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Review

A Prompt Decarbonization Pathway for Shipping: Green Hydrogen, Ammonia, and Methanol Production and Utilization in Marine Engines

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Abstract: The shipping industry has reached a higher level of maturity in terms of its knowledge and awareness of decarbonization challenges. Carbon-free or carbon-neutralized green fuel, such as green hydrogen, green ammonia, and green methanol, are being widely discussed. However, little attention has paid to the green fuel pathway from renewable energy to shipping. This paper, therefore, provides a review of the production methods for green power (green hydrogen, green ammonia, and green methanol) and analyzes the potential of green fuel for application to shipping. The review shows that the potential production methods for green hydrogen, green ammonia, and green methanol for the shipping industry are (1) hydrogen production from seawater electrolysis using green power; (2) ammonia production from green hydrogen + Haber–Bosch process; and (3) methanol production from CO_2 using green power. While the future of green fuel is bright, in the short term, the costs are expected to be higher than conventional fuel. Our recommendations are therefore as follows: improve green power production technology to reduce the production cost; develop electrochemical fuel production technology to increase the efficiency of green fuel production; and explore new technology. Strengthening the research and development of renewable energy and green fuel production technology and expanding fuel production capacity to ensure an adequate supply of low- and zero-emission marine fuel are important factors to achieve carbon reduction in shipping.

Keywords: green hydrogen; green ammonia; green methanol; green power; ship carbon emission reduction

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1. Introduction

Marine engines mainly use low-quality fuel with high sulfur content, high viscosity, and heavy metals, such as cadmium, vanadium, and lead. The complexity of low-quality fuel components leads to more exhaust pollutants from ships. The substances represented by nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), and carbon dioxide (CO_2) have a great impact on human health, the environment, and the climate [1]. After-treatment technology is often used to purify exhaust gas, such as selective catalytic reduction (SCR) technology or exhaust gas recirculation (EGR) technology to purify NOx [2–5], exhaust gas cleaning (EGC) technology to purify SOx [6], and carbon capture technology to purify CO_2 [7]. In 2018, the International Maritime Organization (IMO) adopted a preliminary strategy for reducing greenhouse gas (GHG) emissions from ships, proposing to reduce carbon emissions in the global shipping industry 50% by 2050 (based on carbon emissions in 2008) and to achieve zero carbon emissions in the global shipping industry in the 21st century [8]. Dong et.al. [9] reviewed the decarbonization laws and policies introduced by the IMO, by the European Union, and at the national levels. More ambitious emission control efforts are needed to achieve the climate goals.

From the perspective of energy technology, since fossil fuel are used, internal combustion engines inevitably emit a large amount of CO_2. It is difficult to achieve carbon emission reduction development strategies and goals by relying solely on existing energy efficiency improvement methods [10]. The maritime industry is paying increasing attention to the development and application of low-carbon marine fuel. Wang et al. [11] summarized and analyzed the use potential of low-carbon alternative fuel for ships. At present, the alternative fuels available for ships include liquefied natural gas, liquefied petroleum gas, methanol, biodiesel, hydrogen, and ammonia. In the short term, liquefied natural gas, liquefied petroleum gas, and methanol technologies are relatively mature and can be applied to shipping. In the long run, biodiesel, hydrogen, and ammonia will inevitably become the mainstream alternative fuels for ships. Among these, ammonia, hydrogen, and methanol are the most investigated alternative marine fuels. If renewable resources are used for production, low or zero emissions can be achieved, creating what is called green fuel. Ammonia, hydrogen, and methanol are at different stages of development, as shown in Table 1. If produced from fossil fuel, hydrogen and ammonia are not clean compared to marine gas oil (MGO) when assessed over the entire life cycle.

Table 1. Compared with standard MGO, whole-life-cycle GHG emissions of ammonia, hydrogen, and methanol [12].

Fuel	Proportion of GHG over Whole Life Cycle Compared to MGO		Energy Density (MJ/L)	Emission Reduction Compared to Conventional Fuel		
	Fossil Fuel	Renewable Energy		SOx	NOx	PM
Hydrogen (liquid, −253 °C)	166%	0%	8.5	100%	Varies according to engine design	100%
Ammonia (liquid, −33 °C)	140%	6%	12.7 (−33 °C) 10.6 (45 °C)	100%	Potential for more emissions	100%
Methanol	101%	1%	14.9	100%	30–50%	90%

The shipping industry has high hopes for carbon-free or carbon-neutral green fuel. The use of carbon-free or carbon-neutral green fuel is an effective way to fundamentally solve carbon emissions [13,14]. Carbon-free green fuels include green hydrogen and green ammonia. Carbon-neutral fuels include renewable methanol, renewable natural gas, bioethanol, bio-dimethyl ether, and biodiesel. Producing green fuel from renewable energy, especially by converting CO_2 into fuel using renewable energy, has attracted great interest for the following reasons [15–19]: (1) it can achieve large-scale, long-term energy storage to meet the seasonal, long-distance demand for renewable energy, which becomes a commodity in international energy trade; (2) the production technology and end-use technology are mature, and existing fuel distribution infrastructure can be used to meet the renewable energy needs of transport, mobile devices, and construction machinery; (3) the whole-life-cycle resource consumption is less, and the understanding of its environmental impact is clearer, which can reduce the increase of CO_2 concentration in the atmosphere and ocean acidification.

Green hydrogen, green ammonia, and green methanol are being widely discussed for shipping [20]. Because green methanol and ammonia have higher energy densities and are relatively easier to transport and store on ships, they have become the most promising near-zero-emission marine fuel for the next decade. In the long run, hydrogen can be a more advantageous zero-emission solution, and it poses the least potential threat to the environment when it leaks.

Interest in using renewable energy to reduce carbon emissions from shipping has in-creased significantly in recent years [21]. Although it is possible to achieve carbon reduction by directly employing renewable energy sources such as wind, solar, and wave energy during a ship's voyage at sea, their indirect nature means uncertainty regarding the emission reduction effect, which is undesirable for ship operators. Another pathway is to use renewable energy to produce fuel that can then be transported for shipping. The mainstream route is to use renewable energy to produce green power first, and then use it to produce fuel such as hydrogen. Of course, renewable energy can also be used to produce fuel directly. The above two processes are referred to as the green fuel pathway from renewable energy to shipping in this paper.

Studies on the decarbonization of shipping are popular, especially on promising alternative fuels such as hydrogen, ammonia, and methanol [22,23], but little attention has been paid to the green fuel pathway from renewable energy to shipping. Therefore, this paper analyzes green production methods for hydrogen, ammonia, and methanol. In addition, since most of the production pathways require green power, the production methods for green power are analyzed in detail. This paper is intended to provide a new understanding of carbon reduction in shipping using green fuel production methods. However, the construction and the promotion of green-fuel-supporting facilities remain a challenge and require a careful trade-off between the cost of green governance and the economic efficiency of the shipping company or port. The structure of this paper is as follows: Section 1 introduces the importance of green fuel for ship carbon emission reduction. Section 2 mainly discusses renewable energy power generation and its importance to carbon emission reduction. Section 3 discusses the production methods of green hydrogen, green ammonia, and green methanol, and their potential application to shipping. Section 4 provides the conclusions. This paper is limited in length, so it is not possible to review in detail the topics covered in this paper. On the contrary, this paper provides a macro understanding for interested readers.

2. Electrochemical Energy and Carbon Cycle

2.1. Carbon Capture and Carbon Cycling

Undisturbed, carbon moves between each reservoir in an exchange known as the carbon cycle, which maintains relatively stable carbon concentrations in the atmosphere, on land, in plants, and in oceans. This balance helps to keep the Earth's temperature relatively stable [24]. However, today, due to the continuous intensive use of fossil fuel, land-use change, and other human activities, the concentration of CO_2 in the atmosphere is rising at an unprecedented rate; the carbon cycle is disrupted, and a large amount of CO_2 enters the atmosphere, causing the Earth's temperature to rise [25]. In general, there are two ways to remove CO_2. One is to attempt to accelerate the absorption of atmospheric CO_2 by enhancing natural sinks, such as afforestation to increase carbon storage in biomass [26]. Another way is to reduce CO_2 through artificial methods, such as carbon capture technology [27,28], which is currently popular. As a result, it is increasingly necessary to remove the CO_2 emitted by humans to achieve net-zero CO_2 emission.

Carbon capture technologies include carbon capture and storage (CCS) and carbon capture and utilization (CCU). The captured CO_2 can be stored in geological formations as well as in the oceans. In addition to storage, CO_2 can be used directly in different industrial sectors, including the food, beverage, and pharmaceutical industries. It can also be converted into high-demand products such as urea, methanol, and biofuels. Although both CCS and CCU technologies seek to mitigate climate change, they can only be seen as temporary solutions, as they merely delay CO_2 emissions rather than permanently eliminate them [29]. Compared to CCS, CCU may play a small role in mitigating climate change. However, CCU may offer a very cost-effective option for CO_2 abatement, and even generate profits in some cases. One option that could be deployed on a large scale is the conversion of CO_2 into fuel. However, this would require significant progress in catalysis and process design. In addition, this route will not store CO_2 for a long time but will provide carbon-neutral fuel under the best conditions [30]. CO_2 utilization focuses on the reduction of CO_2 emissions, which is the end problem of today's industry. Artz et al. [31] provided a detailed review of the methods and processes of CO_2 conversion, which sought to identify opportunities, through the development of new feedstocks, to avoid the use of fossil resources in the transition to a more sustainable future of production. Furthermore, the current rate of CO_2 emissions and the variable nature of point sources suggest that capture at the point of emission alone is not sufficient to mitigate the increasing greenhouse effect of CO_2. Large-scale deployment of technologies involving the direct capture of CO_2 from the atmosphere is essential [32]. Electrochemical CO_2 capture technology is interesting due to its flexibility and its ability to address dispersed emissions (e.g., atmospheric). Although electrochemical CO_2 capture technology is costly compared to amine-based capture, it could be particularly interesting if cheaper renewable electricity and materials (e.g., electrodes and membranes) become widely available. In addition, electrochemical methods can convert captured CO_2 into value-added chemicals and fuel, thus preparing the way for a fully electrified circular carbon economy [33]. Galimova et al. [34] analyzed the global demand for CO_2 as a feedstock for fuel and chemical production during the global energy transition to 100% renewable energy. The CO_2 capture and utilization potential of key industrial point sources, including cement plants, pulp and paper mills, and waste incinerators, were assessed. According to the study's estimates, the demand for carbon dioxide will increase from 0.6 million tons in 2030 to 6.1 billion tons in 2050. Key industrial point sources are likely to supply 2.1 billion tons of CO_2 to meet most demand in the 2030s. By 2050, however, direct air capture is expected to meet most of the demand, producing 3.8 billion tons of CO_2 a year.

The application of carbon capture on board ships could be a transitional solution to reducing CO_2 emissions from the maritime industry in the short term, providing the time necessary to fully develop and implement zero-emission technologies. There are three main types of carbon capture technologies available: pre-combustion carbon capture, post-combustion carbon capture, and O_2 fuel combustion capture. Post-combustion carbon capture, which captures CO_2 from the exhaust of the ship, has gained widespread interest. This process is suitable for ships sailing on conventional carbon-containing fuel and is expected to mature and be commercialized earlier than alternative fuel because it is based on proven technology and does not require as much research and development as alternative fuel. Luo et al. [35] explored how a solvent-based carbon capture process could be applied to capture CO_2 from a typical cargo ship's energy system, with a capture cost of EUR 77.50/tonne CO_2 at a carbon capture rate of 73%. Feenstra et al. [36] evaluated a 3000 kW LNG carrier-based carbon capture. The cost of using 30 wt % aqueous monoethanolamine was EUR 120/tonne CO_2, and the cost of using aqueous piperazine was EUR 98/tonne CO_2, both of which had 90% capture efficiency. The implementation of amine-based carbon capture systems on board ships was evaluated by Stec et al. [37], with total CO_2 recovery rates ranging from 31.4% to 56.5%. Long et al. [38] developed an efficient sea-based CO_2 capture, CO_2 compression, and liquefaction technology for a 3000 kW diesel engine, with a CO_2 removal rate of 94.7%. Ros et al. [39] discussed advances in marine carbon capture technology for LNG ships, based on the results of the DerisCO$_2$ project. Oh et al. [40] presented a membrane carbon capture and liquefaction system for LNG ships with much smaller dimensions compared to conventional amine-based processes.

Carbon capture technology on board ships shows great potential for carbon reduction; however, the cost is one of the barriers to the development of carbon capture on board. As emissions regulations become more stringent, conventional ships need to install not only after-treatment units to remove pollutants such as NOx and SOx, but also carbon capture units to remove CO_2, which inevitably takes up valuable space on board, and the physical operating conditions on board are becoming a barrier to the application of carbon capture [41].

2.2. Renewable Energy and Green Power

Renewable energy sources are naturally replenished and never depleted on Earth; they include bioenergy, hydropower, geothermal, solar, wind, and ocean (tidal and wave) energy [42]. To harness wind energy on modern ships, a range of wind-assisted ship propulsion (WASP) products have been developed and tested [43]: rotors, towing kites, suction wings, rigid sails/wing sails, soft sails, wind turbines, and hull sails. Wang et al. [44]

proposed an integrated collaborative decision-making approach to optimizing the energy consumption of sail-assisted ship, which can make full use of wind energy while keeping the hybrid system operating at optimal conditions under various operating conditions and can reduce energy consumption and CO_2 emissions by approximately 8.9% during a single voyage. However, the high-cost investment in research into WASP and the uncertainty about reducing fuel consumption have limited WASP in the maritime industry. Ships harness solar energy by using photovoltaic installations: sunlight is converted into electricity by photovoltaic systems installed on board; this electricity is temporarily stored in batteries and then used for propulsion or to supply electrical equipment. Solar energy on ships is very promising, but the question remains as to how to install more PV panels in the limited area on the ship's deck to increase the installed capacity of the PV system. Even in areas with sufficient solar radiation, it is not feasible to connect the PV system directly to the ship's main grid due to the low conversion efficiency of the PV panels [45]. Waves can damage coastal structures and affect the stability of a ship, increasing the resistance of a ship underway and even leading to capsizing. If used properly, wave energy can be converted into propulsion for the ship, reducing the interference of waves with the ship's stability, but this requires devices capable of extracting wave energy [46]. However, in general, if wave energy is used while the ship is sailing, the wave energy device needs to be in direct contact with the water surface, which undoubtedly increases the contact area between the ship and the water surface, causing additional resistance to the ship's navigation. This may also affect the stability of the ship due to the weight of the device. Wind and solar energy are undoubtedly the most promising renewable energy sources for ships. However, they are hardly used as the main power source for ships and are generally used as auxiliary power sources to reduce CO_2 emissions. For the above reasons, alternative ways of applying renewable energy to ships are needed.

Green fuel produced from renewable energy can be used as the main power for ships, so this paper is concerned with methods of producing green fuel for ships from renewable energy. The main green fuel production processes are based on green power technology. Green power [47] refers to electricity supplied from more readily renewable energy sources than traditional electrical power sources. The following subsection, therefore, analyzes green power production technologies with the intent to gain a better understanding of green fuel production technologies, as discussed in Section 3.

