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Perspective

A Perspective on the Overarching Role of Hydrogen, Ammonia, and Methanol Carbon-Neutral Fuels towards Net Zero Emission in the Next Three Decades

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Abstract: Arguably, one of the most important issues the world is facing currently is climate change. At the current rate of fossil fuel consumption, the world is heading towards extreme levels of global temperature rise if immediate actions are not taken. Transforming the current energy system from one largely based on fossil fuels to a carbon-neutral one requires unprecedented speed. Based on the current state of development, direct electrification of the future energy system alone is technically challenging and not enough, especially in hard-to-abate sectors like heavy industry, road trucking, international shipping, and aviation. This leaves a considerable demand for alternative carbon-neutral fuels such as green ammonia and hydrogen and renewable methanol. From this perspective, we discuss the overarching roles of each fuel in reaching net zero emission within the next three decades. The challenges and future directions associated with the fuels conclude the current perspective paper.

Keywords: carbon-neutral fuels; decarbonization; hydrogen; ammonia; methanol

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1. Introduction

As the catalyst for economic expansion and urbanization, industrialization has led to the substantial development of several sectors of the global economy in conjunction with a growth in world population and wealth [1,2]. The world population is projected to grow to 9.9 billion in 2050 from 7.8 billion in 2020, creating an environment where energy requirements increase by 80% [3,4]. The historical patterns of growth in human population, activities, and energy demands have had a huge influence on the environment. The Mauna Loa Observatory in Hawaii's latest data suggests that the carbon dioxide (CO_2) in the atmosphere as of 2022 had exceeded 415 ppm, which represents approximately a 14% increase in less than 25 years when compared to the levels in 1997 [5]. It has been projected that by 2050, greenhouse gas (GHG) emissions will increase by 50%, mainly as a consequence of the expected 70% increase in energy-related CO_2 emissions [4,6]. At the current rate of emission increase, the carbon cycle is likely to be pushed out of its dynamic equilibrium, causing an irreversible change to the climate system [7].

Against this backdrop, several rounds of climate negotiations to tackle climate change have been carried out by the international community. The adoption and signing of a series of international treaties such as the Kyoto Protocol and the 2015 Paris Agreement has led to real progress toward national climate change mitigation commitments. The Paris Agreement for instance aims to limit global warming to 1.5 °C above pre-industrial levels [8]. However, compared to where current policies stand, a median warming of 2.6–3.1 degrees Celsius by 2100 is more likely even if all parties were to deliver on their climate pledges [9].

Thus, more long-term stringent measures have to be put forward. According to the Intergovernmental Panel on Climate Change (IPCC), the 1.5 °C goal requires a global realization of net zero CO_2 emissions by 2050—a goal collectively termed "reaching carbon neutrality". Carbon neutrality refers to the balance between CO_2 emissions and absorptions within a specific period to achieve "net zero emissions of carbon dioxide" [10]. Carbon neutrality means the output of CO_2 is offset by other approaches and thus has neutral effects on the environment. Today, a total of 194 countries have joined the Paris Agreement [11]. Countries like the United Kingdom, Germany, Canada, France, South Africa, South Korea, and Denmark have pledged to reach carbon neutrality by 2050, Iceland and Sweden by 2040 and 2045, respectively, China by 2060, India by 2070, and more countries are expected to make similar pledges in the near future [12,13].

The development of carbon-neutral fuels is very crucial in reaching carbon neutrality, especially in decarbonizing the major energy-consuming sectors such as heavy-duty transport, power, industry, etc. [14–16]. Carbon-neutral fuels are carbon-based fuels that do not increase the atmospheric CO_2 when combusted. A net zero amount of atmospheric carbon is achieved from the combustion of these fuels in the sense that they are typically produced with CO_2 as a key component in the process—implying that there is no net gain of carbon in the atmosphere. There are several carbon-neutral fuels and all these fuels are important to the realization of a net zero future. However, the remaining discussions in this perspective paper are limited to green hydrogen, green ammonia, and renewable methanol. There are several existing reviews on their production technologies and pathways such as hydrogen [17–19], ammonia [20–22], and methanol [23–25]. Despite the key contributions of such reviews, there is a limited holistic summary of the role of these fuels in reaching a net zero future. Our current perspective is thus developed to provide a brief overview of the interconnected roles of all three fuels. These are arguably the three most often considered carbon-neutral fuels to significantly contribute to the realization of carbon neutrality within the next three decades, especially in hard-to-abate sectors like long-range transport, energy-intensive industry, and parts of residential heating. The coupling of these sectors with the power sector through the production and consumption of these fuels helps solve one of the most challenging tasks with renewable electricity generation (i.e., matching time of generation to time of load consequently leading to energy curtailment), especially from intermittent sources such as solar and wind energy. The technologies for their production stage to end-use are well understood and have been around for quite some time albeit with certain inherent challenges such as commercialization and large scale-up. Undoubtedly, these three carbon-neutral fuels considered in this perspective have a crucial role to play in reaching the 1.5 °C target by mid-century, and these roles and potential applications will become apparent in the subsequent sections. Figure 1 highlights the energy transition from today's fossil fuel-dominated system to tomorrow's net zero carbon emissions system powered mainly by renewable energies and carbon-neutral fuels.

