approximately 2.5 times more carbon emissions than diesel at the WTT stage in their LCA analysis of a 1678 kW superyacht. In addition, as the most dominant preparation method of methanol fuel at present, methane leakage should be considered in the methanol preparation process from natural gas. However, this was explored in only two cases, which would underestimate the impact of gray methanol on carbon emissions [98,138].

Green methanol, especially bio-methanol, has received widespread attention from researchers due to its excellent carbon reduction potential. For example, Strazza et al. [127] investigated the impact of synthesizing methanol fuel from syngas derived from gasification of woody biomass (such as willow or forest residues) on carbon emissions. The findings revealed that carbon emissions from bio-methanol production were only 12–25% of those from fossil methanol. Furthermore, if the absorption of carbon dioxide by wood was considered, bio-methanol was expected to reduce the GWP value more dramatically. The ability to reduce carbon emissions of bio-methanol is also affected by changes in land use. Selma Brynolf et al. [98] took changes in soil organic carbon (SOC) during crop cultivation into account, and found that GWP per joule of bio-methanol fuel burned was reduced by about 5 gCO₂-eq. However, bio-methanol has some drawbacks. In an examination of using corn stover as feedstock for bio-methanol, Wang et al. [128] found that compared with coal methanol, the emission reductions of CO₂, SO_x, PM, and methane reached 59.39%, 48.13%, 81.51%, and 92.37%, respectively, but the emissions of NO_x, N₂O, and CO were 2.4, 3.18, and 5.63 times higher than that of coal methanol. Brynolf et al. [98] looked ahead to the development and application of e-methanol, and the study of Bugra Arda Zincir et al. [131] on sustainable e-methanol found that it has a negative impact on climate change at the WTT stage. The authors' study demonstrated that the GHG emissions of e-methanol were, on average, 75–80% lower than those of marine LNG fuel [156]. They concluded that it is one of the most concerned methods of methanol preparation in subsequent studies.

In the TTW stage, the research on the emission level of methanol-fueled ships mainly focused on ship operation parameters and power types [157]. Huang et al. [117] found that compared with MGO-powered ships, the 320,000 t DWT ferry can reduce greenhouse gas emissions by 7.6% when using methanol fuel at 13.5 knots of actual sailing speed, and the emission reduction can be further increased by 0.34% at 14.5 knots of design sailing speed.

Regarding the pollutant emission of marine methanol fuel, fossil fuel methanol has the same or even higher GWP than diesel throughout the WTW phase, but can significantly improve the overall environmental performance in terms of acidification, eutrophication, particulate matter and photochemical ozone formation [122,127,128,130,131,143,152,154,158]. For instance, Tripathi et al. [158] proved in the study that the acidification potential of methanol fuel was 33% of that of traditional fuel (HFO, MGO), and the EP level was only 50% of that of MGO. With the development of renewable energy sources and green power grids, green methanol is expected to develop rapidly and improve the environmental friendliness of ships [117,140,159]. Elin Malmgren et al. [159] proposed the HyMethShip concept (installing carbon dioxide capture devices on ship board), and explored the climate impacts of the use of marine gasoline, e-methanol, fossil methanol, and bio-methanol on ships. The study suggested that this concept may contribute to further reducing PM, GWP GHG emissions, photochemical ozone, and ocean and land eutrophication levels.

In addition, a few articles of LCA literature have conducted economic assessment on marine methanol fuel, including power costs, market prices, etc. [116,122,126,130,144,154,155,160]. In the case of a DWT967 cargo vessel studied by Perčić et al. [116], the cost of utilizing a

methanol power system was found to be only 15% more expensive than that of a diesel power system. Fan et al. [144] calculated the full life cycle cost using the average market price of methanol fuel, and determined that the use of methanol fuel was 78% less expensive than diesel fuel for the 1296 kW inland bulk carrier. In conclusion, the production and transportation technology of methanol fuel is now highly developed and only requires retrofitting of existing engines before use, which can significantly reduce the initial investment and maintenance costs [130,161]. According to the research findings of Lee et al. [162], the cost of e-methanol is higher than that of other alternative fuels at the current stage, followed by bio-methanol, natural gas-based methanol, MGO, and LNG. It is expected that with the development of science and technology, bio-based methanol and e-methanol will become more competitive after 2050.