2.2.1. Hydropower

Hydropower [48] is a renewable energy source where power is derived from the energy of water moving from higher to lower elevations. It is a proven, mature, predictable, and price-competitive technology. Hydropower has among the best conversion efficiencies of all known energy sources (about 90% efficiency). Hydropower projects are usually classified into four major types: run of river, storage (reservoir)-based, pumped storage, and instream technologies (hydrokinetic). Kougias et al. [49] reviewed recent research and development activities in the field of hydropower technology, including the following topics: (1) techniques supporting the wide-range operation of hydraulic turbines; (2) instabilities in Francis turbines of pumped hydro energy storage stations; (3) the digitalization of hydropower operation; (4) hydro generators with current-controlled rotors; (5) variable speed hydropower generation; (6) innovative concepts in hydroelectric energy storage; (7) novel technologies in small-scale hydropower; and (8) fish-friendly hydropower technologies. With rapid economic development and the global need to reduce carbon emissions, hydropower is playing a greater role than ever before as an important source of clean energy. For examples, hydropower plays an important role in stabilizing Poland's power generation system [50] and is the best option for meeting Southeast Asia's energy needs [51]. However, the environmental impact of hydropower is controversial. Developed countries have stopped building dams because the best sites for them have been developed and because environmental and social issues make the costs unacceptable. Today, more dams are being removed than are being built in North America and Europe. The hydropower industry began building dams in developing countries and, since the 1970s, has begun building larger hydropower dams in the Mekong, Amazon, and Congo river basins. The same problems are being repeated [52]: destruction of river ecology, deforestation, loss of aquatic and terrestrial biodiversity, release of large amounts of greenhouse gases, displacement of thousands of people, change of livelihoods, and impact on nearby food systems, water quality, and agriculture. The widespread perception that a small run-of-river hydropower plant is a renewable energy source with little or no environmental impact has led to a global spread [53]. However, it may alter natural flow regimes and damage river ecosystems. Pata et al. [54] investigated the relationship between hydropower energy consumption, ecological footprint, and economic growth in the top six hydropower-consuming countries (China, Canada, Brazil, the US, Norway, and India, as of 2016). In terms of policies' impact, policies to encourage the use of hydropower energy can be implemented in China and Brazil, which saw the fastest growth in hydropower energy consumption over a 52-year period (1965–2016). From an economic perspective, the efficient use of hydropower and the increase of investment in hydropower energy in China and Brazil were appropriate policies to support economic growth. Concerning the relationship between the environmental and ecological footprints, the environment should be taken into account when implementing economic policies in the USA and Norway. In Canada and India, the causal relationship between the environmental footprint and the ecological footprint showed that environmental issues affected the ecological footprint. Environmental pollution in these countries could provide direction for economic policy. From an environmental perspective, hydropower energy consumption had not been used effectively to reduce the ecological footprint. A better understanding of environmental issues, ecological issues, and the continued development of new technologies and a sound planning system, as shown in Figure 1, is therefore essential for future hydropower development.

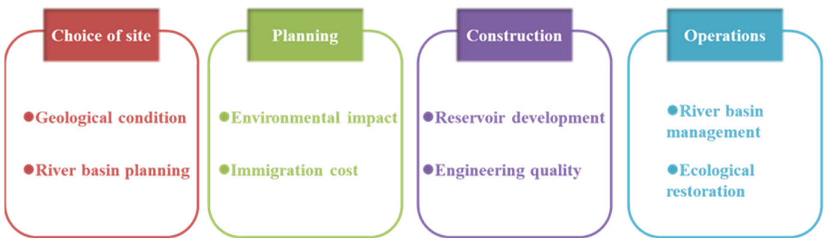

Figure 1. Planning system of hydropower [55].

2.2.2. Wind Power

As a high-storage-capacity, non-polluting, clean energy source using proven technology, the main applications of wind energy are large turbines, onshore or offshore, used to generate electricity [56]. Wind turbines can be classified into four basic categories based on the means of speed control [57]: fixed-speed wind turbines, limited-variable-speed-controlled wind turbines, doubly-fed-induction-generator-based wind turbines, and full-variable-speed-controlled wind turbines. López-Manrique et al. [58] reviewed the criteria and wind turbine standards used for wind power evaluation and outlined the technologies needed to make reliable wind power grid penetration more efficient. In 2021, wind electricity generation increased by a record 273 TWh (up 17%). This was 55% higher growth than that achieved in 2020 and was the highest among all renewable power technologies [59]. China has become a global leader in wind power, and its wind power development has contributed significantly to the global wind power growth rate [60,61]. As wind power accounts for an increasing share of the electricity supply, the challenges posed by the intermittent nature of wind power are becoming more prominent. Wind power is inherently intermittent [62–64]. It cannot be controlled and dispatched in the same way as a conventional power plant. As a result, the intermittent nature of large-scale wind power integration leads to low system reliability, high reverse capacity, and high costs. Many countries are seeking to harness wind energy and see it as a promising energy, and continued expansion of wind power requires a good understanding of its intermittency to reduce the uncertainties associated with wind power output. In recent years, there have been several studies aimed at assessing the wind power potential of target sites, the most commonly used methods being Measure-Correlate-Predict models and artificial neural network methods [65].

2.2.3. Solar Power

There are two types of solar power generation: direct photovoltaic (PV) [66] and indirect concentrated solar power (CSP) [67,68]. Solar PV generation increased by a record 179 TWh (up 22%) in 2021 to exceed 1000 TWh. It showed the second-largest absolute generation growth of all renewable technologies in 2021, after wind [69]. Solar PV systems on a global scale of 8519 GW would reduce 4.9 Gt of greenhouse gas emissions and fulfill 25% of global electricity demand by 2050 [70]. Interest in deploying solar power systems is growing around the world. In China, it is predicted that a 14-fold increase in PV facilities would be required to meet the 2060 carbon neutrality target. For PV development in China [71]: (1) cost is still a major obstacle currently facing the PV industry; (2) national economic performance and policy incentives have a limited impact on the development of solar PV; and (3) technological innovation and grid absorption capacity are key factors influencing the path of solar PV development. China's 1.7% increase in solar power generation in 2020, due to air pollution controls and stricter air quality targets, could reduce the need for installed PV capacity needed to meet the 2060 carbon neutrality target [72]. The Indian government planned to invest over USD 237 billion in the solar sector and has announced incentives, including funding for up to 70% of project costs and public tax breaks. Renewable energy generation is expected to account for 35% of total electricity generation by 2022, with a solar share of 100 GW [73]. However, solar power still receives little attention in some countries, where they face socio-economic, policy, and technical barriers related to solar electrification [74]. For example, the price of 1 kWh of carbon-fueled electricity generation in Azerbaijan is several times cheaper than the price of 1 kWh of solar power, making it difficult to attract investment in developing solar energy [75]. The current development of solar energy in Vietnam is not commensurate with its potential, and the barriers and challenges to its development are institutional, technical, financial, and economic [76]. In the future, the deployment of advanced optimization technologies in the field of solar power will help to achieve sustainable development in terms of clean energy, emissions reduction, and economic development [77].

2.2.4. Bioenergy Power

Bioenergy is a renewable energy source derived from biological resources. Biomass energy resources can be obtained from agricultural, forestry and municipal waste, including wood, crop residues, sawdust, straw, manure, paper waste, household waste, and wastewater [78]. It can be used to produce biofuels, bioelectricity, and heat [79]. The advantage of using biomass for energy is that biomass contains carbon that plants absorb through photosynthesis. When biomass is used to generate energy, the carbon is released during combustion and simply returned to the atmosphere, making modern bioenergy a promising near-zero-emission fuel. Modern bioenergy is the largest source of renewable energy globally, accounting for 55% of renewable energy and over 6% of the global energy supply [80]. Liu et al. [81] reviewed the common technologies used for biomass power generation, including the steam turbine generator, the high-temperature biomass fuel cell, the microbial fuel cell, and the concept of the low-temperature biomass flow fuel cell. Chen et al. [82] discussed the process flow and characteristics of four biomass power generation technologies: biomass direct combustion power generation, biomass gasification power generation, biomass mixed combustion power generation, and biomass biogas power generation. It was also pointed out that biomass gasification power generation had the best environmental benefits, with an emission reduction rate of 97.69% compared to coal-fired power generation. The use of biomass for power generation has huge potential for carbon reduction. The analysis by Ardebili et al. [83] found that Iran had considerable potential for biopower, with a total potential of about 62,808 $\times$ 10^6 kWh year^{-1}, which represented 27% of the country's total electricity consumption. The GHG emissions reduction from bio-based electricity generation were approximately 4.096 Mt CO_2-eq/year, which represented 0.6% of Iran's annual GHG emissions. The annual biomass power potential of Rajasthan in India was assessed to be 3056 MW, where crop residues contributed 2496 MW, and livestock manure contributed 560 MW [84]. However, the total potential could vary from 2445 MW to 6045 MW depending upon the biomass collection and energy conversion efficiency. Annual emission-saving potential of 11.4 Mt CO_2eq could be achieved by utilizing the locally available biomass in place of coal for power. This emission-saving potential could vary from 8.7 Mt to 22.7 Mt CO_2eq based on biomass power generation capacity. Sagani et al. [85] assessed the potential benefits of using tree pruning biomass for electricity generation in Greece from a techno-economic and environmental perspective. Tree pruning biomass power plants can have a positive impact by not only generating significant annual net electricity production, thereby saving fossil fuel and reducing CO_2 emissions, but also by providing new jobs and income opportunities. Woody biomass helps to reduce fossil emissions from heat and electricity generation in Northern Europe [86], and the use of woody biomass could reduce direct emissions from the electricity and heat sectors in Northern Europe by 4–27% if the carbon price in 2030 is in the range of EUR 5–103/tonne CO_2eq, compared to a scenario where woody biomass cannot be used for electricity and heat generation.

2.2.5. The Importance of Green Power in Carbon Emission Reduction

Global renewable electricity capacity is expected to grow by more than 60% between 2020 and 2026, reaching more than 4800 GW [87]. This is equivalent to the current global fossil fuel and nuclear power generation capacity combined. Green power from renewable energy sources, such as wind and solar, is essential in the low-carbon transition of the entire energy system [88]. Renewable electricity production has negative effects, whereas non-renewable electricity production has a positive effect, on CO_2 emissions [89,90]. This means that the more green power a country uses, the lower its carbon emissions. Electrification is therefore a viable solution for achieving deep decarbonization [91], based on the production of green electricity from renewable sources, and the contribution of electrification to the reduction of energy-related CO_2 emissions would be significantly enhanced, with an increase of 0.038–0.66% in CO_2 emission efficiency for every 1% increase in the share of renewable energy in total electricity generation [92]. Yet without green power, electrification will still bring a continued increase in carbon emissions [93]. In addition to renewable energy power generation, nuclear power is also a focus of carbon emission reduction. Jin et al. [94] investigated the determinants of carbon emissions based on energy consumption, analyzing the data of 30 countries using nuclear energy for the period 1990–2014. The results of the long-run cointegrating vector and Granger causality tests indicated that nuclear energy did not contribute to carbon reduction, unlike renewable energy. Sovacool et al. [95] used multiple regression analyses on global datasets of national carbon emissions and renewable and nuclear electricity production across 123 countries over 25 years to systematically examine patterns in how countries using nuclear power and renewables contrastingly showed higher or lower carbon emissions. They found that larger-scale national nuclear attachments did not tend to associate with significantly lower carbon emissions, while renewables did. They also found a negative association between the scales of national nuclear and renewables attachments. This suggests that nuclear and renewables attachments tend to crowd each other out. Therefore, renewable energy generation should be developed and expanded instead of nuclear power. Moreover, to be truly sustainable, an energy system must meet the following criteria [96]: (1) minimal or no negative environmental or social impact; (2) no natural resource depletion; (3) being able to supply the current and future population's energy demand; (4) equitable and efficient manner; (5) air, land, and water protection; (6) little or no net carbon or other GHG emissions; and (7) safety today without burdening future generations.

3. Green Fuel Production

3.1. Green Hydrogen Production and Challenge of Application to Ship

Hydrogen is considered to be one of the potential future fuels for eliminating GHG emissions from the shipping industry, and it can be produced in several ways from different energy sources. Different production routes are often indicated by colors [97], such as “grey”, “blue”, “blue-green”, and “green”. The material source for grey hydrogen is fossil fuel, and the production of this hydrogen is accompanied by large amounts of CO_2. The most common production process for grey hydrogen is steam reforming [98], where fossil hydrocarbons are catalytically cracked into carbon monoxide (CO) and hydrogen (H_2) in the presence of steam (H_2O) at temperatures of 700–900 °C. The material for blue hydrogen is usually fossil fuel, but the blue hydrogen production process uses CCS. This means that the carbon emissions released during the process are recycled and do not enter the atmosphere. However, in reality, the GHG produced by blue hydrogen production can be quite high. Taking into account the emissions of methane and carbon dioxide, the total carbon dioxide equivalent emissions of blue hydrogen are only 9–12% lower than those of grey hydrogen [99]. Blue-green hydrogen is produced by the pyrolysis of methane, heating the methane to produce hydrogen and solid carbon [100]. In this case, no CO_2 emissions are generated, but the literature is usually limited to the pyrolysis of methane as a single molecule, and the challenges posed by the use of natural gas have not been addressed [101]. Hydrogen that meets certain sustainability criteria is called “green” hydrogen, but there is no universally accepted international definition of green hydrogen. Four key words can be summarized from the different definitions [102]: low-carbon, carbon-free, renewable, and non-renewable. The broad definition of green hydrogen is hydrogen produced from low-carbon energy sources, while the strictest definition entails carbon-free renewable hydrogen production. Countries that are more focused on achieving GHG reductions than on promoting renewable energy and accelerating market uptake tend to consider a broader definition of green hydrogen, including fossil fuel pathways and CCS technology. In contrast, countries that focus more on renewable energy research and innovation tend to limit the definition of green hydrogen to carbon-free renewable hydrogen production. The world’s largest green hydrogen plant [103] has been planned to operate with a capacity of 650 t/day hydrogen production by using electrolysis and 4 GW of renewable energy from solar, wind, and storage in 2025. At present, there are many reviews on green hydrogen production technology. Li et al. [104] discussed the electrochemical water-splitting hydrogen production technology in detail. Gopinath et al. [105] discussed the different methods of photocatalytic water-splitting hydrogen production. Sürer et al. [106] discussed in detail a new method of electrolytic hydrogen production from seawater to meet the demand for hydrogen fuel in ships. These reviews can provide us with an understanding of green hydrogen production technology. Atilhan et al. [107] conducted a critical assessment of the potential use of green hydrogen in the shipping industry by assessing production routes, technical and economic performance, storage, and safety. Creating global hydrogen fuel utilization and demand is a necessary condition for supply chain development to achieve the grand goal of carbon dioxide emission reduction in the shipping industry. The following section briefly describes the production of green hydrogen from electrolytic water and bioenergy, focusing on the challenges of green hydrogen in the shipping industry.