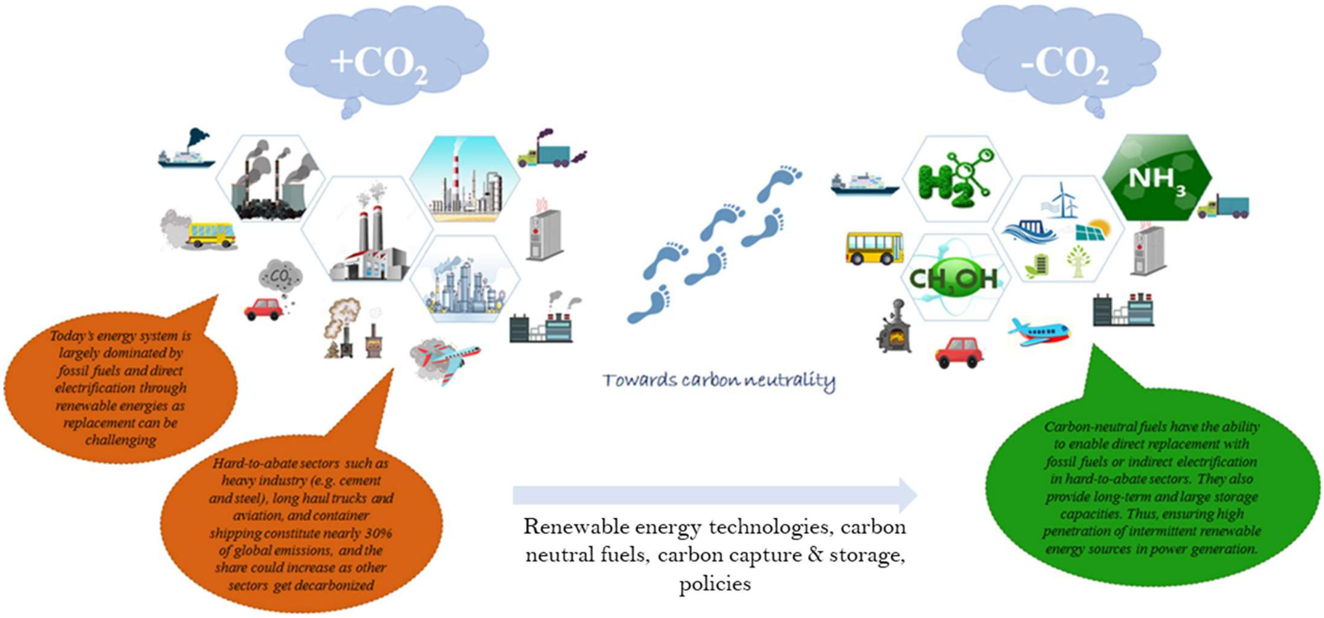


Figure 1. Carbon neutral fuels in future net zero carbon emissions.

2. Role and Prospects of Carbon-Neutral Fuels in the Future Energy System

2.1. Green Hydrogen

The International Energy Agency (IEA) reports that in 2020 the demand for hydrogen was approximately 90 million metric tons, with approximately 80% being used as pure hydrogen and the remainder being mixed with carbon-containing gases for steel manufacturing and methanol production [26]. In a scenario where net zero emissions are targeted, the demand for hydrogen is projected to increase to 530 million metric tons by 2050, a nearly six-fold increase from the 2020 level [27]. Green hydrogen is a synonym for renewable energy produced through water electrolysis using renewable energy sources. Currently, green hydrogen accounts for only 0.1% of global energy production [28]. However, since the scale-up of green hydrogen is crucial for achieving net zero emissions by 2050 and limiting global temperature to 1.5 °C, green hydrogen, and its derivates could be responsible for supplying up to 12% of final energy consumption by 2050. Therefore, 63% of final energy consumption could be realized from both green hydrogen and electricity alone [29]. By 2023, investment in green hydrogen production could exceed $1 billion due to the fall in renewable power and electrolyzer costs as a result of several governmental interventions and policies regarding green hydrogen [30]. For example, the US Department of Energy is putting up $100 million for research and development of green hydrogen. By 2030, the European Union will have invested $430 billion in green hydrogen to aid in the realization of its Green Deal. Chile, Japan, China, Germany, and Australia are all making huge investments in green hydrogen [31]. Based on several assessments of different agencies such as BloombergNEF [32], Energy Transition Commission [33], Hydrogen council [34], IRENA [29], and IEA [35] as compiled by the authors of [36], it is clear that 2050′s hydrogen will be mainly green and blue hydrogen (hydrogen production from fossil fuels with carbon capture and storage (CCS) technologies), with the former contributing more than half of total production (Figure 2). Both are carbon-neutral pathways but CCS is yet to be widely commercial and requires significant scale-up as well.

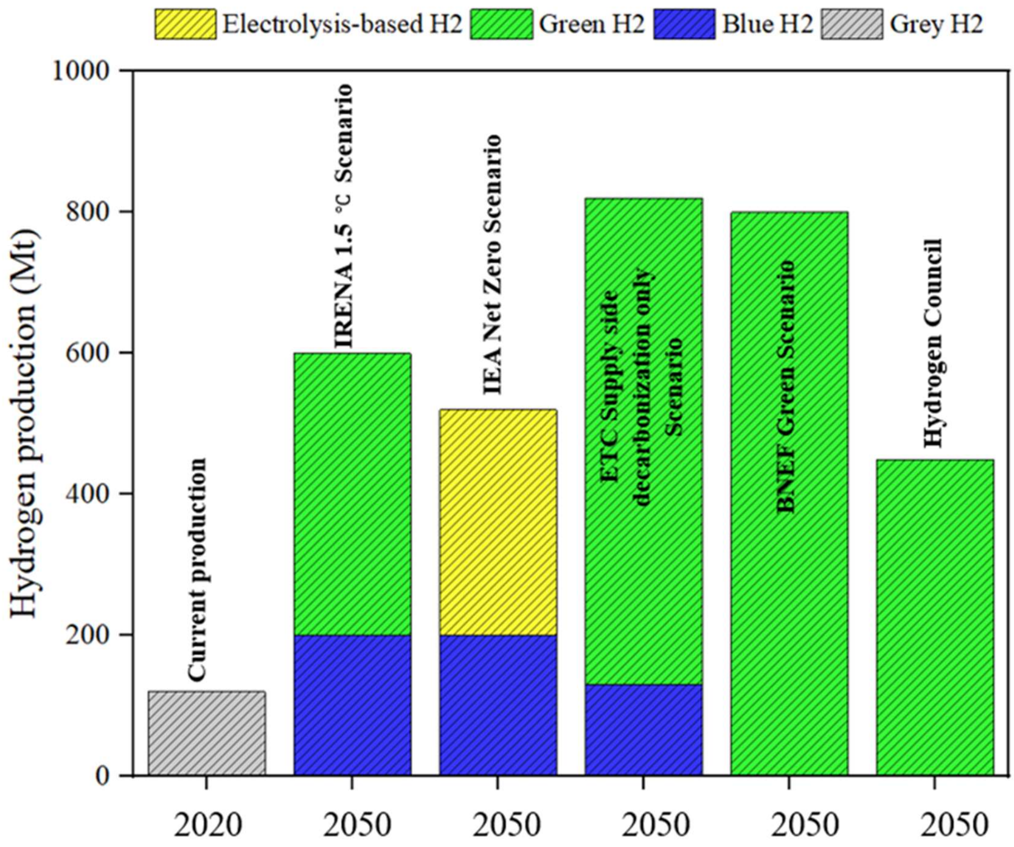


Figure 2. Hydrogen production by source by 2050 according to different agency assessments. Based on data from Ref. [36].