4.4. LCA Research on Marine Ammonia Fuel

Currently, there are limited LCA studies on carbon emissions of marine ammonia fuel, and 11 of these articles are reviewed and analyzed in this part. The whole life cycle carbon emissions of ammonia-fueled ships are also divided into two stages, WTT and TTW, for comparative discussion. At the present stage, the production of marine ammonia fuel mainly relies on natural gas [155,160]. Due to the fact that fossil ammonia consumes a large amount of energy and generates certain losses in the cracking and purification processes, it does not generate emission reduction effects in the WTT stage [116,156,163]. For example, Tripathi et al. [160] showed that the carbon emission of ammonia fuel in the WTT stage was about 5 times higher than that of MGO, and the SO₂ emission was about 6 times higher than that of MGO. The addition of CCS technology in the process of ammonia production from natural gas doubled the sulfur dioxide emission, although it can reduce the GWP and EP levels by 50%. With the introduction and development of green sustainable energy concepts, the electrolytic production of green ammonia from renewable energy sources such as wind and solar energy has gradually received attention [146]. However, fewer studies have been carried out on carbon emissions of green and blue ammonia in the WTT stage, and only two articles have explored the composition of energy sources for power generation [117,146]. As an example, the GWP emissions from coal-fired power generation for ammonia production were about 155 times that of nuclear power generation in the study by Park et al. [146]. In addition, when coupled with electric power and solar photovoltaic (PV) systems as a power system for ammonia-fueled ships, the GWP value was only 22.2% of that using MGO. Therefore, e-ammonia based on sustainable energy is expected to play an important role in carbon reduction of ships.

In the TTW phase, ammonia-fueled engines can reduce carbon emissions to a certain extent because the only major GHG emission is N₂O. The type of ammonia-powered ship engine directly affects its carbon emission level [114,153,157]. Case studies have shown that the use of ammonia as dual fuel in a 50,000 DWT bulk carrier can reduce total GHG emissions by up to 34.5% per ton-kilometer compared to the combustion of MGO [114]. In a comparative study between ammonia dual fuel engines and ammonia-fueled engines, Bicer et al. [153] found that the combination of ammonia and oil fuel can significantly reduce carbon emissions during the operation of ocean-going vessels. Specifically, when ammonia accounts for 11.4% of dual fuel, carbon emissions can be reduced by 34.5% per ton kilometer in the TTW stage, and the total carbon emission reduction in the whole life cycle can reach 27%.

A total of 25% of the cases studied the emission levels of other pollutants [116,130,158]. As an important potential emission reduction fuel to achieve IMO goals, ammonia has a negative impact on environmental eutrophication and acidification. Tripathi et al. [158] found in their research that the AP level of ammonia fuel was twice that of MGO and

six times that of methanol, while the EP level of ammonia fuel was more than two times that of traditional fuel and four times that of methanol. Among them, the AP impact of ammonia fuel from natural gas was slightly higher than that of water electrolytic ammonia, and the EP impact level was the same. How to reduce the emission of NO_x from combustion is the focus of the development of ammonia fuel.

In terms of economic analysis, ammonia is less difficult to store and transport than hydrogen fuel, and storage costs are moderate. However, the initial investment cost of zero-carbon ammonia fuel depends on the development of hydrogen production technology. At present, the total life cycle cost of marine ammonia fuel remains high, nearly twice that of diesel [116,130]. It is anticipated that e-ammonia fuel will have more room for development and application in the years 2040–2050 [162].

4.5. LCA Research on Marine Biofuels

The LCA analysis literature for marine biofuels involves biodiesel made from soybean oil, canola oil, palm oil, waste and residues [128,133,155,156,164], bio-liquefied petroleum gas produced by palm oil CPO and RBD [165], bio-oil extracted from forest residues, pine and poplar [155], and B20 mixed with biodiesel and crude oil [122,133,145], all of which are included in the study of biofuels in this paper.

Unlike other alternative fuels, carbon emissions of biodiesel in the WTT stage are small or even negative due to the carbon capture process of feedstock growth [133,164–166]. Winebrake et al. [133] found that 90% of total life-cycle greenhouse gas emissions from biodiesel came from the TTW stage. Masum et al. [166] specifically explored the impact of biofuel preparation pathways on carbon emissions, involving eleven biofuel pathways and five raw materials, which are poplar, woody biomass, landfill gas, wastewater sludge, and manure. The results showed that biofuels can reduce greenhouse gas emissions by 41–163% compared to low-sulfur fuels. Among them, biofuels derived from manure can reduce greenhouse gas emissions by 148% or more if methane emissions from lagoons or sinkholes are avoided. In addition, hydrogenation of bio-crude oil from manure or sludge can also reduce sulfur oxide emissions by 22% and 18%, and particulate matter emissions by 86%. Zincir et al. [155] found that in the fuel conversion stage of WTT, marine bio-oil was the only alternative fuel that can consume CH₄ and CO₂ without emitting N₂O. All other fuels—including MGO, LNG, electric methanol, and natural gas ammonia—emit greenhouse gases.