3.1.1. Green Hydrogen Production by Electrolysis of Water

Electrolytic water to hydrogen technology [108] converts water or steam into hydrogen through an electrochemical reaction. With the rise of green power, interest in water electrolysis has increased significantly, and the use of green power for electrolytic water to produce hydrogen is a very promising green hydrogen production technology. There are four types of hydrogen production technologies, namely alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE), solid oxide water electrolysis (SOWE), and anion exchange membrane water electrolysis (AEMWE). Kumar et al. [109] provided an overview of various water electrolysis techniques and the challenges and possible solutions from the point of view of cost reduction and commercialization. AWE is a proven green hydrogen production technology; however, fluctuating and highly intermittent renewable energy sources make it challenging to achieve, as conventional electrolyzers are designed to operate under fixed process conditions [110]. PEMWE has the advantages of high operating current density, high gas purity, high outlet pressure, and a small footprint compared to AWE. Bareiß et al. [111] showed that hydrogen production by PEMWE could reduce CO_2 emissions from the hydrogen sector by 75% if the electrolysis system was run entirely on electricity generated from renewable energy sources. The main challenge associated with this technology, however, is the cost of the components. As a result, significant developments are required to reduce costs. AEMWE can challenge the state-of-the-art in PEMWE electrolysis systems and has cost advantages [112]. However, the limited durability of anion exchange membrane cells remains a challenge to be addressed in the future [113]. SOWE is an emerging and highly efficient electrolytic technology [114]. Solid oxide electrolytic cells (SOECs) offer two main advantages over other electrolytic technologies. First, their high operating temperatures result in favorable thermodynamics and reaction kinetics, enabling unparalleled conversion efficiencies. Second, SOECs can be thermally integrated with downstream chemical synthesis, such as methanol, dimethyl ether, synthetic fuel, or ammonia production. A techno-economic analysis of AWE, PEMWE, SOWE with an electric heater, and SOWE with a waste heat source was carried out by Jang et al. [115]. The results showed that the solid oxide water electrolysis combined with a waste heat source had the best economics. The main challenge, however, is durability, so major improvements in this area to improve durability are essential.

There are two reactions [116] in the process of water electrolysis: oxygen evolution reaction (OER) at the anode and hydrogen evolution reaction (HER) at the cathode. Noble metal catalysts are usually used for HER and OER reactions, but precious metals are expensive and have low availability as catalysts for water electrolysis, which hinders their practical application. In recent years, non-noble metal electrocatalysts for OER and HER reactions have been extensively studied to reduce or replace the use of noble metals. However, the preparation of non-noble-metal catalysts that can exceed the performance of noble metals remains a challenge [117].

Oxygen evolution reaction (OER):

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{1}$$

Hydrogen evolution reaction (HER):

$$4H^+ + 4e^- \rightarrow 2H_2 \tag{2}$$

Hydrogen production by water electrolysis is an active research field. Guo et al. [118] demonstrated that water in the air could be directly used for hydrogen production by electrolysis, demonstrating a method for direct hydrogen production from the air by in situ capture of fresh water in the atmosphere (hygroscopic electrolytes) and then electrolysis to produce hydrogen using solar or wind power. Li et al. [113] reported an ammonia-rich anion exchange ionomer that could improve the performance of an AEM electrolyzer, bringing it close to the most advanced proton exchange membrane electrolyzer. Lee et al. [119] proposed a base water electrolysis system based on a lithium-ion exchange membrane. Compared with traditional AWE, the system exhibited a current density 3 times higher at 1.7 V. Sanchez et al. [120] studied methanol-water electrolysis for hydrogen production. The results showed that methanol-water electrolysis required much less electricity than water electrolysis (about 65%).

The demand for high-purity water for electrolysis and the wide availability of seawater led people's attention to the electrolysis of seawater for hydrogen production [121]. However, there are problems with direct electrolysis using seawater [122]: low power density operations and the possibility of electrolysis of only a small portion of water in contact with the electrode, corrosion and contamination problems, and the generation of unwanted electrochemical products such as chlorine. Wang et.al. [123] reported an outstanding anodic catalyst consisting of a three-dimensional standing array of hetero-lateral Ni_3S_2/Co_3S_4 (NiCoS) nanosheets uniformly grown on Ni foam for alkaline seawater electrolysis, in which the in situ-derived Ni/Co(oxy)hydroxide surface layer provided abundant active sites and superior resistance to chloride corrosion. Liu et al. [124] used solid oxides to electrolyze seawater. The electrolysis was carried out at a constant current density of 200 mA/cm^{-2} for 420 hours. The hydrogen production rate was 183 mL/min, and the degradation rate was 4.0%. An energy conversion efficiency of 72.47% is achieved even without reusing high-temperature exhaust gas. It showed that the solid oxide electrolytic cell had an excellent performance in seawater electrolysis. Despite some achievements, the development of active, stable, and selective catalysts remains the most difficult challenge in seawater electrolysis [125].

3.1.2. Green Hydrogen Production from Biomass

Biomass [126] is plant or animal material that stores chemical and solar energy. Biomass contains large amounts of hydrogen, and of the various renewable resources, only biomass can produce hydrogen directly. The rest of the renewable resources require electrolysis to produce hydrogen. Moreover, by considering the absorption of CO_2 by growing plants for photosynthesis, the hydrogen produced is close to carbon neutral, making biomass an ideal raw material for hydrogen production. There are many biological methods of hydrogen production [127], which are briefly described in this section according to the thermochemical, biochemical, and bioelectrochemical methods.

Thermochemical methods for hydrogen production mainly include gasification, pyrolysis, and reforming. A review of thermochemical routes for hydrogen production from biomass, which have a high potential for industrial application compared to other biomass treatment routes, was presented by Arregi et al [128]. Steam gasification of biomass is one of the main thermochemical routes studied in the literature, and steam gasification is considered to be one of the most efficient technologies for generating hydrogen from biomass. Steam gasification provides the highest stoichiometric yield of hydrogen of all thermochemical processes. Several factors affect the yield of hydrogen in steam gasification. Some of the prominent factors are [129]: biomass type, biomass feed size, reaction temperature, steam-to-biomass ratio, catalyst addition, and sorbent-to-biomass ratio.

Biochemical methods for hydrogen production mainly include photolysis (direct and indirect) [130,131], and fermentation (light and dark) [132]. The main advantages of using biomass to produce hydrogen via the fermentation route are the absence of greenhouse gas emissions and the high potential to reuse waste biomass as a renewable feedstock. The use of dark fermentation as a sustainable biorefinery process with an ecological and economic approach to hydrogen production is a promising but challenging approach in the field of bioenergy [133]. Improved fermentation microbial hydrogen production and hydrogen plant planning using advanced technologies could lead to viable and sustainable hydrogen production [134].

Microbial electrolytic cell (MEC) technology [135] is a bioelectrochemical approach to hydrogen production using anodic bio-catalytic oxidation and cathodic reduction processes. It is one of the most attractive green hydrogen production technologies of the future because not only does it produce higher yields of hydrogen than other biotechnologies, it requires a lower external energy input than water electrolysis. However, it also requires the application of an external power source, which inevitably makes MEC systems a less sustainable option. Hybrid light-assisted MEC and other renewable energy MEC hybrid systems are promising ways to achieve self-sustainable hydrogen production [136].

3.1.3. Potential Application of Green Hydrogen in Ship

There are two main forms of hydrogen application on ships: hydrogen internal combustion engines and fuel cells. Fernández-Ríos et al. [137] conducted an environmental assessment of two promising ship propulsion technologies, H_2 polymer electrolyte membrane fuel cell (PEMFC) and H_2 internal combustion engine (ICE), to determine their feasibility and eligibility compared with a traditional diesel internal combustion engine. The conclusion: ICE was the most sustainable alternative; in other words, PEMFC had worse environmental performance. However, this was only an assessment based on the current level of the technology, and the sustainability of the technology may change as it is widely deployed and developed.

The technology of green hydrogen production is booming. The use of green power for electrolytic water production of green hydrogen is expected to achieve commercial adoption. Hydrogen internal combustion engines [138] and hydrogen fuel cells [139] help ships achieve cleaner and longer-distance transportation. The production or final use of green hydrogen may not be the bottleneck for the application of green hydrogen to ships. The main challenge for the application of green hydrogen to ships is the storage of H_2. In response to this challenge, a variety of different storage technologies have been developed, which can be divided into two categories: physical-based and material-based. The main hydrogen storage technologies with potential applicability for ships are shown in Figure 2 [140,141]. Details of the technology can be found in [141]. Wang et al. [142] summarized the latest technology of hydrogen storage in ships, focusing on the mechanical testing, selection of materials, and failure mechanisms for cryo-compressed and liquid hydrogen tanks and their insulation. For marine applications, there is currently a lack of research on ship storage tanks. The material selection and failure mechanism of hydrogen storage tanks and insulation layers have not been fully understood. Van et al. [143] evaluated the usefulness of several hydrogen storage methods, including compressed hydrogen, liquid hydrogen, ammonia, Fischer–Tropsch diesel, synthetic natural gas, methanol, formic acid, aromatic liquid organic hydrogen carriers, and several solid hydrogen carriers: MgH_2, $NaAlH_4$, AB_2-Laves phase alloys, $NaBH_4$, and NH_3BH_3. The results showed that no storage method combined high energy density, low energy input, easy availability of all resources, non-toxicity, and easy processing and storage. In addition, carrying large amounts of hydrogen on board in harsh marine environments is inherently a risky operation [143]. Hydrogen is extremely flammable and has little flame radiation, making it difficult to detect flames. Another associated risk is the explosion.

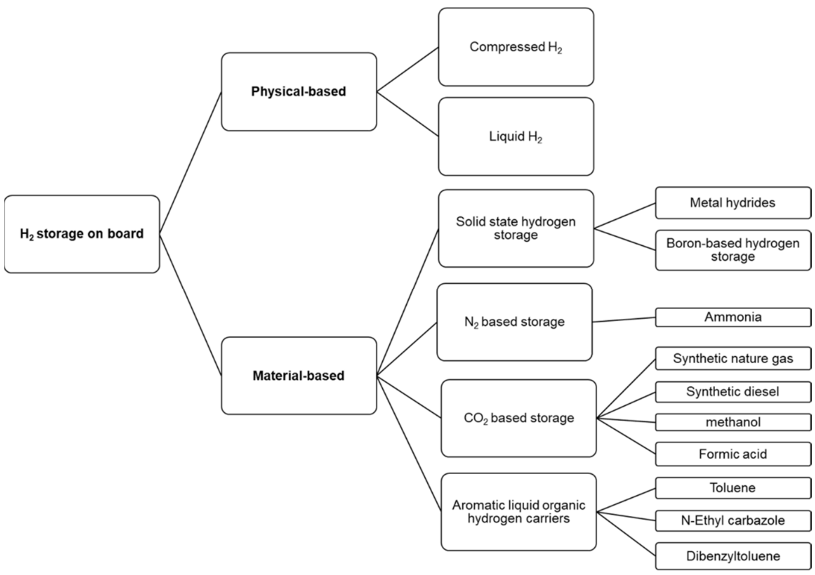

Figure 2. Potential onboard hydrogen storage technology.

Producing hydrogen directly on ship or establishing offshore hydrogen refueling facilities are also possible ways to cope with the challenge of H_2 storage. Li et al. [144] explored a new technology combining photovoltaic and photoelectric catalysis, and designed and manufactured a photovoltaic-photocatalysis (PPC) hydrogen production system to achieve efficient solar hydrogen production. The maximum solar hydrogen production efficiency of the system was higher than 9.82%. In a real ship experiment, the hydrogen production system produced 63 Nm^3 (2813 mol) of hydrogen per day, which could generate 96 kWh of electricity after conversion by the fuel battery pack. At the same time, the effects of energy saving and emission reduction were also obvious, reducing 6.1 tons of diesel consumption and 18.9 tons of carbon dioxide emissions every year. Bonacina et al. [145] proposed an offshore liquefied hydrogen production and ship refueling plant, as shown in Figure 3. The plant includes wind power plants for renewable power generation, electrolyzers for hydrogen production, water treatment units for desalination, and hydrogen liquefaction plants, as well as hydrogen storage and distribution to ship. For each device, the most suitable technology for offshore hydrogen production applications is selected from existing technologies. This type of factory is economically viable and can be replicated similarly in different locations by rescaling different selected technologies. The marine configuration avoids the problem of space occupation on land and simplifies ship refueling. Platforms formerly used in the oil and gas industry can be reused to accommodate plants producing liquefied green hydrogen.

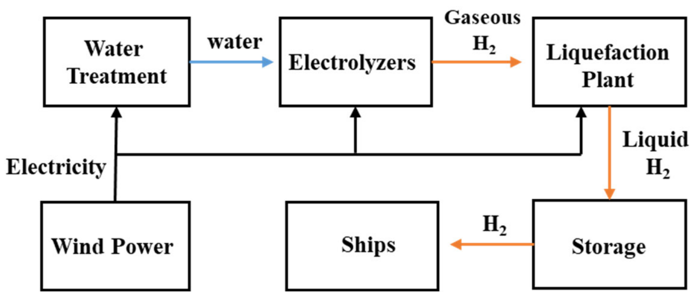

Figure 3. Offshore liquefied hydrogen production and ship refueling plant [145].

Compared with green hydrogen, grey hydrogen is still more cost-effective [146]. However, advances in various technologies for the production of green hydrogen have gradually given green hydrogen a cost advantage and may replace traditional hydrogen production. Onboard hydrogen storage still faces challenges. It is particularly noteworthy that it is not only the technology for onboard storage of H_2 that faces challenges but also the development of hydrogen supporting facilities and the establishment of a complete hydrogen production and hydrogenation system. Hydrogen is expected to be applied to ships soon.

3.2. Potential of Green Ammonia Production and Application on Ship

Ammonia production routes are divided into three different terms and defined by color: brown, blue, and green. Brown ammonia is fossil ammonia produced from coal, oil, or natural gas, and accompanied by a large amount of CO_2 emissions. Blue ammonia is also fossil ammonia, but the carbon capture system is integrated into ammonia production. Green ammonia is ammonia resulting from a carbon-free production process. The production route uses renewable energy (solar energy, wind energy, etc.). The Haber–Bosch (HB) process [147] is currently the main route for ammonia production. Gaseous N_2 and H_2 react to form NH_3 in the presence of an iron-based catalyst at high pressure (>100 bar) and temperature (~500 °C). NH_3 is carbon-free, so its decarbonization depends largely on the source of H_2. Traditional NH_3 production is based on natural gas steam reforming to produce H_2, accompanied by CO_2 emissions. Three possible decarbonization methods are currently being considered: (1) capture CO_2 by carbon capture technology in the traditional HB process, and then transport CO_2 through pipelines for storage or utilization; (2) improve the HB process and use renewable energy to produce hydrogen by electrolysis of water; (3) develop alternative production methods, such as electrochemical methods. Compared with the traditional natural-gas-based HB ammonia production method, the new ammonia production with carbon capture technology can reduce greenhouse gas emissions by 55–70% [148], which has significant potential. However, due to the sharp decline in the cost of hydrogen production from renewable energy, its cost may not be competitive in the future. Therefore, the following section focuses on the latter two methods, especially reviewing the latest alternative green ammonia production methods, to provide readers with a more comprehensive map of green ammonia production methods.

3.2.1. Green Hydrogen + HB Process

As shown in Figure 4, improving the HB process to produce hydrogen from renewable energy provides a feasible green ammonia production route. The ongoing active research and development in academia and industry are likely to push this technology to the forefront of sustainable hydrogen production [149]. Green ammonia production based on hybrid photovoltaic wind power plants shows great global potential [150,151]. Using solar photovoltaic and wind and battery energy storage systems as a balancing technology, the 100 MMTPA Green Ammonia Plant in Gladstone, Australia, will begin operation in 2030 with an estimated LCOA of between USD 690 and 920/tonne [152]. The cost of converting renewable hydrogen to ammonia depends largely on geographical conditions and systems must be installed in countries with very low electricity costs to be profitable [153]. In 2030, 2040, and 2050, up to 10 billion tons of ammonia based on on-site renewable electricity can be produced annually at the most suitable locations in the world, with costs ranging from EUR 345–420/tonne, EUR 300–330/tonne, and EUR 260–290/tonne, respectively. For such power generation costs, green ammonia production may be cost competitive in the niche market by 2030. After 2030, with the reduction of renewable energy and balanced technology costs, green ammonia production may be higher [150].