Hydrogen can help tackle various critical energy challenges regarding future energy transition [37,38]. Most importantly, it offers an enabling environment to decarbonize some difficult-to-decarbonize sectors including heavy industrial sectors such as steel, cement, chemicals, and aluminum, and long-distance sectors such as shipping, aviation, and long-distance road transport. Together these account for about 30% (10 Gt) of all emissions but the share could rise reaching 16 Gt by 2050 as other sectors such as power get decarbonized [39,40]. In addition, there exist several prominent studies advocating for a 100% renewable energy future—however, the immediate challenge with a 100% renewable energy scenario with complete direct electrification concerns the intermittent nature of solar and wind sources which cannot be overlooked, leading to power curtailment. Against this concern, the introduction of Power-to-X (P2X) provides a key solution to making 100% renewable energy possible. Hydrogen aids in balancing the intermittent supply and providing the required system flexibility through the coupling of various sectors. Through the use of electrolyzers, excess electricity that would have been otherwise curtailed could potentially be converted to hydrogen and re-injected into the network as electricity during power deficits or delivered to other sectors such as industry, transport, or residential. Of the available energy storage technologies currently available, P2X storage presents the most overall optimal long-term and carbon-free seasonal storage. The timespan and power capacity needed to address seasonal imbalances cannot be handled alone by the likes of batteries, supercapacitors, and compressed air. Pumped hydro storage, on the other hand, can provide long-term and large-scale energy storage but it is characterized by geographical restrictions for the remaining untapped potential and its global output capacity of 170 GW is about only 2% of the total installed electricity capacity in the world. Another role of hydrogen concerns its ability to supply energy to areas where energy is conventionally imported. To wit, electricity can be produced in areas with high levels of solar and wind energy, and through P2X, converted to hydrogen or hydrogen-based fuels and transported to import regions. Huge energy losses are incurred during the transportation of electricity over longer distances but a 100% efficient pipeline transport of hydrogen is feasible—making hydrogen an economically attractive alternative for transporting large-scale renewable energy over long distances. In summary, hydrogen and its derivatives will allow high penetration rates of variable renewable energies, leading to a significant reduction of CO_2 emissions (avoiding up to 60 Gt CO_2 in 2021–2050, a 6.5% of total cumulative emission reduction [41]), playing a crucial role in hard-to-decarbonize sectors, and functioning as a catalyst for sector coupling (Figure 3).

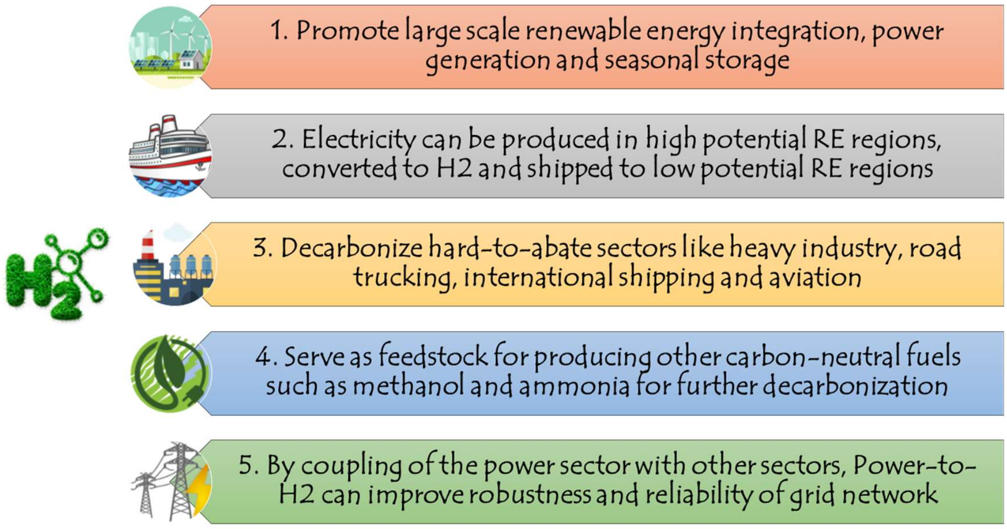


Figure 3. Role of green hydrogen in a carbon-neutral future.

2.2. Green Ammonia

Ammonia as the basis for all mineral nitrogen fertilizers forms the bridge between the nitrogen in the air and the foods we consume. The production of ammonia, however, is far from being clean. The nitrogen is captured from the air but almost all of the hydrogen required is currently produced from fossil fuels. Thus, the conventional production of ammonia is a very carbon-intensive process. The process accounts for 1.3% of global CO_2 emissions from the energy system [42] of which 80% originate from the hydrogen production stage [43]. This provides room for the decarbonization of ammonia synthesis where hydrogen production can be achieved through water electrolysis using low-carbon electricity sources (green hydrogen) to react with nitrogen from the air to form green ammonia. This green process of ammonia synthesis could potentially reduce the carbon footprint of conventional ammonia production from 1.6 to 0.1 tCO_2/tNH_3 which can further reach near zero in the future with technological advancement [44].