From the WTW perspective, biofuels have significant potential for decarbonization [110,116,122,124,128,130,131,133,140,155,156,164–167]. Kesieme et al. [164] compared the emission results of direct vegetable oil SVO with biodiesel, and proposed that biodiesel based on soybean feedstock can reduce greenhouse gas emissions by nearly 70%. Li, C. et al. [168] showed that biofuels can reduce greenhouse gas emissions by 57–59% compared to conventional fuels. Kim et al. [165] examined the reduction effects of using biofuels instead of traditional fossil fuels on fishing vessels, and found that it can reduce greenhouse gas emissions by more than 65%. Stathatou et al. [167] measured the pollutant emissions of biofuel, low-sulphur MGO, and a blend of the two on dry bulk carriers, and found that the blend fuel reduced CO₂ emissions by 1.24%, SO₂ emissions by 50%, and NO_x emissions by 3% during the TTW phase. From the perspective of WTW, the carbon reduction capacity of biofuel blend can reach 40% of that of MGO.

It is important to note that although biofuels can reduce GWP, they may increase the level of eutrophication potential. When factors such as agricultural land occupation are considered, the actual environmental impact of biofuels may be much greater [116,122,130,145,166]. A study by the Centre for Marine Sustainability found that N₂O contributes significantly to biodiesel GHG emissions, accounting for about 45.3% of

the GWP value, and its emission mainly originates from nitrogen-based fertilizers in the cultivation process [140]. Therefore, to reduce the environmental impact of biofuels in the WTT stage, researchers should pay attention to the selection of planting sites, bioraw materials with minimal impact, and appropriate production systems and processing technologies [110]. Krantz et al. [131] distinguished between aLCA (average emissions) and cLCA (predicted marginal environmental impacts) in his study, and stated that the average GHG emissions of biofuels and fossil fuels were 19–73 kg/J and 169–220 kg/J, respectively, but the cLCA of biofuels (169–220 kg/J) was significantly higher than that of fossil fuels (148–262 kg/J). Based on the cLCA results, the authors suggested that the development of biofuels needs to focus on their production efficiency, reduction of transportation, and incorporation of carbon capture technologies to reduce GWP levels in depth.

In terms of life cycle economic costs, high-quality biofuels can be used as a direct replacement for conventional fossil fuels without the need of modifications to marine engines, which somewhat improves its overall economics [145]. Winebrake et al. [116,122] took carbon tax into economic consideration and explored the carbon cost of biodiesel blend B20, which was about 80–87% of that of conventional diesel. In general, biofuels are derived from biomass and have good carbon neutrality capabilities. Although the current fuel cost of biofuels is lower than that of e-fuels, it is about 2.5 times higher than the cost of fossil fuels [162]. Due to the limitations of production technology, the initial investment and production cost of biofuels is still high, which brings certain challenges to their marine application.

4.6. LCA Research on Other Marine Fuels

In recent years, battery power has received extensive attention in the field of shipping due to its high technical maturity and abundant market experience. Therefore, this paper also explores the impact of battery on the whole life cycle pollutant emissions and economy of ships.

Overall, battery power can reduce the level of emissions from ships, with the specific reduction mainly determined by the type of battery and ship [124,147,163,169–175]. In a case study of a Croatian offshore ro-ro passenger ship [147,163,169], researchers compared diesel engines, photovoltaic cells, nickel-metal hydride batteries, lithium-ion batteries, solid oxide batteries, and lead-acid battery. Results found that lithium-ion batteries were the best alternative for short-haul vessels in terms of environmental benefits and economic costs. Zhou et al. [170] recommended the design and optimization of molten carbonate batteries be the focus of the development of marine electric fuels in their LCA analysis of marine fuel cell devices. Furthermore, the authors conducted a comparative analysis of purely electric vessels versus hybrid electric vessels [124]. The results demonstrated that battery power can reduce the life cycle cost of a vessel by 15% and reduce greenhouse gas emissions by 30% [171]. In comparison to diesel-powered vessels, fully battery-powered ships have the potential to reduce the global warming potential by 35.7%, the photochemical ozone generation potential by 77.2%, the acidification potential by 77.6%, and the eutrophication potential by 87.8% [172]. A hybrid system combining battery power with renewable energy generation, or fuel cells, has been demonstrated to reduce carbon emissions by 33.4% in the case of a 6700-ton bulk carrier, compared to the use of diesel fuel. In the case of a 1165-ton canal ship, the reduction in carbon emissions was 14.5% [173].