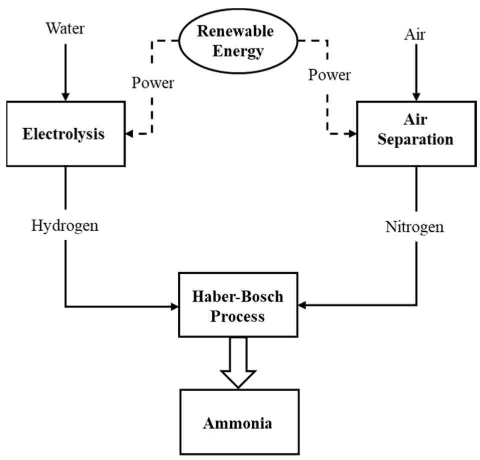

Figure 4. Green ammonia production process using green hydrogen + HB process.

3.2.2. Alternative Production Methods

Green hydrogen + HB production produces almost no greenhouse gases. However, the disadvantage of this method is the use of two separate reactors (one for hydrogen production and the other for ammonia production), and the HB reactor requires additional energy to compress the raw gas. Electrochemical, photocatalytic, and biocatalytic methods have been proposed as alternative ammonia production methods.

(1). Electrochemical nitrogen reduction reaction to produce ammonia

The electrochemical nitrogen reduction reaction (NRR) for ammonia synthesis has attracted extensive attention from researchers because the direct conversion of N_2 to NH_3 completely avoids the need for the Haber–Bosch process [141,154]. As shown in Equation

(3), it is feasible to produce ammonia by NRR using protons in water as hydrogen sources at room temperature and atmospheric pressure. If the electricity comes from renewable energy, the method can produce ammonia from water and air (N_2) in a carbon-neutral manner at room temperature and atmospheric pressure. Kaiprathu et al. [155] discussed the reaction mechanism of the N_2 reduction reaction in detail. Unfortunately, in this process, the electrochemical reduction of N_2 to NH_3 competes with the hydrogen evolution reaction (Equation (2)), which reduces the Faraday efficiency by reducing proton (H^+) to H_2, meaning that ammonia production in this process is very challenging.

$$N_2(g) + 6H^+(aq) + 6e^- \rightleftharpoons 2NH_3(aq) \tag{3}$$

The production of ammonia by electrochemical nitrogen reduction reaction is an active research field, and the development of catalysts is a research hotspot. Mo-based electrocatalysts have a strong ability to catalyze NRR. Considerable progress has been made in the production and structural adjustment of Mo-based catalysts. Arif et al. [156] reviewed the research progress of Mo-based electrocatalysts in recent years and described reasonable modulation techniques to prepare various types of Mo-based catalysts. Iron-based catalysts are feasible and efficient. Wang et al. [157] reviewed the research progress of iron-based electrocatalysts in electrochemical nitrogen reduction reactions. The coordination environment and synergistic effect have a significant effect on the activity and selectivity of iron-based catalysts, and low-valent iron atoms are more likely to form strong bonds with N_2 molecules. Adjusting the coordination environment and electronic structure are the keys to improving the catalytic performance of iron-based catalysts. Li et al. [158] reviewed the research progress in the design strategies of high-efficiency NRR electrocatalysts in recent years. Yang et al. [159] systematically discussed strategies to improve the reactivity and selectivity of catalysts and catalytic systems. Although electrocatalysts have made great progress, they still cannot meet the demands of practical applications in terms of NH_3 yield, NH_3 separation, and catalyst stability. Therefore, it is still important to develop practical catalysts.

(2). Electrochemical nitrate reduction reaction

The electrocatalytic nitrate ($NO_3{}^-$) reduction reaction (NO_3RR) at room temperature and pressure provides another method for ammonia production. This method is easier to implement than the electrochemical nitrogen reduction reaction. Theerthagiri et al. [160] reviewed the research progress of electrocatalytic nitrification of industrial and agricultural wastes to ammonia, focusing on catalysts, reaction intermediates, side reactions, and reaction conditions. Cu-based catalysts have obvious advantages in the $NO_3{}^-$ reduction reaction. Zheng et al. [161] reported the first zero-valent copper atom catalyst that converted $NO_3{}^-$ to NH_3 at room temperature and pressure, with excellent catalytic activity and efficiency. Teng et al. [162] reviewed the research progress of copper-based catalysts in electrocatalytic NO_3RR in recent years. However, there is still a lack of efficient and selective electrocatalysts for the large-scale production of ammonia from nitrate-containing wastewater, which provides a large number of research opportunities.

(3). Solar photocatalysis

A more sustainable and environmentally friendly ammonia production process is solar photocatalysis ammonia synthesis. Photocatalysts effectively capture solar energy, which is then used to generate electrons to reduce N_2 to NH_3 under environmental conditions. The detailed mechanism of photocatalytic ammonia synthesis can be read in [163]. Zhang et al. [163] reviewed the development of photocatalytic ammonia synthesis. Some photocatalytic materials have been found to have a positive effect on photocatalytic ammonia synthesis: semiconductor oxides materials (such as Fe_2O_3, WO_3, ZnO, Ga_2O_3), metal sulfides, bismuth oxyhalides, carbonaceous materials, layered double hydroxides, biomimetic photocatalysts, and biohybrid complexes. The discovery of the above potential materials encourages more extensive research in this field. Hui et al. [164] discussed in detail the research progress of tungsten-based and other related photocatalysts. With the development of photocatalytic ammonia synthesis technology, pure N_2 in the nitrogen source for the synthesis of NH_3 is gradually replaced by air, and the ultraviolet light source is gradually replaced by visible light [165]. However, there is still no meaningful NH_3 production rate, and industrial application is facing severe challenges.

(4). Biocatalysis

Another alternative pathway for sustainable ammonia synthesis is the biotechnological pathway, using nitrogenase organisms to produce ammonia. Bacteria convert N_2 and H^+ to NH_3 and H_2 using an enzyme called nitrogenase. Nitrogenase is a two-component metalloenzyme composed of Fe-protein and Fe-Mo-protein. Fe-protein, an ATP-dependent enzyme, contains a Fe-S cluster that provides electrons for the catalytic component. Fe-Mo-protein is a catalytic component that binds N_2 and converts it into NH_3. A significant attraction of nitrogenase is that it can reduce N_2 to ammonia at room temperature and pressure. However, the industrial application of this enzyme for fuel production still needs to overcome many obstacles, such as the poor stability of protein-based catalysts. Rapson et al. [166] analyzed in detail the obstacles and opportunities of solid enzymes for energy production.

3.2.3. Potential of Green Ammonia Application on Ships

Green ammonia has always been considered one of the most promising alternative marine fuels to reduce greenhouse gas emissions in the shipping industry, which can be burned in engines and used in fuel cells [167]. Green ammonia has great potential to be applied to ships [168]. Ammonia has attracted more and more attention as a solution to decarbonization in the maritime industry. The deployment of green ammonia can start using technologies familiar to the maritime sector: diesel or dual-fuel engines on new ships and existing ships [169]. Large shipping companies and engine manufacturers are guiding their research activities to demonstrate and commercialize ammonia in ships. According to Bicer et al. [170], based on life cycle analysis, the use of ammonia as a dual fuel in marine engines can reduce total greenhouse gas emissions to 33.5% per tonne-kilometer, and if only ammonia is used in the engine, this number increases to 69%. Zincir et al. [171] evaluated the environmental and economic effects of ammonia-diesel dual-fuel engines through case studies of actual ship navigation data. The CO_2 emission of brown ammonia was worse (137.7%) or slightly lower (3%) than MDO, depending on the feedstock. The carbon dioxide emission reduction of blue ammonia was 42.8%, while that of solar green ammonia was similar to blue ammonia, and the CO_2 emission reduction of wind green ammonia was 79.2%.

Several key obstacles to the widespread use of green ammonia are as follows [172]: (1) high production costs due to high capital costs associated with the ammonia supply chain; (2) availability—in particular, the limited geographical location for ammonia fuel replenishment; (3) the challenge of increasing current ammonia production; (4) to formulate special regulations on the toxicity, safety, and storage of ammonia. Ammonia is a safer fuel than hydrogen, with lower cost, fewer storage problems, and higher sustainability [173]. Although scientific and industrial circles attach great importance to ammonia, the practical application of ammonia fuel in internal combustion engines is still limited [174]. Toxicity and poor combustion performance limit ammonia as a direct alternative to standard fuel in internal combustion engines. When using pure ammonia, a higher boost and compression ratio are required to compensate for the low ammonia flame speed. In a spark ignition engine, adding hydrogen to ammonia helps to accelerate flame front propagation and stabilize combustion. In a compression ignition engine, ammonia can be successfully used with diesel in dual-fuel mode. The increase of NOx and unburned NH_3 in exhaust gas require corresponding after-treatment systems. N_2O is a significant greenhouse gas. N_2O emission from ammonia combustion makes the greenhouse gas emission reduction benefits of ammonia uncertain. If the nitrogen released by ammonia is not strictly controlled, it will significantly change the global nitrogen cycle [175].

3.3. Potential of Green Methanol Production and Application on Ships

Methanol contains no sulfur and has a lower calorific value than conventional fuel, resulting in lower NOx emission, and is therefore promoted as a clean marine fuel. Commercially, methanol is produced from natural gas via syngas. This includes two processes: steam reforming of methane and methanol production. The approach consumes a lot of energy and emits CO_2, which is not conducive to the sustainable development of human beings. Methanol production is classified as renewable or green when (1) the carbon source is waste, (2) hydrogen is not produced from fossil fuel sources, and (3) energy comes from renewable resources [176]. Two main ways to produce green methanol are (1) producing methanol from biomass and (2) producing methanol from CO_2.

3.3.1. Producing Methanol from Biomass

For the former, methanol can be produced by biomass or waste gasification, biogas upgrading, or as a by-product of wood pulping. Biomass gasification to methanol is a feasible way, with high technical maturity and a commercially competitive market price [177]. De Fournas and Wei [178] conducted a technical-economic and environmental assessment of renewable methanol produced from the gasification of California forest residues. More specifically, even if much lower than in Northern California, the forest residue quantities available in Southern California could potentially meet 30% of the San Pedro Bay Port Complex fuel demand for medium-range shipping. Nugroho et al. [179] recommended using biogas for methanol production, considering the capacity of biogas digesters to absorb carbon dioxide and the low capital investment, as well as the economic attractiveness to investors in methanol production.

3.3.2. Producing Methanol from CO_2

For the latter, methanol is produced by the hydrogenation of carbon dioxide [180], in which the CO_2 feedstock comes from industrial sources, direct air capture, and so on. This usually involves one of two methods: direct hydrogenation and indirect hydrogenation. Direct hydrogenation of CO_2 to methanol by direct activation of CO_2 with H_2 under the action of a catalyst is mainly divided into three methods: thermochemical synthesis, electrochemical synthesis, and photochemical synthesis. Biswal et al. [181] reviewed the progress of various methods for converting CO_2 into methanol using several homogeneous and heterogeneous catalysts. Since the traditional methanol synthesis catalyst ($Cu/ZnO/Al_2O_3$) is used in the direct synthesis process, the CO_2 conversion rate is low. Therefore, an indirect hydrogenation method is proposed, that is, carbon dioxide hydrogenation to methanol via reverse water gas shift reaction (CAMERE). First, syngas is produced by CO_2 hydrogenation in a reverse water gas shift (RWGS) reactor, and then the syngas is transported to the reactor as a raw material to produce methanol [182]. In general, the catalysts for CO_2 hydrogenation to methanol mainly include the following three types: (1) Cu-based catalysts with Cu as the main active component; (2) supported noble metal catalysts, represented by Pd-based catalysts; (3) metal oxides with semiconductor properties, such as In_2O_3. Researchers have conducted a lot of experiments focusing on the mechanism of the reaction, which is the key information for the development of the next generation of catalysts. At least three possible mechanisms have been proposed, namely the formate pathway, RWGS pathway, and trans-COOH* pathway [183]. Cu-based catalysts have been widely studied due to their low cost and effective synthesis of methanol ($Cu/ZnAl_2O_4$ [184], $CuZrO_2$ [185]). Niu et al. [186] reviewed the structure and surface properties of Cu-based catalysts and their effects on the reaction mechanism and further discussed the effects of Cu-based catalysts on the selectivity, stability, and activity of CO_2 hydrogenation to methanol. Combining experimental work with theoretical analysis can accelerate the pace of catalyst innovation, and it is inevitable to adopt an interdisciplinary approach. In addition, with the rapid development of computational science, the application of big data technology to molecular simulation will further promote the computational catalytic design and preparation of CO_2 conversion catalysts. However, there are still some problems, such as the low unidirectional conversion of CO_2 hydrogenation to methanol catalyst, RWGS reducing the utilization rate of carbon atoms, easy deactivation of catalyst, and unclear reaction mechanism. In_2O_3 is of great significance in the process of CO_2 hydrogenation to methanol due to its selectivity. For most In-based catalysts, oxygen vacancies on the surface of In_2O_3 are active sites for adsorbing and activating CO_2. However, the single conversion of CO_2 over In_2O_3 catalyst is relatively low, which still leads to low methanol yield. Shi et al. [187] prepared MIL-68(In)-derived In_2O_3 hollow tube catalysts with CO_2 conversion of 14.0% and methanol selectivity of 65%. They showed good methanol activity. Zhang et al. [188] synthesized a Co-In catalyst with excellent structure from layered double hydroxides. At 350 °C, the conversion of CO_2 was 13.8%, and the selectivity of CH_3OH was 83.7%. Sun et al. [189] supported Pt on In_2O_3 and believed that the strong metal–support interaction between Pt and In_2O_3 enhanced the stability of the catalyst and prevented the excessive reduction of In_2O_3, improving the activity of methanol production. Further, Sun et al. [190] added ZrO_2 to Pt/In_2O_3, and the oxygen vacancies of ZrO_2-modified In_2O_3 promoted the activation of CO_2. The synergistic effect of Zr-modified oxygen vacancies and Pt catalyst promoted the hydrogenation of CO_2 to methanol via the formate route. This is different from the CO hydrogenation route of Pt/In_2O_3.

3.3.3. Potential of Applying Green Methanol to Ships

Methanol has attracted increasing interest in the shipping sector as a low-greenhouse-gas-emission solution for the following main reasons [191–193]:

(1) Methanol is easy to store and transport, and its supply chain can be established with minor modifications to existing infrastructure. Methanol is liquid at ambient temperature and pressure, which makes it easier and cheaper to transport and store on board than gaseous or cryogenic fuel (e.g., liquid hydrogen, liquefied natural gas). Since methanol and diesel have similar physical properties, existing conventional fuel transport and storage infrastructure would only require minor modifications to supply methanol as a marine fuel. Meanwhile, over the past decades, chemical and other industries have gained experience in transporting methanol around the world. There are currently more than 100 ports around the world where methanol can be loaded and unloaded, so the infrastructure to transport and supply methanol as a bunker fuel is available in many ports.

(2) A large number of studies have been carried out to explore various aspects of methanol utilization in engines. Saxena et al. [194] presented a detailed analysis of the effect of methanol on performance, combustion, and emission (NOx, CO, HC, and soot) characteristics on a conventional compression ignition engine.

(3) Existing international guidelines guide the safe use of methanol as a marine fuel: IMO has approved the Interim Guidelines for the Use of Methanol and Ethanol on Ships.

(4) Methanol poses less threat to human health and the marine environment than traditional fuel and ammonia: methanol is toxic, but its toxicity is lower than ammonia. Moreover, compared with diesel or heavy fuel oil, methanol is less harmful to the environment because it can be dissolved in water and can be rapidly biodegradable in case of leakage.