Ammonia has an important role to play in the carbon-neutral future scheduled for the next three to four decades. As mentioned earlier, the 1.5 °C goal will lead to significant growth in green hydrogen demand, and the transport of green hydrogen from one region to another will become a common feature in this future transition. However, it is challenging to store, handle, and transport hydrogen. Though this is achievable with compressed or liquified hydrogen at −253 °C, the process requires huge capital investments, energy (for cooling), energy losses due to cooling, and poses safety concerns. Alternatively, it is safer, easier, and cheaper to transport and store hydrogen in the form of ammonia. This is because, relative to volume, liquid hydrogen has a lower energy density than ammonia. Also, at −35 °C, ammonia is already in a liquified state, and can then be easily and safely transported. In addition, the required infrastructure for transporting ammonia is already in place for decades as millions of tons of ammonia are annually transported by sea. About 20 Mt of ammonia (out of the 185 Mt of production) were globally traded in 2020 [42].

In the coming years, several ammonia projects are scheduled to come online with an expected minimum of 3 Mt electrolytic ammonia production for conventional uses, considering projects that were announced as of June 2021 (Figure 4a). In the Sustainable Development Scenario (SDS) of IEA assessment, the ammonia production via electrolysis will play a crucial role. By 2050, electrolytic ammonia will account for about 20% of global ammonia production (a rise from the current <0.01%), with Europe, India, and China being the main regions of green hydrogen production (Figure 5). The green ammonia in the global output according to IEA's Net Zero Emission (NZE) scenario by 2050 has higher shares than SDS. In the NZE scenario, ammonia for power generation could reach 85 Mt as opposed to a near zero share in 2020 (Figure 4b). Furthermore, due to the emission reduction targets in the shipping sector (cut maritime emissions by at least 50% by 2050) and sulfur content limits of marine fuels, ammonia which is considered to be the "destination fuel" will be an important shipping fuel. As seen in Figure 4c, the share of total fuel consumption of ammonia in national and international maritime shipping could reach around 25% in the SDS and around 45% in the NZE scenario by 2050 [42].

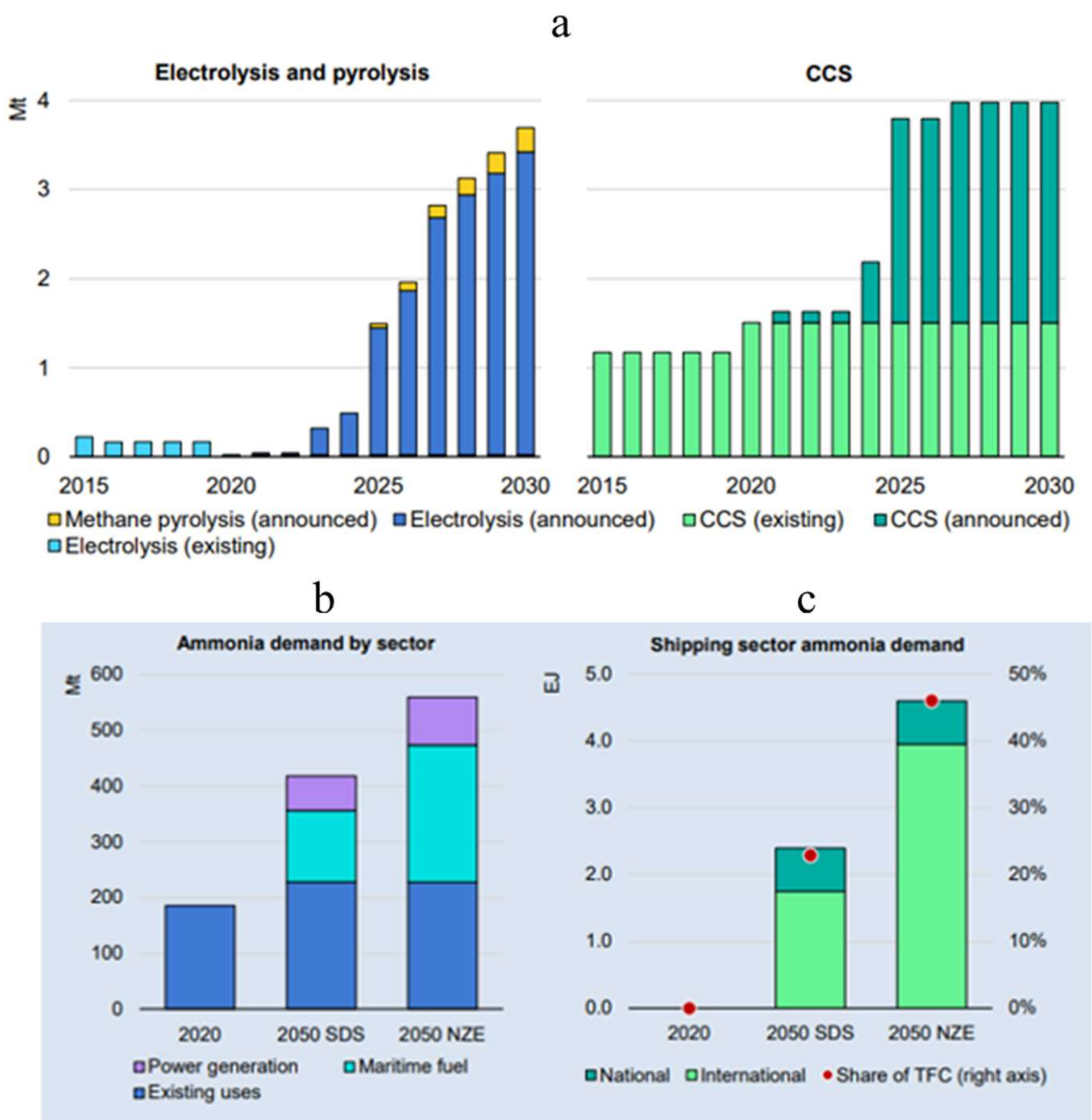


Figure 4. (**a**) Pathways to near zero emission ammonia production (current and announced); (**b**) ammonia demand by sector (SDS: sustainable development scenario; NZE: net zero emissions); (**c**) shipping sector ammonia demand [42] (Published under license CC BY 4.0).