When using battery power, a renewable energy power plant can be installed on board to further reduce carbon emissions and life cycle cost. For both short-haul and ocean-going vessels, the ability of solar power system to reduce operating cost and emissions is considerable. For example, in a case study conducted in 2019, researchers found that the implementation of a solar panel system on a ship resulted in a reduction of fuel costs by

\$300,000 and CO₂ emissions by 3×10^6 kg CO₂-equivalent over the ship's full operational lifespan, as compared to the use of a diesel generator [174]. In the long run, with improved solar energy conversion efficiency, PV-powered electric propulsion systems on ocean-going vessels will also be more effective in reducing emissions. However, fuel selection needs to be tailored to local and ship conditions, including the specific level of technological development, geographic location, availability of resources, and ship voyage [175].

4.7. Comprehensive Analysis

Figure 16 summarizes the number of cases of alternative fuel vessels in the LCA analysis and their corresponding vessel types. Among them, a total of forty-two study cases compared LNG with MGO, while the LCA analyses on hydrogen (twenty study cases), methanol (eighteen study cases), ammonia (eight study cases), and biofuels (sixteen study cases) still need to be improved. In total, 85% of the cases chose transportation vessels as the object of analysis, and the remaining 15% of cases concerned other vessel types, such as engineering vessels, workboats, and fishing vessels, which is a gap in the current life cycle assessment studies on marine alternative fuels.

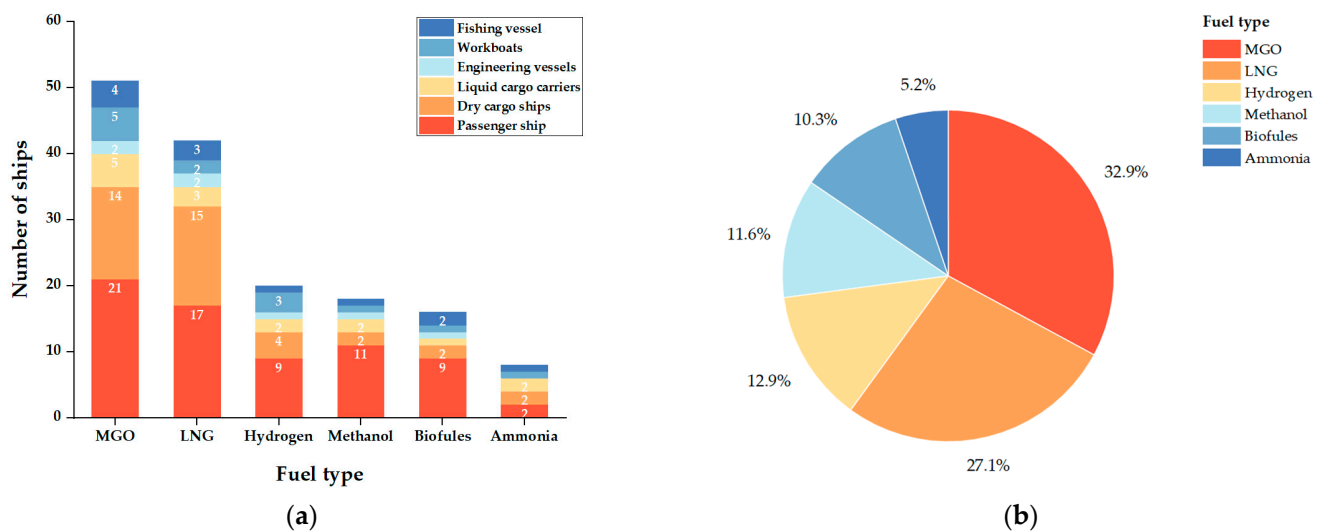


Figure 16. Case statistics of fuel types and ship types: (a) Case statistics of fuel types and ship types; (b) Case statistics of fuel types.