Previous studies have shown that adding water to methanol fuel during combustion can help the engine meet the IMO Tier III NOx emission standard, without using expensive selective catalytic reduction or an exhaust gas recirculation system. Therefore, compared with ammonia fuel, which needs to use an SCR after-treatment device to control the emission of NOx, methanol is a relatively low-cost marine fuel option for controlling air pollution. At present, the biggest obstacle to using methanol as a low-emission marine fuel is not the operation on board, but finding the source of supply of low- or zero-emission methanol. Ishaq et al. [195] evaluated a system for the synthesis of methanol, dimethyl ether, and methane from hydrogen production by electrolysis of CO_2 using renewable electricity. Studies have shown that methanol provides a relatively low cost and the highest chemical conversion efficiency (H_2 to fuel). Methanol is considered to be a more promising approach than other carbon-based synthetic fuels. Considering global warming, methanol can greatly help the utilization and removal of CO_2. However, methanol is carbon-containing. When a ship uses methanol, other measures need to be taken to achieve near-zero carbon emissions. The HyMethShip (Hydrogen-Methanol Ship Propulsion Using On-board Pre-combustion Carbon Capture) project [196], funded by the EU's Horizon 2020 research and innovation program, provides a promising marine methanol application solution. As shown in Figure 5, the hydrogen produced by the electrolytic cell supplied by renewable energy is used together with the captured carbon to produce green methanol. The production of green methanol is used as a hydrogen carrier stored on the ship. There are two propulsion modes of the engine: one is to use methanol directly, and the other is to pump methanol into the pre-combustion system (reforming system). In a membrane reformer, methanol and water are converted to H_2 and CO_2. Hydrogen is used to propel the ship. CO_2 is captured and liquefied and stored on the ship, then transported to a port where it is stored and involved in the synthesis of green methanol. The concept allows the ship's propulsion system to have an almost closed carbon dioxide cycle, and CO_2 emission reduction of 97%, in addition to NOx emission reduction of more than 80%, eliminating SOx and particulate emissions. Life cycle assessment shows that the scheme has less impact on acidification, climate change, marine eutrophication, particulate matter, photochemical ozone formation, and terrestrial eutrophication than internal combustion engines using marine gas oil (sulfur content of 0.1%), bio-methanol, fossil methanol, or electro-methanol. This technology can be used as an alternative to reduce the impact of shipping on the climate [197].

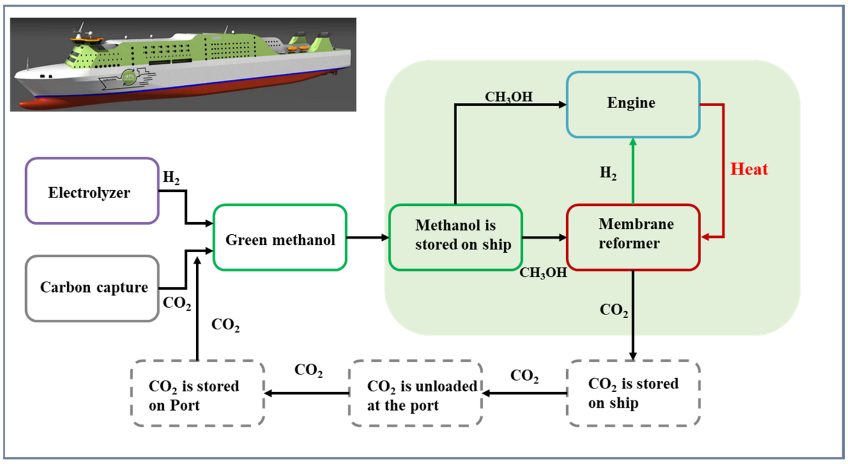

Figure 5. HyMethShip project diagram.

Green methanol is a technically feasible option to reduce shipping emissions, and there are no significant challenges in the potential supply chain [198]. McKinlay et al. [199] estimated that to meet the demand of 50,000 ships per year, the annual production of methanol needs to increase by 859%. Although the methanol fuel engine cannot replace the dominant position of the diesel engine at present, it is believed that the green methanol engine has unlimited prospects, and future solutions can be expected from extensive consideration of the source of green methanol.

3.4. Summary

Table 2 shows the green fuel production methods mentioned in this paper, along with the advantages and challenges of their application to ships. The dominant technology in the green fuel pathway from renewable energy to ships is the use of green power for fuel. The hydrogen produced through the electrolysis of water is in turn the feedstock for green ammonia and green methanol production. The key technologies for green power and green hydrogen production are therefore likely to be the key technologies for renewable-energy-to-fuel conversion. It is also important to improve the efficiency of existing green ammonia and green methanol production technologies and to develop new production technologies. Therefore, our suggestions are as follows: improve green power production technologies to reduce the production cost; develop electrochemical production fuel technology to increase the efficiency of green fuel production; and explore new technology.

Table 2. Production methods of green hydrogen, green ammonia, and green methanol.

Fuel	Production Method	Advantages in Ship	Challenges in Ship
Hydrogen	♦ Electrolytic water ♦ From biomass	a. Low toxicity; b. The leakage has less impact on the environment; c. No CO_2 emission.	a. High storage and transportation costs; b. High explosive risk; c. Lack of fuel supply infrastructure.
Ammonia	♦ Green hydrogen + HB process ♦ Electrochemical nitrogen reduction reaction ♦ Electrochemical nitrate reduction reaction ♦ Solar photocatalysis ♦ Biocatalysis	a. Low flammable risk; b. Easy to store and transport; c. Goods that have been traded globally; d. No CO_2 emission.	a. High toxicity; b. Possible N_2O emission and ammonia slip; c. Poor combustion characteristics; d. Lack of fuel supply infrastructure; e. No safety regulations; f. Corrosive to some materials.
Methanol	♦ From biomass ♦ From CO_2	a. Methanol-powered engine has been commercialized; b. Easy to store and transport; c. The leakage is less harmful to the environment than traditional fuels; d. The existing fuel supply infrastructure can be used with only minor modifications; e. The cost of using methanol to transform the engine in service is lower than that of other alternative fuels; f. The IMO has adopted provisional safety guidelines; g. Goods that have been traded globally.	a. High explosive risk; b. Corrosive to some materials.

For offshore shipping, as shown in Tables 1 and 2, the most promising current fuel solution with low or zero greenhouse gas emissions is methanol, due to its higher energy density and the advantages of being relatively easy to store and handle, with no significant challenge in the potential supply chain. Ammonia also has a high energy density, but a more difficult application than methanol due to ammonia's toxicity and poor combustion properties. Currently, major global marine engine manufacturers are actively developing ammonia-fueled engines, and green ammonia may be the most promising low/zero-greenhouse-gas-emissions fuel solution for the next decade. Challenges of storing hydrogen on board have not been solved; however, in the long term, if fuel supply infrastructure on busy shipping routes can be strategically planned and developed, hydrogen-powered ships will become a priority for ocean shipping. The path towards decarbonization of shipping through the production and application of green marine fuel is becoming clear. Therefore, strengthening the research and development of renewable energy use in green fuel production technology and expanding fuel production capacity to ensure adequate supply of low- and zero-emission marine fuel is essential for reducing carbon emissions from ships.

4. Conclusions

The main production methods of green power, green hydrogen, green ammonia, and green methanol are summarized in Figure 6. The application potential of green hydrogen, green ammonia, and green methanol on ships is analyzed. The main conclusions are as follows:

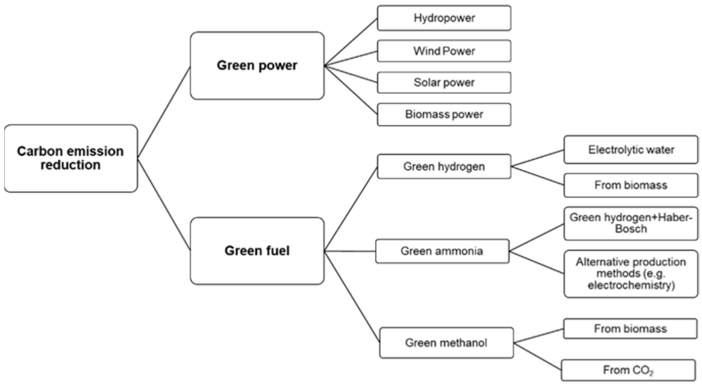

Figure 6. Production methods of green power, green hydrogen, green ammonia, and green methanol.

Using green fuel to replace traditional fossil fuel is an effective way for the maritime sector to reduce carbon emissions. Green fuel is mostly produced from green power, and the production of green fuel is promoted by the technological progress of renewable energy such as wind energy and solar energy. Therefore, green power generated by renewable energy is crucial in the low-carbon transformation of the maritime sector. Supporting and developing marine renewable energy power generation technology and then producing green fuel according to the environmental characteristics of ship operation may help the maritime sector to decarbonize. In the short term, onboard carbon capture technology can reduce CO_2 emissions in the maritime industry and provide the necessary time for the maritime sector to fully develop and use green fuel.

Electrolysis of water to produce hydrogen using green electricity is promising, and seawater electrolysis may be the key technology to obtain hydrogen for ships. However, the main challenge of applying green hydrogen to ships is the storage of H_2 on ships. Developing hydrogen-supporting facilities, and establishing a complete hydrogen production and hydrogenation system, may be the feasible solution.

Hydrogen production from renewable energy provides a feasible green ammonia production route, showing great global potential. At the same time, researchers are actively exploring breakthroughs in electrochemistry, photocatalysis, and biocatalysis to achieve cleaner and more efficient ammonia production. Ammonia is a safer, cheaper fuel than hydrogen and has no onboard storage problems compared with H_2. All of these factors indicate that ammonia is more suitable for application on ships than hydrogen. However, if the nitrogen released by ammonia is not strictly controlled, it may significantly change the global nitrogen cycle.

Methanol production from CO_2 has a bright prospect. It is technically feasible for engines to use methanol, and there are no major challenges to the potential supply chain of green methanol. Therefore, compared with hydrogen and ammonia, green methanol is easier to apply to shipping. Considering that methanol contains carbon, a relatively closed carbon cycle can be achieved by combining carbon capture technology, and the captured CO_2 can then be used to produce methanol.

It is worth mentioning that biomass is a potential form of renewable energy. Biomass can produce green fuel such as hydrogen, ammonia, and methanol through thermochemistry, electrochemistry, and biochemistry. Therefore, it is suggested to produce green fuel in areas rich in biomass energy, and then transport the fuel to the port, which may meet the demand of some ships for green fuel.

Finally, from the perspective of the universality of raw materials and the diversity of technologies for the production of green hydrogen, green ammonia, and green methanol, as well as the reduction of the production cost of green power, it is concluded that the future of the application of green fuels in shipping is bright. It is believed that green fuels such as green hydrogen, green ammonia, and green methanol will be able to compete with fossil fuels soon. Therefore, it is suggested to strengthen the research and development of low- and zero-emission marine fuel production technology and expand fuel production capacity.

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References

1. Mueller, N.; Westerby, M.; Nieuwenhuijsen, M. Health impact assessments of shipping and port-sourced air pollution on a global scale: A scoping literature review. *Environ. Res.* **2023**, *212*, 114460. [CrossRef]
2. Zhu, Y.; Zhou, W.; Xia, C.; Hou, Q. Application and Development of Selective Catalytic Reduction Technology for Marine Low-Speed Diesel Engine: Trade-Off among High Sulfur Fuel, High Thermal Efficiency, and Low Pollution Emission. *Atmosphere* **2022**, *13*, 731. [CrossRef]
3. Xia, C.; Zhu, Y.; Zhou, S.; Peng, H.; Feng, Y.; Zhou, W.; Shi, J.; Zhang, J. Simulation study on transient performance of a marine engine matched with high-pressure SCR system. *Int. J. Engine Res.* **2022**, 14680874221084052. [CrossRef]
4. Zhang, Y.; Xia, C.; Liu, D.; Zhu, Y.; Feng, Y. Experimental investigation of the high-pressure SCR reactor impact on a marine two-stroke diesel engine. *Fuel* **2023**, *335*, 127064. [CrossRef]
5. Qu, J.; Feng, Y.; Xu, G.; Zhang, M.; Zhu, Y.; Zhou, S. Design and thermodynamics analysis of marine dual fuel low speed engine with methane reforming integrated high pressure exhaust gas recirculation system. *Fuel* **2022**, *319*, 123747. [CrossRef]
6. Vasilescu, M.-V.; Dinu, D.; Panaitescu, M.; Panaitescu, F.-V. Research on Exhaust Gas Cleaning System (EGCS) used in shipping industry for reducing SO_x emissions. *E3S Web Conf.* **2021**, *286*, 04002. [CrossRef]
7. Negri, V.; Charalambous, M.A.; Medrano-García, J.D.; Guillén-Gosálbez, G. Navigating within the Safe Operating Space with Carbon Capture On-Board. *ACS Sustain. Chem. Eng.* **2022**, *10*, 17134–17142. [CrossRef]
8. IMO. Marine Environment Protection Committee (MEPC), 72nd Session, 9–13 April 2018. 2018. Available online: https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-72nd-session.aspx (accessed on 20 July 2020).
9. Dong, J.; Zeng, J.; Yang, Y.; Wang, H. A review of law and policy on decarbonization of shipping. *Front. Mar. Sci.* **2022**, *9*, 1076352. [CrossRef]
10. Barreiro, J.; Zaragoza, S.; Diaz-Casas, V. Review of ship energy efficiency. *Ocean Eng.* **2022**, *257*, 111594. [CrossRef]
11. Wang, Y.; Cao, Q.; Liu, L.; Wu, Y.; Liu, H.; Gu, Z.; Zhu, C. A review of low and zero carbon fuel technologies: Achieving ship carbon reduction targets. *Sustain. Energy Technol. Assessments* **2022**, *54*, 102762. [CrossRef]
12. Lindstad, E.; Lagemann, B.; Rialland, A.; Gamlem, G.M.; Valland, A. Reduction of maritime GHG emissions and the potential role of E-fuels. *Transp. Res. Part D: Transp. Environ.* **2021**, *101*, 103075. [CrossRef]
13. Moshiul, A.M.; Mohammad, R.; Hira, F.A.; Maarop, N. Alternative Marine Fuel Research Advances and Future Trends: A Bibliometric Knowledge Mapping Approach. *Sustainability* **2022**, *14*, 4947. [CrossRef]
14. Cullinane, K.; Yang, J. Evaluating the Costs of Decarbonizing the Shipping Industry: A Review of the Literature. *J. Mar. Sci. Eng.* **2022**, *10*, 946. [CrossRef]
15. Dostál, Z.; Ladányi, L. Demands on energy storage for renewable power sources. *J. Energy Storage* **2018**, *18*, 250–255. [CrossRef]