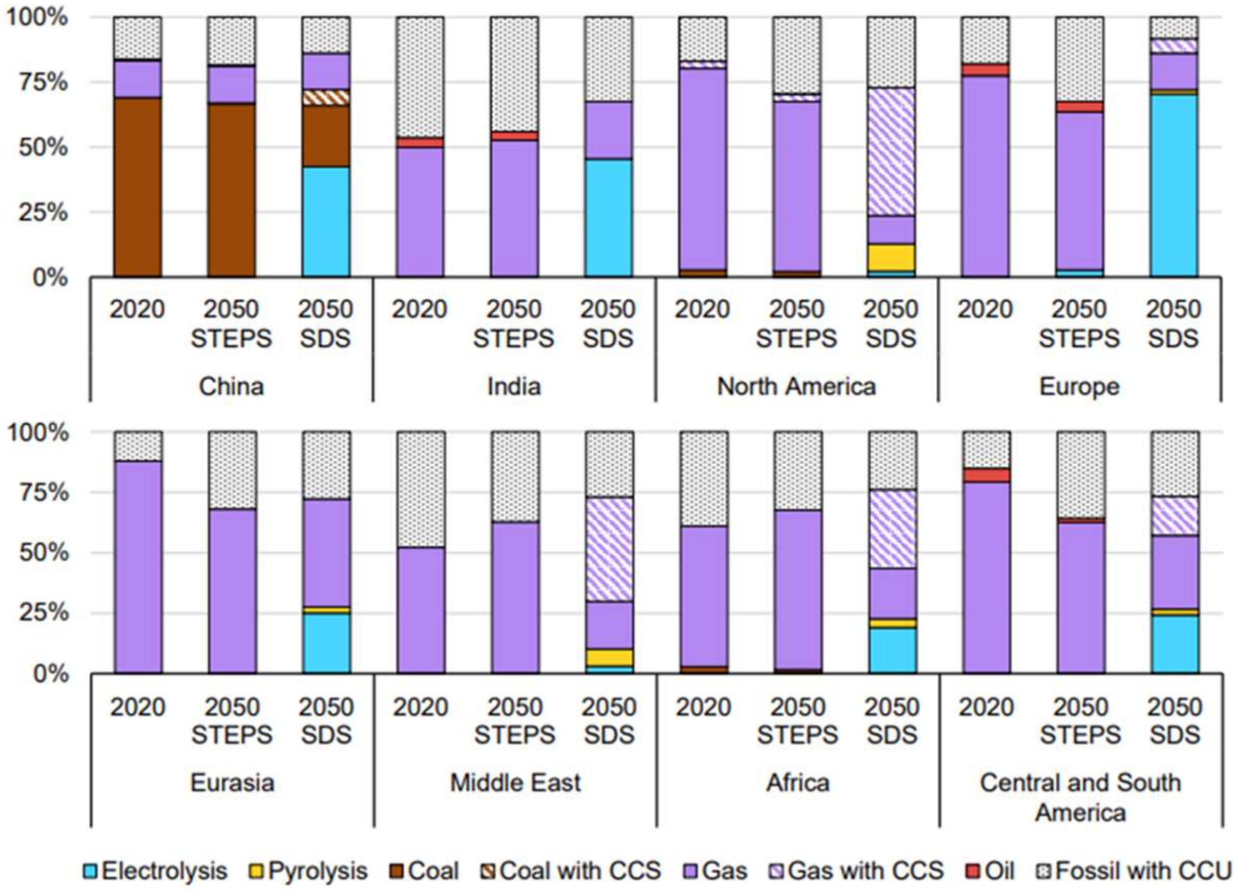


Figure 5. Various ammonia production pathways and scenarios in major ammonia-producing regions (STEPS: Stated Policies Scenario) [42] (Published under license CC BY 4.0).

According to IRENA's assessment, the global transition towards the 1.5 °C goal could potentially lead to a 688 Mt ammonia market which is about 4 times larger than the existing market, and green ammonia will dominate the global ammonia market. Over the next 30 years, 566 Mt of new green ammonia production must come on-stream. This will constitute about 20% of the global green hydrogen market [29]. The future green ammonia market opens up channels for the penetration of high shares of renewable generation capacity. In other words, the interaction between renewable power and ammonia sectors will significantly increase the renewable electricity generation capacity due to the increased demand for green hydrogen in the synthesis of green ammonia. With the estimated 566 Mt of green hydrogen by 2050, 2.3 TW of renewable generation would be required which is nearly 30% of the current global cumulative electricity capacity [45]. From Power-to-ammonia (P2A) concepts, surplus electricity from variable renewable energy sources such as wind and solar can be converted into green ammonia, which can provide long-term storage. As seen in Figure 6, P2A provides better seasonal storage and capacity than other alternatives with similar purposes. In the future energy system, therefore, P2A will provide the required balance to the grid that would have otherwise been overloaded and unstable (due to the mismatch between high renewable generation and demand) by minimizing power curtailment.