Figure 17 categorized and summarized the analysis methods and data sources in the literature cases. More than half of the life cycle calculations of alternative marine fuels employed GREET and GaBi as analytical instruments. These calculation software and databases can provide an important basis for marine fuel LCA assessment. However, it should be noted that the resource endowment of each country or region varies greatly, and the emission factors of the specific fuels are not the same. Accordingly, the validity and reasonableness of the relevant parameters and factors must be discussed and analyzed thoroughly when conducting LCA analysis.

In order to reasonably compare the literature data on carbon emissions, this part has extracted the impact scores from the cases to harmonize the results. In this instance, the climate change impact score was defined as the equivalent carbon emission per shaft power of the ship. Since some of the LCA literatures did not specify the information of ships or functional units, this paper has extracted and compared the climate change impact scores from 33 case studies for MGO, 32 case studies for LNG, 39 case studies for hydrogen, 31 case studies for methanol, 26 case studies for biofuel, and 18 case studies for ammonia. The results are shown in Figure 18. The different points indicate the results of the carbon

impact scores of various cases. The black line in the middle represents the median, while the boxed area covers the range of $\pm 50\%$.

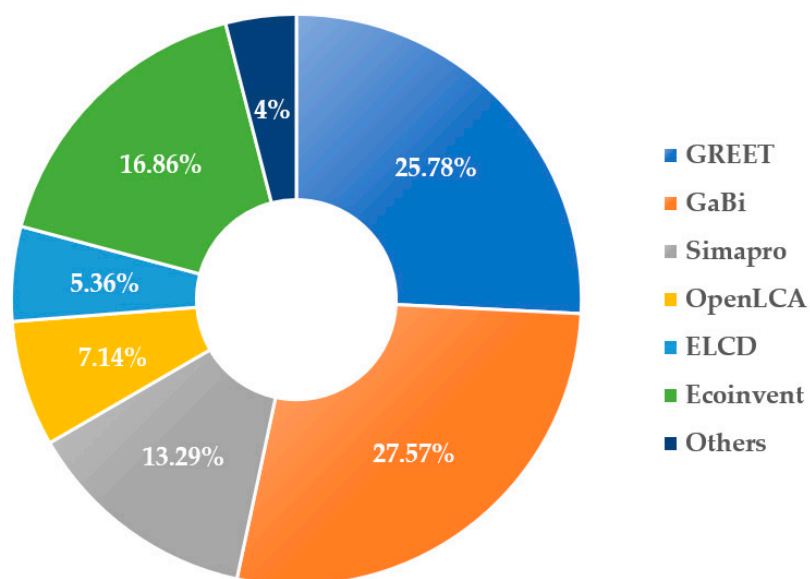


Figure 17. Case data source statistics.

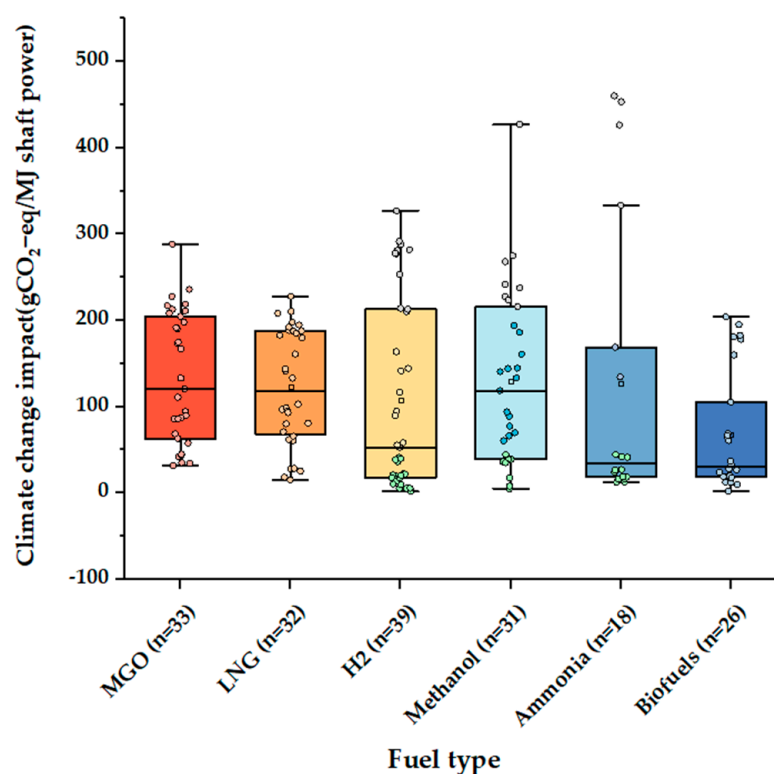


Figure 18. Climate change impact scores for marine alternative fuels.