16. Ager, J.W.; Lapkin, A.A. Chemical storage of renewable energy. *Science* **2018**, *360*, 707–708. [CrossRef]
17. He, M.; Sun, Y.; Han, B. Green Carbon Science: Efficient Carbon Resource Processing, Utilization, and Recycling towards Carbon Neutrality. *Angew. Chem. Int. Ed.* **2022**, *61*, e202112835. [CrossRef]
18. Sterner, M.; Specht, M. Power-to-Gas and Power-to-X—The History and Results of Developing a New Storage Concept. *Energies* **2021**, *14*, 6594. [CrossRef]
19. Palys, M.J.; Daoutidis, P. Power-to-X: A review and perspective. *Comput. Chem. Eng.* **2022**, *165*, 107948. [CrossRef]
20. Xing, H.; Stuart, C.; Spence, S.; Chen, H. Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *J. Clean. Prod.* **2021**, *297*, 126651. [CrossRef]
21. Hoang, A.T.; Foley, A.M.; Nižetić, S.; Huang, Z.; Ong, H.C.; Ölçer, A.I.; Pham, V.V.; Nguyen, X.P. Energy-related approach for reduction of CO_2 emissions: A strategic review on the port-to-ship pathway. *J. Clean. Prod.* **2022**, *355*, 131772. [CrossRef]
22. Liu, H.; Ampah, J.D.; Zhao, Y.; Sun, X.; Xu, L.; Jiang, X.; Wang, S. A Perspective on the Overarching Role of Hydrogen, Ammonia, and Methanol Carbon-Neutral Fuels towards Net Zero Emission in the Next Three Decades. *Energies* **2022**, *16*, 280. [CrossRef]
23. Karvounis, P.; Tsoumpris, C.; Boulougouris, E.; Theotokatos, G. Recent advances for sustainable and safe marine engine operation with alternative fuels. *Front. Mech. Eng.* **2022**, *8*, 994942. [CrossRef]
24. Riebeek, H. The Carbon Cycle. NASA Earth Observatory 16. Available online: https://earthobservatory.nasa.gov/features/CarbonCycle/page1.php. (accessed on 20 January 2023).
25. Reichstein, M.; Bahn, M.; Ciais, P.; Frank, D.; Mahecha, M.D.; Seneviratne, S.I.; Zscheischler, J.; Beer, C.; Buchmann, N.; Frank, D.C.; et al. Climate extremes and the carbon cycle. *Nature* **2013**, *500*, 287–295. [CrossRef] [PubMed]
26. Sonntag, S.; Pongratz, J.; Reick, C.H.; Schmidt, H. Reforestation in a high-CO_2 world-Higher mitigation potential than expected, lower adaptation potential than hoped for. *Geophys. Res. Lett.* **2016**, *43*, 6546–6553. [CrossRef]
27. Madejski, P.; Chmiel, K.; Subramanian, N.; Kuś, T. Methods and Techniques for CO_2 Capture: Review of Potential Solutions and Applications in Modern Energy Technologies. *Energies* **2022**, *15*, 887. [CrossRef]
28. Reimer, J.A. A molecular perspective on carbon capture. *Matter* **2022**, *5*, 1330–1333. [CrossRef]
29. Cuéllar-Franca, R.M.; Azapagic, A. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *J. CO_2 Util.* **2015**, *9*, 82–102. [CrossRef]
30. Bui, M.; Adjiman, C.S.; Bardow, A.; Anthony, E.J.; Boston, A.; Brown, S.; Fennell, P.S.; Fuss, S.; Galindo, A.; Hackett, L.A.; et al. Carbon capture and storage (CCS): The way forward. *Energy Environ. Sci.* **2018**, *11*, 1062–1176. [CrossRef]
31. Artz, J.; Müller, T.E.; Thenert, K.M.; Kleinekorte, J.; Meys, R.; Sternberg, A.; Bardow, A.; Leitner, W. Sustainable Conversion of Carbon Dioxide: An Integrated Review of Catalysis and Life Cycle Assessment. *Chem. Rev.* **2018**, *118*, 434–504. [CrossRef]
32. Castro-Pardo, S.; Bhattacharyya, S.; Yadav, R.M.; Teixeira, A.P.D.C.; Mata, M.A.C.; Prasankumar, T.; Kabbani, M.A.; Kibria, G.; Xu, T.; Roy, S.; et al. A comprehensive overview of carbon dioxide capture: From materials, methods to industrial status. *Mater. Today* **2022**, *60*, 227–270. [CrossRef]
33. Sharifian, R.; Wagterveld, R.M.; Digdaya, I.A.; Xiang, C.; Vermaas, D.A. Electrochemical carbon dioxide capture to close the carbon cycle. *Energy Environ. Sci.* **2020**, *14*, 781–814. [CrossRef]
34. Galimova, T.; Ram, M.; Bogdanov, D.; Fasihi, M.; Khalili, S.; Gulagi, A.; Karjunen, H.; Mensah, T.N.O.; Breyer, C. Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals. *J. Clean. Prod.* **2022**, *373*, 133920. [CrossRef]
35. Luo, X.; Wang, M. Study of solvent-based carbon capture for cargo ships through process modelling and simulation. *Appl. Energy* **2017**, *195*, 402–413. [CrossRef]
36. Feenstra, M.; Monteiro, J.; Akker, J.T.V.D.; Abu-Zahra, M.R.; Gilling, E.; Goetheer, E. Ship-based carbon capture onboard of diesel or LNG-fuelled ships. *Int. J. Greenh. Gas Control.* **2019**, *85*, 1–10. [CrossRef]
37. Stec, M.; Tatarczuk, A.; Iluk, T.; Szul, M. Reducing the energy efficiency design index for ships through a post-combustion carbon capture process. *Int. J. Greenh. Gas Control.* **2021**, *108*, 103333. [CrossRef]
38. Long, N.V.D.; Lee, D.Y.; Kwag, C.; Lee, Y.M.; Lee, S.W.; Hessel, V.; Lee, M. Improvement of marine carbon capture onboard diesel fueled ships. *Chem. Eng. Process. - Process. Intensif.* **2021**, *168*, 108535. [CrossRef]
39. Ros, J.A.; Skylogianni, E.; Doedée, V.; Akker, J.T.V.D.; Vredeveldt, A.W.; Linders, M.J.; Goetheer, E.L.; Monteiro, J.G.M.-S. Advancements in ship-based carbon capture technology on board of LNG-fuelled ships. *Int. J. Greenh. Gas Control.* **2022**, *114*, 103575. [CrossRef]
40. Oh, J.; Anantharaman, R.; Zahid, U.; Lee, P.; Lim, Y. Process design of onboard membrane carbon capture and liquefaction systems for LNG-fueled ships. *Sep. Purif. Technol.* **2021**, *282*, 120052. [CrossRef]
41. Fang, S.; Xu, Y.; Li, Z.; Ding, Z.; Liu, L.; Wang, H. Optimal Sizing of Shipboard Carbon Capture System for Maritime Greenhouse Emission Control. *IEEE Trans. Ind. Appl.* **2019**, *55*, 5543–5553. [CrossRef]
42. Owusu, P.A.; Asumadu-Sarkodie, S. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Eng.* **2016**, *3*, 1167990. [CrossRef]
43. Chou, T.; Kosmas, V.; Acciaro, M.; Renken, K. A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology. *Sustainability* **2021**, *13*, 1880. [CrossRef]
44. Wang, K.; Guo, X.; Zhao, J.; Ma, R.; Huang, L.; Tian, F.; Dong, S.; Zhang, P.; Liu, C.; Wang, Z. An integrated collaborative decision-making method for optimizing energy consumption of sail-assisted ships towards low-carbon shipping. *Ocean Eng.* **2022**, *266*, 112810. [CrossRef]

45. Pan, P.; Sun, Y.; Yuan, C.; Yan, X.; Tang, X. Research progress on ship power systems integrated with new energy sources: A review. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111048. [CrossRef]
46. Zhang, Y.; Xu, L.; Zhou, Y. A wave foil with passive angle of attack adjustment for wave energy extraction for ships. *Ocean Eng.* **2022**, *246*, 110627. [CrossRef]
47. Demirbaş, A. Electrical Power Production Facilities from Green Energy Sources. *Energy Sources* **2006**, *1*, 291–301. [CrossRef]
48. Killingtveit, Å. Hydropower. In *Managing Global Warming*; Academic Press: Cambridge, MA, USA, 2019; pp. 265–315. [CrossRef]
49. Kougias, I.; Aggidis, G.; Avellan, F.; Deniz, S.; Lundin, U.; Moro, A.; Muntean, S.; Novara, D.; Pérez-Díaz, J.I.; Quaranta, E.; et al. Analysis of emerging technologies in the hydropower sector. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109257. [CrossRef]
50. Kałuża, T.; Hämmerling, M.; Zawadzki, P.; Czekała, W.; Kasperek, R.; Sojka, M.; Mokwa, M.; Ptak, M.; Szkudlarek, A.; Czechlowski, M.; et al. The hydropower sector in Poland: Historical development and current status. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112150. [CrossRef]
51. Tang, S.; Chen, J.; Sun, P.; Li, Y.; Yu, P.; Chen, E. Current and future hydropower development in Southeast Asia countries (Malaysia, Indonesia, Thailand and Myanmar). *Energy Policy* **2019**, *129*, 239–249. [CrossRef]
52. Moran, E.F.; Lopez, M.C.; Moore, N.; Müller, N.; Hyndman, D.W. Sustainable hydropower in the 21st century. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 11891–11898. [CrossRef] [PubMed]
53. Kuriqi, A.; Pinheiro, A.N.; Sordo-Ward, A.; Bejarano, M.D.; Garrote, L. Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition. *Renew. Sustain. Energy Rev.* **2021**, *142*, 110833. [CrossRef]
54. Pata, U.K.; Aydin, M. Testing the EKC hypothesis for the top six hydropower energy-consuming countries: Evidence from Fourier Bootstrap ARDL procedure. *J. Clean. Prod.* **2020**, *264*, 121699. [CrossRef]
55. Oladosu, G.A.; Werble, J.; Tingen, W.; Witt, A.; Mobley, M.; O'Connor, P. Costs of mitigating the environmental impacts of hydropower projects in the United States. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110121. [CrossRef]
56. Asumadu-Sarkodie, S.; Owusu, P.A. The potential and economic viability of wind farms in Ghana. *Energy Sources Part A Recover. Util. Environ. Eff.* **2016**, *38*, 695–701. [CrossRef]
57. Qin, B.; Li, H.; Zhou, X.; Li, J.; Liu, W. Low-Voltage Ride-Through Techniques in DFIG-Based Wind Turbines: A Review. *Appl. Sci.* **2020**, *10*, 2154. [CrossRef]
58. López-Manrique, L.; Macias-Melo, E.; Aguilar-Castro, K.; Hernández-Pérez, I.; Díaz-Hernández, H. Review on methodological and normative advances in assessment and estimation of wind energy. *Energy Environ.* **2019**, *32*, 25–61. [CrossRef]
59. IEA. Wind Electricity, IEA, Paris. Available online: https://www.iea.org/reports/wind-electricity (accessed on 15 October 2022).
60. Zhang, S.; Wei, J.; Chen, X.; Zhao, Y. China in global wind power development: Role, status and impact. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109881. [CrossRef]
61. Duan, H. Emissions and temperature benefits: The role of wind power in China. *Environ. Res.* **2017**, *152*, 342–350. [CrossRef]
62. Tarroja, B.; Mueller, F.; Eichman, J.D.; Brouwer, J.; Samuelsen, S. Spatial and temporal analysis of electric wind generation intermittency and dynamics. *Renew. Energy* **2011**, *36*, 3424–3432. [CrossRef]
63. Gunturu, U.B.; Schlosser, C.A. Characterization of wind power resource in the United States and its intermittency. Mit joint Program on the science and policy of global change. *Atmospheric Meas. Tech.* **2011**, *12*, 9687–9702. [CrossRef]
64. Ren, G.; Wan, J.; Liu, J.; Yu, D.; Söder, L. Analysis of wind power intermittency based on historical wind power data. *Energy* **2018**, *150*, 482–492. [CrossRef]
65. Vargas, S.A.; Esteves, G.R.T.; Maçaira, P.M.; Bastos, B.Q.; Oliveira, F.L.C.; Souza, R.C. Wind power generation: A review and a research agenda. *J. Clean. Prod.* **2019**, *218*, 850–870. [CrossRef]
66. Kumari, N.; Singh, S.K.; Kumar, S. A comparative study of different materials used for solar photovoltaics technology. *Mater. Today: Proc.* **2022**, *66*, 3522–3528. [CrossRef]
67. Ahmadi, M.H.; Ghazvini, M.; Sadeghzadeh, M.; Alhuyi Nazari, M.; Kumar, R.; Naeimi, A.; Ming, T. Solar power technology for electricity generation: A critical review. *Energy Sci. Eng.* **2018**, *6*, 340–361. [CrossRef]
68. Islam, M.T.; Huda, N.; Abdullah, A.B.; Saidur, R. A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: Current status and research trends. *Renew. Sustain. Energy Rev.* **2018**, *91*, 987–1018. [CrossRef]
69. IEA. Solar PV, IEA: Paris, France. 2022. Available online: https://www.iea.org/reports/solar-pv (accessed on 20 January 2023).
70. Jayachandran, M.; Gatla, R.K.; Rao, K.P.; Rao, G.S.; Mohammed, S.; Milyani, A.H.; Azhari, A.A.; Kalaiarasy, C.; Geetha, S. Challenges in achieving sustainable development goal 7: Affordable and clean energy in light of nascent technologies. *Sustain. Energy Technol. Assessments* **2022**, *53*, 102692. [CrossRef]
71. Zhang, X.; Li, H.; Liu, Q.; Tan, X. A Study on the Technology Diffusion of China's Solar Photovoltaic Based on Bass and Generalized Bass Model. *IOP Conf. Series: Earth Environ. Sci.* **2020**, *571*, 012016. [CrossRef]
72. Chen, S.; Lu, X.; Nielsen, C.P.; Geng, G.; He, K.; McElroy, M.B.; Wang, S.; Hao, J. Improved air quality in China can enhance solar-power performance and accelerate carbon-neutrality targets. *One Earth* **2022**, *5*, 550–562. [CrossRef]
73. Singh, A.D.; Sood, B.Y.R.; Deepak, C. Recent Techno-Economic Potential and Development of Solar Energy Sector in India. *IETE Tech. Rev.* **2019**, *37*, 246–257. [CrossRef]
74. Chisika, S.; Yeom, C. Enhancing Sustainable Development and Regional Integration through Electrification by Solar Power: The Case of Six East African States. *Sustainability* **2021**, *13*, 3275. [CrossRef]
75. Gulaliyev, M.G.; Mustafayev, E.R.; Mehdiyeva, G.Y. Assessment of Solar Energy Potential and Its Ecological-Economic Efficiency: Azerbaijan Case. *Sustainability* **2020**, *12*, 1116. [CrossRef]