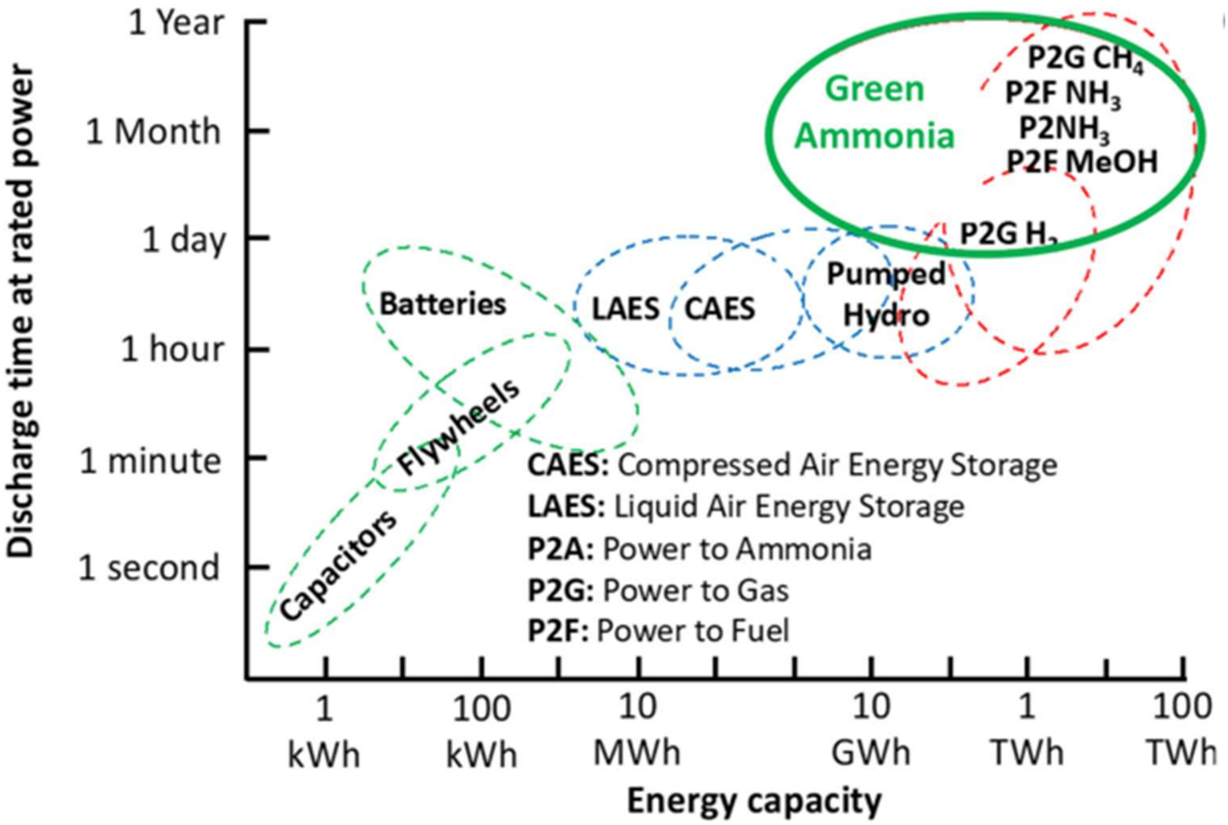
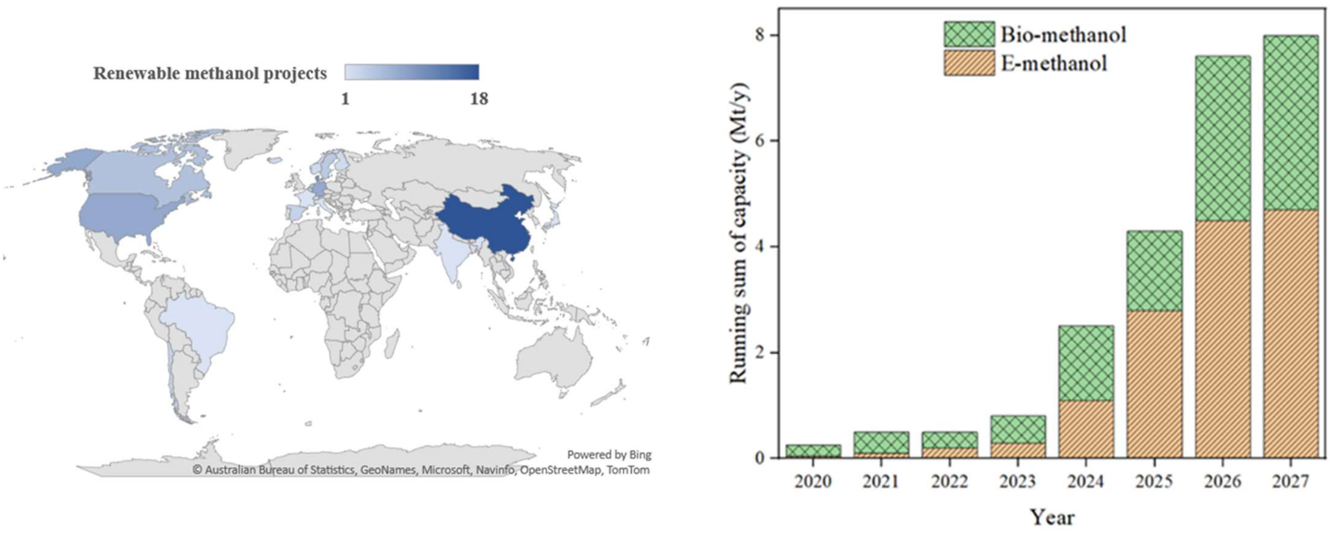


Figure 6. Energy storage capacity and discharge time of different storage technologies [44] (published under the terms of the Creative Commons CC-BY license).

2.3. Renewable Methanol

One of the most popular and important liquid chemicals used in producing daily products, including plastics, paints, cosmetics, and fuels, is methanol. Methanol produced from sustainable biomass (bio-methanol) or by reaction between captured CO_2 and renewable electricity-based hydrogen (e-methanol) is typically referred to as renewable or green methanol, and it is a low carbon and net carbon neutral liquid chemical and fuel. Renewable methanol reduces CO_2 and NO_x emissions by 95% and up to 80%, respectively, and eliminates SO_x and PM emissions in contrast to traditional fuels [46]. Each year, approximately 98 Mt of methanol is produced, almost all of which is via fossil fuels (natural gas or coal). The amount of renewable methanol (mostly bio-methanol) produced yearly is less than 0.2 Mt. Life cycle emissions show that around 0.3 Gt of CO_2 production per year is recorded from the conventional methanol production and use, representing about 10% of the total chemical sector's emissions [47]. More than 80 renewable methanol projects around the world are being tracked by the Methanol Institute, and they are projected to produce annually at least 8 MMT of renewable methanol by 2027. In the next five years, the capacity of individual renewable methanol plants is expected to rise from 5000–10,000 tonnes of methanol per year to 50,000–250,000 tonnes per year (see Figure 7a,b) [46].