As can be seen, the carbon emissions of MGO are concentrated in 58–212.98 gCO₂-eq/MJ. Literature analyses have shown that due to consistent fuel preparation methods, carbon emissions in the ship operation stage account for more than 60% of the total, so the difference in results mainly appears in the TTW combustion stage. The carbon emission results of LNG fuels are similar to those of MGO. However, the actual carbon emission reduction effects of LNG may not be satisfactory since methane leakage is ignored in most cases (see Section 4.1). For the hydrogen, methanol, and ammonia fuels, the variability

in the results of different cases is more pronounced. This is primarily attributed to the disparate sources and preparation methodologies employed for these fuels in the WTT stage, as indicated by the varying-colored dots in Figure 18. The green dots represent green fuels prepared through renewable energy electrolysis or biomass, while the gray dots represent gray fuels with fossil fuel preparation. The carbon emission levels of the fossil fuel-based hydrogen, methanol, and ammonia fuels exceed or even significantly exceed the emission results of MGO in some of the cases, which seriously reduces the overall emission reduction effect of the three fuels. The carbon emission reduction effects of the green hydrogen, methanol, and ammonia fuels are very considerable, with carbon emission results ranging from 2–44.8 gCO₂-eq/MJ. The carbon emission of biofuels is exhibited in the range of 2.3 to 204.2 gCO₂-eq/MJ, with its median 80% lower than that of MGO. The difference arose in the WTT stage, and the main influencing factors include the application of feedstock types, the choice of planting sites, the use of nitrogen-based fertilizers, and soil use. Although the demarcation of research boundaries and the selection of assessment methods in LCA can explain differences in the results of the whole life cycle assessment of alternative marine fuels to a certain extent, the dispersion of the results leads to the fact that it is not possible to draw a clear conclusion on the emission reduction effects of specific fuels, and a large number of case studies and data statistics are still needed.

Regarding the pollutant emissions of marine alternative fuels, there are also significant differences even for the same fuel due to factors such as preparation technology and ship type. In general, methanol fuel has a higher level of CO emission among several alternative fuel types, followed by LNG. Compared to other alternative fuels, the performance of biofuels in reducing sulfur oxide emissions is not ideal, basically on par with MGO. In terms of NO_x emission levels, the reduction effect of alternative fuels varies greatly, especially for biofuels. The results are even slightly higher than MGO, LNG, and methanol, and hydrogen fuels have the lowest emissions. Notably, all alternative fuels are good at reducing particulate matter emissions.

5. Conclusions and Suggestion

The green transformation of shipping is a long-term and complex process. The whole life cycle analysis of alternative marine fuels, as well as the quantitative evaluation of energy consumption and environmental and economic costs at each stage of the alternative fuels can provide a valuable reference for the low-carbon development of shipping. This review comprehensively analyzed the basic characteristics of various marine alternative fuels that have attracted much attention at the present stage, including LNG, hydrogen, methanol, ammonia, and biofuels. The whole chain of production, storage, transmission, and ship application of these fuels was described in detail. The LCA methodology and its framework for marine alternative fuels were also expounded for clear understanding. On this basis, the status of research on the carbon emissions of marine alternative fuels throughout their life cycle was summarized. In view of the existing problems and challenges, the following suggestions are put forward:

1. In order to provide a complete and reasonable LCA analysis of alternative marine fuels, appropriate measurements of carbon trajectories during the WTT and TTW stages are required. In existing studies, the carbon emission measurement unit for the WTT stage is consistently set as gCO_{2e}/MJ_{fuel}. However, there is a large variability in the functional units for the TTW stage, e.g., gCO_{2e}/MJ_{shaft work}, gCO_{2e}/kWh_{engine output}, gCO_{2e}/tonne-nm, gCO_{2e}/MJ_{fuel}, and tCO_{2e}/t_{fuel}, which poses difficulties for comparative analysis of carbon emissions from different ships. Consequently, further clarification is required on the functional units of different types of ships in subsequent studies.