76. Sanseverino, E.R.; Thuy, H.L.T.; Pham, M.-H.; Di Silvestre, M.L.; Quang, N.N.; Favuzza, S. Review of Potential and Actual Penetration of Solar Power in Vietnam. *Energies* **2020**, *13*, 2529. [CrossRef]
77. Al-Shahri, O.A.; Ismail, F.B.; Hannan, M.; Lipu, M.H.; Al-Shetwi, A.Q.; Begum, R.; Al-Muhsen, N.F.; Soujeri, E. Solar photovoltaic energy optimization methods, challenges and issues: A comprehensive review. *J. Clean. Prod.* **2020**, *284*, 125465. [CrossRef]
78. Antar, M.; Lyu, D.; Nazari, M.; Shah, A.; Zhou, X.; Smith, D.L. Biomass for a sustainable bioeconomy: An overview of world biomass production and utilization. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110691. [CrossRef]
79. Appels, L.; Lauwers, J.; Degrève, J.; Helsen, L.; Lievens, B.; Willems, K.; Van Impe, J.; Dewil, R. Anaerobic digestion in global bio-energy production: Potential and research challenges. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4295–4301. [CrossRef]
80. IEA. Bioenergy, IEA, Paris. 2022. Available online: https://www.iea.org/reports/bioenergy (accessed on 9 January 2023).
81. Liu, W.; Liu, C.; Gogoi, P.; Deng, Y. Overview of Biomass Conversion to Electricity and Hydrogen and Recent Developments in Low-Temperature Electrochemical Approaches. *Engineering* **2020**, *6*, 1351–1363. [CrossRef]
82. Chen, S.; Feng, H.; Zheng, J.; Ye, J.; Song, Y.; Yang, H.; Zhou, M. Life Cycle Assessment and Economic Analysis of Biomass Energy Technology in China: A Brief Review. *Processes* **2020**, *8*, 1112. [CrossRef]
83. Ardebili, S.M.S. Green electricity generation potential from biogas produced by anaerobic digestion of farm animal waste and agriculture residues in Iran. *Renew. Energy* **2020**, *154*, 29–37. [CrossRef]
84. Vijay, V.; Kapoor, R.; Singh, P.; Hiloidhari, M.; Ghosh, P. Sustainable utilization of biomass resources for decentralized energy generation and climate change mitigation: A regional case study in India. *Environ. Res.* **2022**, *212*, 113257. [CrossRef] [PubMed]
85. Sagani, A.; Hagidimitriou, M.; Dedoussis, V. Perennial tree pruning biomass waste exploitation for electricity generation: The perspective of Greece. *Sustain. Energy Technol. Assessments* **2018**, *31*, 77–85. [CrossRef]
86. Jåstad, E.O.; Bolkesjø, T.F.; Trømborg, E.; Rørstad, P.K. The role of woody biomass for reduction of fossil GHG emissions in the future North European energy sector. *Appl. Energy* **2020**, *274*, 115360. [CrossRef]
87. IEA. Renewables 2021, IEA, Paris. Available online: https://www.iea.org/reports/renewables-2021 (accessed on 20 December 2022).
88. Hoang, A.T.; Pham, V.V.; Nguyen, X.P. Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process. *J. Clean. Prod.* **2021**, *305*, 127161. [CrossRef]
89. Jun, W.; Mughal, N.; Kaur, P.; Xing, Z.; Jain, V.; Cong, P.T. Achieving green environment targets in the world's top 10 emitter countries: The role of green innovations and renewable electricity production. *Econ. Res.-Ekon. Istraživanja* **2022**, *35*, 5310–5335. [CrossRef]
90. Xiaosan, Z.; Qingquan, J.; Iqbal, K.S.; Manzoor, A.; Ur, R.Z. Achieving sustainability and energy efficiency goals: Assessing the impact of hydroelectric and renewable electricity generation on carbon dioxide emission in China. *Energy Policy* **2021**, *155*, 112332. [CrossRef]
91. Jing, R.; Zhou, Y.; Wu, J. Electrification with flexibility towards local energy decarbonization. *Adv. Appl. Energy* **2022**, *5*, 100088. [CrossRef]
92. Dong, F.; Li, Y.; Gao, Y.; Zhu, J.; Qin, C.; Zhang, X. Energy transition and carbon neutrality: Exploring the non-linear impact of renewable energy development on carbon emission efficiency in developed countries. *Resour. Conserv. Recycl.* **2022**, *177*, 106002. [CrossRef]
93. Nam, E.; Jin, T. Mitigating carbon emissions by energy transition, energy efficiency, and electrification: Difference between regulation indicators and empirical data. *J. Clean. Prod.* **2021**, *300*, 126962. [CrossRef]
94. Jin, T.; Kim, J. What is better for mitigating carbon emissions–Renewable energy or nuclear energy? A panel data analysis. *Renew. Sustain. Energy Rev.* **2018**, *91*, 464–471. [CrossRef]
95. Sovacool, B.K.; Schmid, P.; Stirling, A.; Walter, G.; MacKerron, G. Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power. *Nat. Energy* **2020**, *5*, 928–935. [CrossRef]
96. Dincer, I.; Acar, C. A review on clean energy solutions for better sustainability. *Int. J. Energy Res.* **2015**, *39*, 585–606. [CrossRef]
97. Hermesmann, M.; Müller, T. Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems. *Prog. Energy Combust. Sci.* **2022**, *90*, 100996. [CrossRef]
98. Carapellucci, R.; Giordano, L. Steam, dry and autothermal methane reforming for hydrogen production: A thermodynamic equilibrium analysis. *J. Power Sources* **2020**, *469*, 228391. [CrossRef]
99. Howarth, R.W.; Jacobson, M.Z. How green is blue hydrogen? *Energy Sci. Eng.* **2021**, *9*, 1676–1687. [CrossRef]
100. Scheiblehner, D.; Neuschitzer, D.; Wibner, S.; Sprung, A.; Antrekowitsch, H. Hydrogen production by methane pyrolysis in molten binary copper alloys. *Int. J. Hydrog. Energy* **2022**, *48*, 6233–6243. [CrossRef]
101. Schneider, S.; Bajohr, S.; Graf, F.; Kolb, T. State of the Art of Hydrogen Production via Pyrolysis of Natural Gas. *ChemBioEng Rev.* **2020**, *7*, 150–158. [CrossRef]
102. Abad, A.V.; Dodds, P.E. Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. *Energy Policy* **2020**, *138*, 111300. [CrossRef]
103. Ondrey, G. The World's Largest "Green Hydrogen" Project Will Supply 650 ton/d Hydrogen. Chemical Engineering. Available online: https://www.chemengonline.com/the-worlds-largest-green-hydrogen-project-will-supply-650-ton-d-hydrogen/?printmode=1 (accessed on 20 July 2022).
104. Li, X.; Zhao, L.; Yu, J.; Liu, X.; Zhang, X.; Liu, H.; Zhou, W. Water Splitting: From Electrode to Green Energy System. *Nano-Micro Lett.* **2020**, *12*, 131. [CrossRef]

105. Gopinath, C.S.; Nalajala, N. A scalable and thin film approach for solar hydrogen generation: A review on enhanced photocatalytic water splitting. *J. Mater. Chem. A* **2020**, *9*, 1353–1371. [CrossRef]
106. Sürer, M.G.; Arat, H.T. Advancements and current technologies on hydrogen fuel cell applications for marine vehicles. *Int. J. Hydrogen Energy* **2022**, *47*, 19865–19875. [CrossRef]
107. Atilhan, S.; Park, S.; El-Halwagi, M.M.; Atilhan, M.; Moore, M.; Nielsen, R.B. Green hydrogen as an alternative fuel for the shipping industry. *Curr. Opin. Chem. Eng.* **2021**, *31*, 100668. [CrossRef]
108. Grigoriev, S.; Fateev, V.; Bessarabov, D.; Millet, P. Current status, research trends, and challenges in water electrolysis science and technology. *Int. J. Hydrogen Energy* **2020**, *45*, 26036–26058. [CrossRef]
109. Kumar, S.S.; Lim, H. An overview of water electrolysis technologies for green hydrogen production. *Energy Rep.* **2022**, *8*, 13793–13813. [CrossRef]
110. Brauns, J.; Turek, T. Alkaline Water Electrolysis Powered by Renewable Energy: A Review. *Processes* **2020**, *8*, 248. [CrossRef]
111. Bareiß, K.; de la Rúa, C.; Möckl, M.; Hamacher, T. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. *Appl. Energy* **2019**, *237*, 862–872. [CrossRef]
112. Miller, H.A. Green hydrogen from anion exchange membrane water electrolysis. *Curr. Opin. Electrochem.* **2022**, *36*, 2114–2133. [CrossRef]
113. Li, D.; Park, E.J.; Zhu, W.; Shi, Q.; Zhou, Y.; Tian, H.; Lin, Y.; Serov, A.; Zulevi, B.; Baca, E.D.; et al. Highly quaternized polystyrene ionomers for high performance anion exchange membrane water electrolysers. *Nat. Energy* **2020**, *5*, 378–385. [CrossRef]
114. Hauch, A.; Küngas, R.; Blennow, P.; Hansen, A.B.; Mathiesen, B.V.; Mogensen, M.B. Recent advances in solid oxide cell technology for electrolysis. *Science* **2020**, *370*, eaba6118. [CrossRef]
115. Jang, D.; Kim, J.; Kim, D.; Han, W.-B.; Kang, S. Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies. *Energy Convers. Manag.* **2022**, *258*, 115499. [CrossRef]
116. Jiao, Y.; Zheng, Y.; Jaroniec, M.; Qiao, S.Z. Design of electrocatalysts for oxygen- and hydrogen-involving energy conversion reactions. *Chem. Soc. Rev.* **2015**, *44*, 2060–2086. [CrossRef]
117. Anwar, S.; Khan, F.; Zhang, Y.; Djire, A. Recent development in electrocatalysts for hydrogen production through water electrolysis. *Int. J. Hydrogen Energy* **2021**, *46*, 32284–32317. [CrossRef]
118. Guo, J.; Zhang, Y.; Zavabeti, A.; Chen, K.; Guo, Y.; Hu, G.; Fan, X.; Li, G.K. Hydrogen production from the air. *Nat. Commun.* **2022**, *13*, 5046. [CrossRef]
119. Lee, Y.-S.; Mo, Y.-H.; Park, D.-H.; Lee, H.-J.; Lee, W.-J.; Park, H.-S.; Han, S.-B.; Park, K.-W. Highly efficient lithium-ion exchange membrane water electrolysis. *J. Power Sources* **2022**, *529*, 231188. [CrossRef]
120. Sanchez, C.; Espinos, F.J.; Barjola, A.; Escorihuela, J.; Compañ, V. Hydrogen Production from Methanol–Water Solution and Pure Water Electrolysis Using Nanocomposite Perfluorinated Sulfocationic Membranes Modified by Polyaniline. *Polymers* **2022**, *14*, 4500. [CrossRef] [PubMed]
121. Jiang, S.; Suo, H.; Zhang, T.; Liao, C.; Wang, Y.; Zhao, Q.; Lai, W. Recent Advances in Seawater Electrolysis. *Catalysts* **2022**, *12*, 123. [CrossRef]
122. Abdel-Aal, H.; Zohdy, K.; Kareem, M.A. Hydrogen Production Using Sea Water Electrolysis. *Open Fuel Cells J.* **2010**, *3*, 1–7. [CrossRef]
123. Wang, C.; Zhu, M.; Cao, Z.; Zhu, P.; Cao, Y.; Xu, X.; Xu, C.; Yin, Z. Heterogeneous bimetallic sulfides based seawater electrolysis towards stable industrial-level large current density. *Appl. Catal. B Environ.* **2021**, *291*, 120071. [CrossRef]
124. Liu, Z.; Han, B.; Lu, Z.; Guan, W.; Li, Y.; Song, C.; Chen, L.; Singhal, S.C. Efficiency and stability of hydrogen production from seawater using solid oxide electrolysis cells. *Appl. Energy* **2021**, *300*, 117439. [CrossRef]
125. Gao, F.-Y.; Yu, P.-C.; Gao, M.-R. Seawater electrolysis technologies for green hydrogen production: Challenges and opportunities. *Curr. Opin. Chem. Eng.* **2022**, *36*, 100827. [CrossRef]
126. Pang, S. Advances in thermochemical conversion of woody biomass to energy, fuels and chemicals. *Biotechnol. Adv.* **2019**, *37*, 589–597. [CrossRef]
127. Aziz, M.; Darmawan, A.; Juangsa, F.B. Hydrogen production from biomasses and wastes: A technological review. *Int. J. Hydrogen Energy* **2021**, *46*, 33756–33781. [CrossRef]
128. Arregi, A.; Amutio, M.; Lopez, G.; Bilbao, J.; Olazar, M. Evaluation of thermochemical routes for hydrogen production from biomass: A review. *Energy Convers. Manag.* **2018**, *165*, 696–719. [CrossRef]
129. Parthasarathy, P.; Narayanan, K.S. Hydrogen production from steam gasification of biomass: Influence of process parameters on hydrogen yield–A review. *Renew. Energy* **2014**, *66*, 570–579. [CrossRef]
130. Luo, N.; Montini, T.; Zhang, J.; Fornasiero, P.; Fonda, E.; Hou, T.; Nie, W.; Lu, J.; Liu, J.; Heggen, M.; et al. Visible-light-driven coproduction of diesel precursors and hydrogen from lignocellulose-derived methylfurans. *Nat. Energy* **2019**, *4*, 575–584. [CrossRef]
131. Ban, S.; Lin, W.; Luo, J. Ca2+ enhances algal photolysis hydrogen production by improving the direct and indirect pathways. *Int. J. Hydrogen Energy* **2019**, *44*, 1466–1473. [CrossRef]
132. Łukajtis, R.; Hołowacz, I.; Kucharska, K.; Glinka, M.; Rybarczyk, P.; Przyjazny, A.; Kamiński, M. Hydrogen production from biomass using dark fermentation. *Renew. Sustain. Energy Rev.* **2018**, *91*, 665–694. [CrossRef]
133. Sarangi, P.K.; Nanda, S. Biohydrogen Production Through Dark Fermentation. *Chem. Eng. Technol.* **2020**, *43*, 601–612. [CrossRef]