Considering ongoing rates, methanol production could rise to 500 Mt per year by 2050 from today's ~100 Mt. If the 500 Mt of methanol is sourced from fossil fuels, CO_2 emissions of 1.5 Gt will be released per year. To meet the 2050 production needs for methanol while adhering to net zero emission targets, about 80% of this production will come from renewable methanol (135 Mt and 250 Mt from bio-methanol and e-methanol, respectively (see Figure 8) [47].



a **b**

Figure 7. (**a**) Countries by the count of existing renewable methanol projects; (**b**) projected renewable methanol production capacity by start-up year. Based on data from Ref. [46].

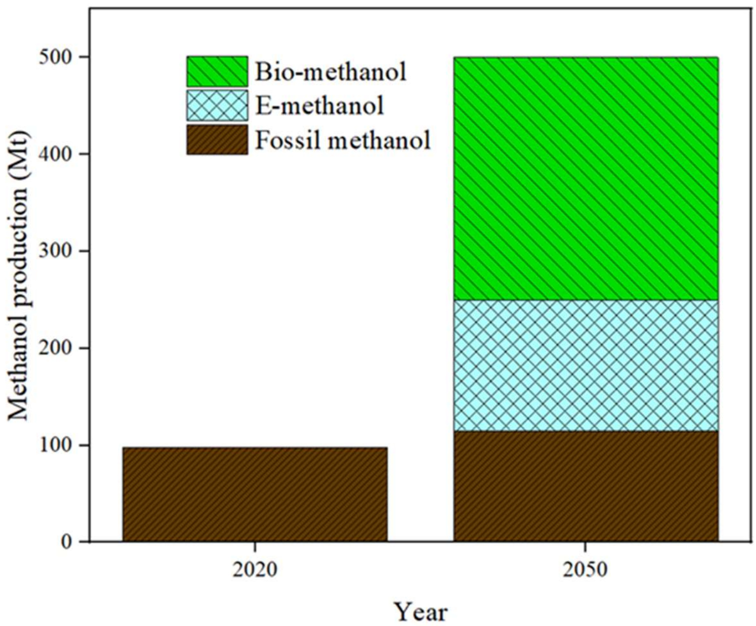


Figure 8. Production capacity of fossil and renewable methanol by 2050. Based on data from Ref. [47].

Renewable methanol cannot only be a fuel for transport applications [48,49] and feedstock in the chemical industry but it can decisively promote the decarbonization of hard-to-abate industrial sectors. Additionally, a local and CO_2-neutral closed-loop system is created for the integration of renewable methanol production into existing industrial facilities such as CHP plants or cement and steel production plants. As more countries seek to ban or limit internal combustion engines (ICE) in line with the 1.5 °C goal, e-methanol could help cut down the emissions during the transition to electric mobility options, vehicle operations for instance. Since it is possible to blend methanol with gasoline and use it in ICEs, renewable methanol provides a carbon-neutral transport alternative. China for instance already piloted M85 and M100 methanol vehicles in 2012, and by 2025, the fleet of M100 vehicles in China could reach 50,000 consuming more than 500,000 tonnes of methanol [50]. The use of direct methanol fuel cells also provides the possibility of running 100% methanol in any type of electric vehicle. Renewable methanol is likely to play an important role in the future decarbonization of the shipping sector [51]. For instance, since 2016 seven oceangoing vessels have been operating equipped with dual fuel, two-stroke engines, which can run on methanol, heavy fuel oil (HFO), marine diesel oil (MDO), or marine gas oil (MGO) [52]. Brynolf et al. [53] showed that the environmental impact of renewable methanol is relatively lower than HFO and other alternatives such as liquified natural gas (LNG), liquified biogas, and fossil methanol. A transition assessment of DNV-GL shows that the uptake of at least three or four different carbon-neutral fuels in the shipping sector could account for 60–100% of shipping energy use by 2050. The tightening of shipping emission regulations in the next two to three decades could ensure that fleets shift directly to carbon-neutral methanol or ammonia while other low-carbon alternatives such as bio-MGO, e-MGO, bio-LNG, e-LNG function as drop-in fuels for existing ships [54]. Within the P2X concepts, methanol is a hot topic and has the potential to be one of the solutions to use and store large-scale renewable electricity as seen in Figure 6. The requirement of electrolyzers in producing the needed hydrogen in the synthesis of e-methanol opens up opportunities to integrate more renewable generation into the future power sector (i.e., matching time of generation to time of load). Therefore, the interactions between the renewable power and methanol (e-methanol) sector could lead to higher shares of intermittent renewable energy resources in a net zero emission world within the next three decades. Last but not least, methanol can play a significant role as a green hydrogen energy carrier. Similar to the case of ammonia, the energy density of methanol is very interesting for transporting green hydrogen from one region to another for example from Australia to Asia. This is feasible as the supply infrastructure for transporting methanol is already in place due to the existing supply of huge quantities of methanol around the world annually. Figure 9 shows the key roles green ammonia and methanol can play in tomorrow's carbon-neutral world.