2. In the LCA analysis method, the boundaries of the entire life cycle of various alternative fuels for ships need to be further clarified. The LCA analysis scope should include the entire life cycle pathway of the fuel, from raw material mining, transportation and pretreatment, conversion preparation, filling, and combustion inputs in the entire supply chain. Especially for biofuels, while clarifying specific processing techniques, it is also necessary to determine the boundaries of the analysis inventory such as waste management and global biosphere management.
3. Regarding fuel types, researches on methanol, hydrogen, ammonia, biofuels, and e-fuels are limited in number and have great differences. Therefore, it is urgent to expand the amount and scope of LCA research. In addition, the analysis process should be combined with the specific energy and environmental conditions of different countries, and cover the impact of two or even multiple fuel combinations.
4. From an energy perspective, ship power applications—as the downstream of the entire life cycle—always rely on the upstream fuel preparation and energy supply. Most studies have neglected the impact of energy sources on carbon emissions of the alternative fuels. In fact, upstream power consumption accounts for a significant proportion and cannot be ignored throughout the fuel life cycle. It is recommended to take the grid composition and its dynamics changes into account.
5. Currently, most of the life cycle analyses of marine alternative fuels have focused on carbon dioxide emissions, with less discussion on pollutant emission, total cost, and technical maturity. In the subsequent studies, the life cycle assessments of pollutant emissions and costs (including carbon tax) of alternative marine fuels should be conducted in conjunction with dynamic forecasts of the maturity of technologies, such as fuel preparation processes and marine engine systems.
6. From the perspective of ship types, most research cases at this stage have focused on transport ships, and there were few analyses on engineering ships and work boats. In addition, in response to the development needs of global ocean trade, the number, power, and emission levels of ocean-going ships are increasing. Considering the requirements of the Air Pollutant Emission Control Area (APECA) program, the development of alternative fuel-powered ocean-going ships is urgent. Therefore, it is recommended to expand the LCA research object to high-power ocean-going vessels.
7. Most of the LCA studies on green fuel-powered ships have only discussed the fuel cycle, and the lifecycle of the ship body and relevant equipment are not involved. It is recommended to consider the construction, modification, operation, and scrapping cycle of ships in the following researches.
8. One of the reasons for the variability in the results of the current case studies is the diversity and uncertainty of the data sources. In order to obtain reasonable and reliable research results, it is recommended that researchers include data quality assessment, sensitivity analysis, and uncertainty analysis in the subsequent LCA analysis of marine alternative fuels.

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Abbreviations

Abbreviation	Meaning
AP	Acidification Potential
CCS	Carbon capture storage
CO ₂	Carbon dioxide
CPO	Calm oil
CML	Center for Environmental Sciences
DWT	Deadweight tonnage
ECAS	Emission Control Areas
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operation Index
EEMP	Energy Efficiency Management Program
EP	Eutrophication Potential
EU ETS	EU Emissions Trading Scheme
GHG	Greenhouse Gas
GWP	Global warming potential
HB	Haber-Bosch
HFO	Heavy fuel oil
HPDF	High-pressure dual fuel
ICS	International Chamber of Shipping
IPCC	Intergovernmental Panel on Climate Change
IMO	International Maritime Organization
ISOTAC	International Society of Environmental Toxicology and Chemistry
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LNG	Liquefied natural gas
LCIA	Life cycle impact assessment
LCI	Life cycle interpretation
LPDF	Low-pressure dual-fuel
LBSI	Lean-burn spark ignited
MEPC	Marine Environment Protection Committee
MRS	Methane Refrigerant System
MRV	Monitoring, Reporting and Verification
NO _x	Nitrogen oxides
N ₂ O	Nitrous oxide
PRS	Partial Re-liquefaction System
PM	Particulate Matter
POCP	Photochemical Ozone Creation Potential
RSE	Renewable energy
RBD	Rice bran biodiesel
SEEMP	Ship Energy Efficiency Management Program
SEDI	Ship Energy Efficiency Design Index
SMR	Steam methane reforming
SO _x	Sulfur oxides
SCR	Selective catalytic reduction
SOC	Soil organic carbon
TTW	Tank-to-Wake
UNEP	United Nations Environment Programme

UNFCCC	United Nations Framework Convention on Climate Change
WTT	Well-to-Tank
WTW	Well-to-Wake
WMO	World Meteorological Organization

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