134. Sivaramakrishnan, R.; Shanmugam, S.; Sekar, M.; Mathimani, T.; Incharoensakdi, A.; Kim, S.-H.; Parthiban, A.; Geo, V.E.; Brindhadevi, K.; Pugazhendhi, A. Insights on biological hydrogen production routes and potential microorganisms for high hydrogen yield. *Fuel* **2021**, *291*, 120136. [CrossRef]
135. Rousseau, R.; Etcheverry, L.; Roubaud, E.; Basséguy, R.; Délia, M.-L.; Bergel, A. Microbial electrolysis cell (MEC): Strengths, weaknesses and research needs from electrochemical engineering standpoint. *Appl. Energy* **2020**, *257*, 113938. [CrossRef]
136. Yang, E.; Mohamed, H.O.; Park, S.-G.; Obaid, M.; Al-Qaradawi, S.Y.; Castaño, P.; Chon, K.; Chae, K.-J. A review on self-sustainable microbial electrolysis cells for electro-biohydrogen production via coupling with carbon-neutral renewable energy technologies. *Bioresour. Technol.* **2021**, *320*, 124363. [CrossRef] [PubMed]
137. Fernández-Ríos, A.; Santos, G.; Pinedo, J.; Santos, E.; Ruiz-Salmón, I.; Laso, J.; Lyne, A.; Ortiz, A.; Ortiz, I.; Irabien, Á.; et al. Environmental sustainability of alternative marine propulsion technologies powered by hydrogen - a life cycle assessment approach. *Sci. Total. Environ.* **2022**, *820*, 153189. [CrossRef]
138. Seddiek, I.S.; Elgohary, M.M.; Ammar, N.R. The hydrogen-fuelled internal combustion engines for marine applications with a case study. *Brodogr. Teor. Praksa Brodogr. Pomor. Teh.* **2015**, *66*, 23–38.
139. Di Micco, S.; Mastropasqua, L.; Cigolotti, V.; Minutillo, M.; Brouwer, J. A framework for the replacement analysis of a hydrogen-based polymer electrolyte membrane fuel cell technology on board ships: A step towards decarbonization in the maritime sector. *Energy Convers. Manag.* **2022**, *267*, 115893. [CrossRef]
140. Niaz, S.; Manzoor, T.; Pandith, A.H. Hydrogen storage: Materials, methods and perspectives. *Renew. Sustain. Energy Rev.* **2015**, *50*, 457–469. [CrossRef]
141. Van Hoecke, L.; Laffineur, L.; Campe, R.; Perreault, P.; Verbruggen, S.W.; Lenaerts, S. Challenges in the use of hydrogen for maritime applications. *Energy Environ. Sci.* **2021**, *14*, 815–843. [CrossRef]
142. Wang, Z.; Wang, Y.; Afshan, S.; Hjalmarsson, J. A review of metallic tanks for H2 storage with a view to application in future green shipping. *Int. J. Hydrogen Energy* **2020**, *46*, 6151–6179. [CrossRef]
143. Depken, J.; Dyck, A.; Roß, L.; Ehlers, S. Safety Considerations of Hydrogen Application in Shipping in Comparison to LNG. *Energies* **2022**, *15*, 3250. [CrossRef]
144. Li, Y.; Tao, R.; Yang, Z.; Fan, Y.; Bian, T.; Fan, X.; Su, C.; Shao, Z. Cuprous oxide single-crystal film assisted highly efficient solar hydrogen production on large ships for long-term energy storage and zero-emission power generation. *J. Power Sources* **2022**, *527*, 231133. [CrossRef]
145. Bonacina, C.N.; Gaskare, N.B.; Valenti, G. Assessment of offshore liquid hydrogen production from wind power for ship refueling. *Int. J. Hydrogen Energy* **2022**, *47*, 1279–1291. [CrossRef]
146. El-Emam, R.S.; Özcan, H. Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. *J. Clean. Prod.* **2019**, *220*, 593–609. [CrossRef]
147. Valera-Medina, A.; Amer-Hatem, F.; Azad, A.K.; Dedoussi, I.C.; de Joannon, M.; Fernandes, R.X.; Glarborg, P.; Hashemi, H.; He, X.; Mashruk, S.; et al. Review on Ammonia as a Potential Fuel: From Synthesis to Economics. *Energy Fuels* **2021**, *35*, 6964–7029. [CrossRef]
148. Lee, K.; Liu, X.; Vyawahare, P.; Sun, P.; Elgowainy, A.; Wang, M. Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production. *Green Chem.* **2022**, *24*, 4830–4844. [CrossRef]
149. MacFarlane, D.R.; Cherepanov, P.V.; Choi, J.; Suryanto, B.H.; Hodgetts, R.Y.; Bakker, J.M.; Vallana, F.M.F.; Simonov, A.N. A Roadmap to the Ammonia Economy. *Joule* **2020**, *4*, 1186–1205. [CrossRef]
150. Fasihi, M.; Weiss, R.; Savolainen, J.; Breyer, C. Global potential of green ammonia based on hybrid PV-wind power plants. *Appl. Energy* **2021**, *294*, 116170. [CrossRef]
151. Armijo, J.; Philibert, C. Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina. *Int. J. Hydrogen Energy* **2020**, *45*, 1541–1558. [CrossRef]
152. Shepherd, J.; Khan, M.H.A.; Amal, R.; Daiyan, R.; MacGill, I. Open-source project feasibility tools for supporting development of the green ammonia value chain. *Energy Convers. Manag.* **2022**, *274*, 116413. [CrossRef]
153. Sousa, J.; Waiblinger, W.; Friedrich, K.A. Techno-economic Study of an Electrolysis-Based Green Ammonia Production Plant. *Ind. Eng. Chem. Res.* **2022**, *61*, 14515–14530. [CrossRef]
154. Gezerman, A.O. A Critical Assessment of Green Ammonia Production and Ammonia Production Technologies. *Kemičara Kem. Inženjera Hrvat.* **2022**, *71*, 57–66. [CrossRef]
155. Kaiprathu, A.; Velayudham, P.; Teller, H.; Schechter, A. Mechanisms of electrochemical nitrogen gas reduction to ammonia under ambient conditions: A focused review. *J. Solid State Electrochem.* **2022**, *26*, 1897–1917. [CrossRef]
156. Arif, M.; Babar, M.; Azhar, U.; Sagir, M.; Tahir, M.B.; Mushtaq, M.A.; Yasin, G.; Mubashir, M.; Chong, J.W.R.; Khoo, K.S.; et al. Rational design and modulation strategies of Mo-based electrocatalysts and photo/electrocatalysts towards nitrogen reduction to ammonia (NH3). *Chem. Eng. J.* **2022**, *451*, 138320. [CrossRef]
157. Wang, T.; Guo, Z.; Zhang, X.; Li, Q.; Yu, A.; Wu, C.; Sun, C. Recent progress of iron-based electrocatalysts for nitrogen reduction reaction. *J. Mater. Sci. Technol.* **2023**, *140*, 121–134. [CrossRef]
158. Li, Z.; Li, M.; Yang, J.; Liao, M.; Song, G.; Cao, J.; Liu, F.; Wang, Z.; Kawi, S.; Lin, Q. Electrocatalyst design strategies for ammonia production via N2 reduction. *Catal. Today* **2022**, *388*, 12–25. [CrossRef]

159. Yang, B.; Ding, W.; Zhang, H.; Zhang, S. Recent progress in electrochemical synthesis of ammonia from nitrogen: Strategies to improve the catalytic activity and selectivity. *Energy Environ. Sci.* **2020**, *14*, 672–687. [CrossRef]
160. Theerthagiri, J.; Park, J.; Das, H.T.; Rahamathulla, N.; Cardoso, E.S.F.; Murthy, A.P.; Maia, G.; Vo, D.N.; Choi, M.Y. Electrocatalytic conversion of nitrate waste into ammonia: A review. *Environ. Chem. Lett.* **2022**, *20*, 2929–2949. [CrossRef]
161. Zheng, Z.; Qi, L.; Xue, Y.; Li, Y. Highly selective and durable of monodispersed metal atoms in ammonia production. *Nano Today* **2022**, *43*, 101431. [CrossRef]
162. Teng, M.; Ye, J.; Wan, C.; He, G.; Chen, H. Research Progress on Cu-Based Catalysts for Electrochemical Nitrate Reduction Reaction to Ammonia. *Ind. Eng. Chem. Res.* **2022**, *61*, 14731–14746. [CrossRef]
163. Zhang, S.; Zhao, Y.; Shi, R.; Waterhouse, G.I.; Zhang, T. Photocatalytic ammonia synthesis: Recent progress and future. *Energychem* **2019**, *1*, 100013. [CrossRef]
164. Hui, X.; Wang, L.; Yao, Z.; Hao, L.; Sun, Z. Recent progress of photocatalysts based on tungsten and related metals for nitrogen reduction to ammonia. *Front. Chem.* **2022**, *10*, 978078. [CrossRef] [PubMed]
165. Wang, L.; Wu, W.; Liang, K.; Yu, X. Advanced Strategies for Improving the Photocatalytic Nitrogen Fixation Performance: A Short Review. *Energy Fuels* **2022**, *36*, 11278–11291. [CrossRef]
166. Rapson, T.D.; Gregg, C.M.; Allen, R.S.; Ju, H.; Doherty, C.M.; Mulet, X.; Giddey, S.; Wood, C.C. Insights into Nitrogenase Bioelectrocatalysis for Green Ammonia Production. *Chemsuschem* **2020**, *13*, 4856–4865. [CrossRef]
167. Feng, Y.; Qu, J.; Zhu, Y.; Wu, B.; Wu, Y.; Xiao, Z.; Liu, J. Progress and prospect of the novel integrated SOFC-ICE hybrid power system: System design, mass and heat integration, system optimization and techno-economic analysis. *Energy Convers. Manag. X* **2023**, *18*, 100350. [CrossRef]
168. Al-Aboosi, F.Y.; El-Halwagi, M.M.; Moore, M.; Nielsen, R.B. Renewable ammonia as an alternative fuel for the shipping industry. *Curr. Opin. Chem. Eng.* **2021**, *31*, 100670. [CrossRef]
169. Ash, N.; Scarbrough, T. *Sailing on Solar: Could Green Ammonia Decarbonise International Shipping*; Environmental Defense Fund: London, UK, 2019.
170. Bicer, Y.; Dincer, I. Clean fuel options with hydrogen for sea transportation: A life cycle approach. *Int. J. Hydrogen Energy* **2018**, *43*, 1179–1193. [CrossRef]
171. Zincir, B. Environmental and economic evaluation of ammonia as a fuel for short-sea shipping: A case study. *Int. J. Hydrogen Energy* **2022**, *47*, 18148–18168. [CrossRef]
172. Mallouppas, G.; Ioannou, C.; Yfantis, E.A. A Review of the Latest Trends in the Use of Green Ammonia as an Energy Carrier in Maritime Industry. *Energies* **2022**, *15*, 1453. [CrossRef]
173. Inal, O.B.; Zincir, B.; Deniz, C. Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. *Int. J. Hydrogen Energy* **2022**, *47*, 19888–19900. [CrossRef]
174. Tornatore, C.; Marchitto, L.; Sabia, P.; De Joannon, M. Ammonia as Green Fuel in Internal Combustion Engines: State-of-the-Art and Future Perspectives. *Front. Mech. Eng.* **2022**, *8*, 944201. [CrossRef]
175. Wolfram, P.; Kyle, P.; Zhang, X.; Gkantonas, S.; Smith, S. Using ammonia as a shipping fuel could disturb the nitrogen cycle. *Nat. Energy* **2022**, *7*, 1112–1114. [CrossRef]
176. Roode-Gutzmer, Q.I.; Kaiser, D.; Bertau, M. Renewable Methanol Synthesis. *ChemBioEng Rev.* **2019**, *6*, 209–236. [CrossRef]
177. Harris, K.; Grim, R.G.; Huang, Z.; Tao, L. A comparative techno-economic analysis of renewable methanol synthesis from biomass and CO_2: Opportunities and barriers to commercialization. *Appl. Energy* **2021**, *303*, 117637. [CrossRef]
178. De Fournas, N.; Wei, M. Techno-economic assessment of renewable methanol from biomass gasification and PEM electrolysis for decarbonization of the maritime sector in California. *Energy Convers. Manag.* **2022**, *257*, 115440. [CrossRef]
179. Nugroho, Y.K.; Zhu, L.; Heavey, C. Building an agent-based techno-economic assessment coupled with life cycle assessment of biomass to methanol supply chains. *Appl. Energy* **2022**, *309*, 118449. [CrossRef]
180. Zhong, J.; Yang, X.; Wu, Z.; Liang, B.; Huang, Y.; Zhang, T. State of the art and perspectives in heterogeneous catalysis of CO_2 hydrogenation to methanol. *Chem. Soc. Rev.* **2020**, *49*, 1385–1413. [CrossRef]
181. Biswal, T.; Shadangi, K.P.; Sarangi, P.K.; Srivastava, R.K. Conversion of carbon dioxide to methanol: A comprehensive review. *Chemosphere* **2022**, *298*, 134299. [CrossRef]
182. Samimi, F.; Karimipourfard, D.; Rahimpour, M.R. Green methanol synthesis process from carbon dioxide via reverse water gas shift reaction in a membrane reactor. *Chem. Eng. Res. Des.* **2018**, *140*, 44–67. [CrossRef]
183. Azhari, N.J.; Erika, D.; Mardiana, S.; Ilmi, T.; Gunawan, M.L.; Makertihartha, I.; Kadja, G.T. Methanol synthesis from CO_2: A mechanistic overview. *Results Eng.* **2022**, *16*, 100711. [CrossRef]
184. Song, L.; Wang, H.; Wang, S.; Qu, Z. Dual-site activation of H2 over Cu/ZnAl2O4 boosting CO_2 hydrogenation to methanol. *Appl. Catal. B: Environ.* **2023**, *322*, 122137. [CrossRef]
185. Marcos, F.C.; Alvim, R.S.; Lin, L.; Betancourt, L.E.; Petrolini, D.D.; Senanayake, S.D.; Alves, R.M.; Assaf, J.M.; Rodriguez, J.A.; Giudici, R.; et al. The role of copper crystallization and segregation toward enhanced methanol synthesis via CO_2 hydrogenation over $CuZrO_2$ catalysts: A combined experimental and computational study. *Chem. Eng. J.* **2023**, *452*, 139519. [CrossRef]
186. Niu, J.; Liu, H.; Jin, Y.; Fan, B.; Qi, W.; Ran, J. Comprehensive review of Cu-based CO_2 hydrogenation to CH3OH: Insights from experimental work and theoretical analysis. *Int. J. Hydrogen Energy* **2022**, *47*, 9183–9200. [CrossRef]
187. Shi, Y.; Su, W.; Wei, X.; Song, X.; Bai, Y.; Wang, J.; Lv, P.; Yu, G. Highly active MIL-68(In)-derived In2O3 hollow tubes catalysts to boost CO_2 hydrogenation to methanol. *Fuel* **2023**, *334*, 126811. [CrossRef]

188. Zhang, H.; Mao, D.; Zhang, J.; Wu, D. Regulating the crystal structure of layered double hydroxide-derived Co-In catalysts for highly selective CO_2 hydrogenation to methanol. *Chem. Eng. J.* **2023**, *452*, 139144. [CrossRef]
189. Sun, K.; Rui, N.; Zhang, Z.; Sun, Z.; Ge, Q.; Liu, C.-J. A highly active Pt/In_2O_3 catalyst for CO_2 hydrogenation to methanol with enhanced stability. *Green Chem.* **2020**, *22*, 5059–5066. [CrossRef]
190. Sun, K.; Shen, C.; Zou, R.; Liu, C.-J. Highly active Pt/In2O3-ZrO2 catalyst for CO_2 hydrogenation to methanol with enhanced CO tolerance: The effects of ZrO2. *Appl. Catal. B Environ.* **2023**, *320*, 122018. [CrossRef]
191. Zhen, X.; Wang, Y. An overview of methanol as an internal combustion engine fuel. *Renew. Sustain. Energy Rev.* **2015**, *52*, 477–493. [CrossRef]
192. Brynolf, S.; Fridell, E.; Andersson, K. Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol. *J. Clean. Prod.* **2014**, *74*, 86–95. [CrossRef]
193. Fridell, E.; Salberg, H.; Salo, K. Measurements of Emissions to Air from a Marine Engine Fueled by Methanol. *J. Mar. Sci. Appl.* **2021**, *20*, 138–143. [CrossRef]
194. Saxena, M.R.; Maurya, R.K.; Mishra, P. Assessment of performance, combustion and emissions characteristics of metha-nol-diesel dual-fuel compression ignition engine: A review. *J. Traffic Transp. Eng. (Engl. Ed.)* **2021**, *8*, 638–680. [CrossRef]
195. Ishaq, H.; Crawford, C. CO_2-based alternative fuel production to support development of CO_2 capture, utilization and storage. *Fuel* **2023**, *331*, 125684. [CrossRef]
196. Wermuth, N.; Lackner, M.; Barnstedt, D.; Zelenka, J.; Wimmer, A. The HyMethShip Project: Innovative Emission Free Propulsion for Maritime Applications. FAD Conference, Dresden, Germany. 2019. Available online: https://pure.tugraz.at/ws/portalfiles/portal/26710351/Wermuth_The_HyMethShip_Project_Authors_manuskript_17th_FAD_Dresden.pdf (accessed on 20 December 2022).
197. Malmgren, E.; Brynolf, S.; Fridell, E.; Grahn, M.; Andersson, K. The environmental performance of a fossil-free ship propulsion system with onboard carbon capture–A life cycle assessment of the HyMethShip concept. *Sustain. Energy Fuels* **2021**, *5*, 2753–2770. [CrossRef]
198. Svanberg, M.; Ellis, J.; Lundgren, J.; Landälv, I. Renewable methanol as a fuel for the shipping industry. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1217–1228. [CrossRef]
199. McKinlay, C.J.; Turnock, S.R.; Hudson, D.A. Route to zero emission shipping: Hydrogen, ammonia or methanol? *Int. J. Hydrogen Energy* **2021**, *46*, 28282–28297. [CrossRef]