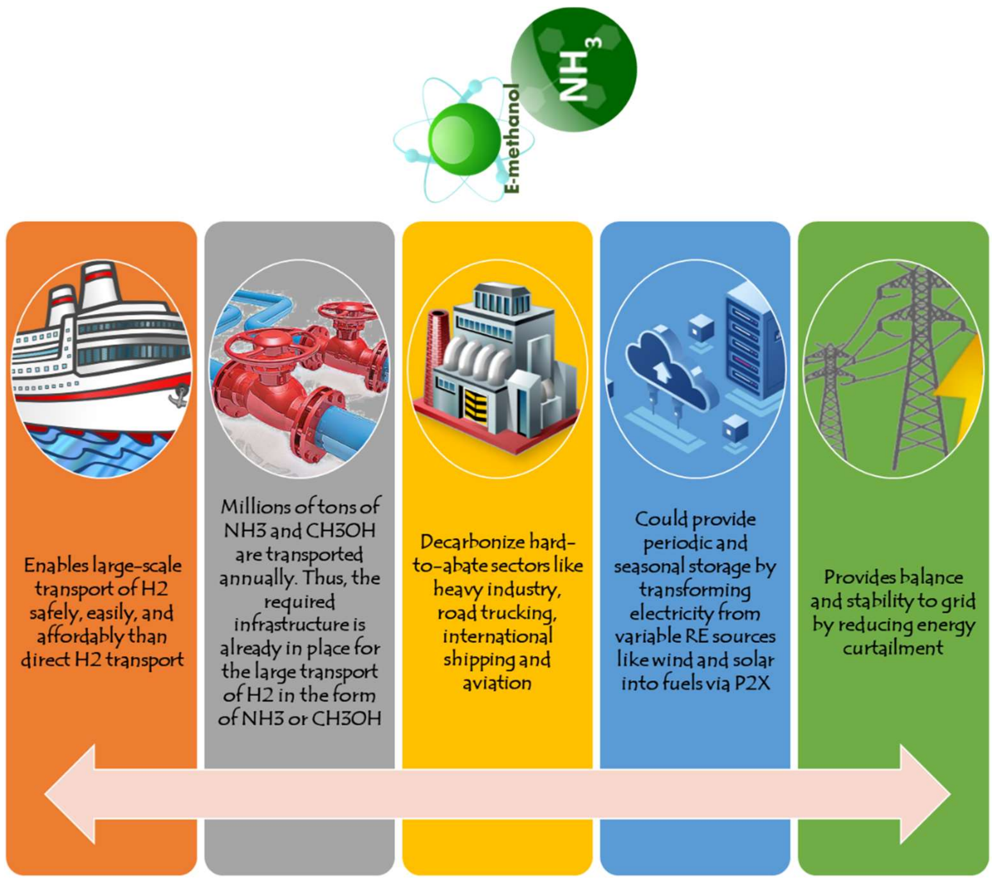


Figure 9. Role of green ammonia and methanol in a carbon-neutral future.

3. Application of Carbon-Neutral Fuels (Power, Transport, Heat)

As discussed above, carbon-neutral fuels have critical roles to play in the realization of carbon neutrality in the next three decades. Today, they are already in application in several sectors of the energy system as summarized in Figure 10. In terms of power generation, these fuels offer cleaner pathways by using technologies such as fuel cells, reciprocating engines, or gas turbines to replace high-carbon fuels. Hydrogen can be utilized in fuel cells and turbines for the generation of power and heat. There are several existing and planned hydrogen-based combined heat and power (CHP) projects. At NREL's Flatinos Campus, a fuel cell generator as part of the ARIES MW-scale hydrogen system is being designed and commissioned. The flexible system comprises a 1.25 MW PEM electrolyzer, a 600 kg H_2 storage system, and a 1 MW fuel cell generator. The platform is designated to demonstrate direct green hydrogen generation, energy storage, power production, and grid integration at MW scale [55]. Across the world, more than 800 MW of large stationary fuel cell systems (rated power >200 kW) have been installed for distributed generation and CHP applications, with the largest shares of installation located in the US and South Korea. More than 4100 fuel cell units for CHP applications have been installed in Europe and a 1.4 MW stationary fuel cell powerplant is the largest in Europe. The transport sector alone is responsible for 20% of the global primary energy demand, and about 96% of this demand is met with petroleum [56]. Due to the progressive growth of fossil fuel consumption, the sector was responsible for 37% of CO_2 emissions from end-use sectors in 2021 [57]. Sectors such as aeronautics, long-haul road, maritime transport, and railways require highly dense fuels and the direct electrification of these sectors with batteries or grid is challenging. The range, capacity, and refueling time of batteries do not make them suitable for these sectors but carbon-neutral fuels, on the other hand, meet the fuel requirement of these hard-to-abate transport sectors and they can directly replace the fossil fuels or indirectly electrify these sectors. The International Maritime Organization (IMO) has plans to reduce shipping carbon intensities by an average of 40% by 2030 and by 70% by 2050 and cut maritime emissions by at least 50% by 2050 in reference to 2008 levels. In addition, as of January 2020, the global sulfur content of marine fuels has been limited to 0.5 wt% [38,58]. These targets have created an important opportunity for the penetration of carbon-neutral fuels in the shipping sector. In the shipping sector, for example, ammonia's popularity is growing significantly. The world's first ammonia-based fuel cell for shipping is being developed by the Fraunhofer Institute in collaboration with 13 European consortium partners as part of the ShipFC project [59]. The project comprises an offshore vessel retrofitted with a large 2 MW ammonia fuel cell that will allow it to sail 100% on ammonia for up to 3000 h per year [60]. Similarly, green ammonia is being developed in the Ammonia Zero Emissions Project (AMAZE) as a substitute ship engine fuel. The project was launched in early 2022 by Bergen Engines to develop technology for a fuel-flexible ICE with green ammonia as the primary fuel [61]. Net carbon-renewable methanol will meet IMO's goal of reducing GHG emissions by 50% by 2050. By using methanol as a marine fuel compared to diesel, emissions of SO_x, NO_x, and PM reduce by 99%, 60%, and 95%, respectively [46]. The application of carbon-neutral fuels in road transport is also gaining momentum in recent years. China has a goal to produce between 100,000 and 200,000 tons of green hydrogen annually and to have around 50,000 hydrogen-powered vehicles on the roads by 2025. Currently, M100 (100% methanol) vehicles are in operation in some countries with China having the largest share of such vehicles. In Italy, methanol-derived fuels such as A20, methanol (15%)-bio-ethanol (5%)-gasoline blends are being trialed. The US has for some time been using methanol regularly in motorsports, and Iceland is fuelling a fleet of cars with renewable methanol [46]. Methanol fuel cells do not only substitute fossil fuels and reduce both CO_2 emissions and fuel consumption but they are also designed to ensure long-range, fast refueling, zero harmful emissions, and lower costs. The range of battery electric vehicles can be extended from 200 km to over 1000 km with methanol fuel cells. An eco-friendly alternative fuel for heating is methanol. As a substitute fuel for cookstoves and boilers, methanol has been adopted in some parts of Tanzania, India, Nigeria, and China. Industrial Methanol is used to heat buildings in Shanxi, dry tea in Darjeeling, and fuel cookstoves in restaurants in Shanghai. Methanol boilers surpass coal in terms of restricting pollution, as they reduce overall emissions of PM, SO_x, and NOx by at least 75% [46].

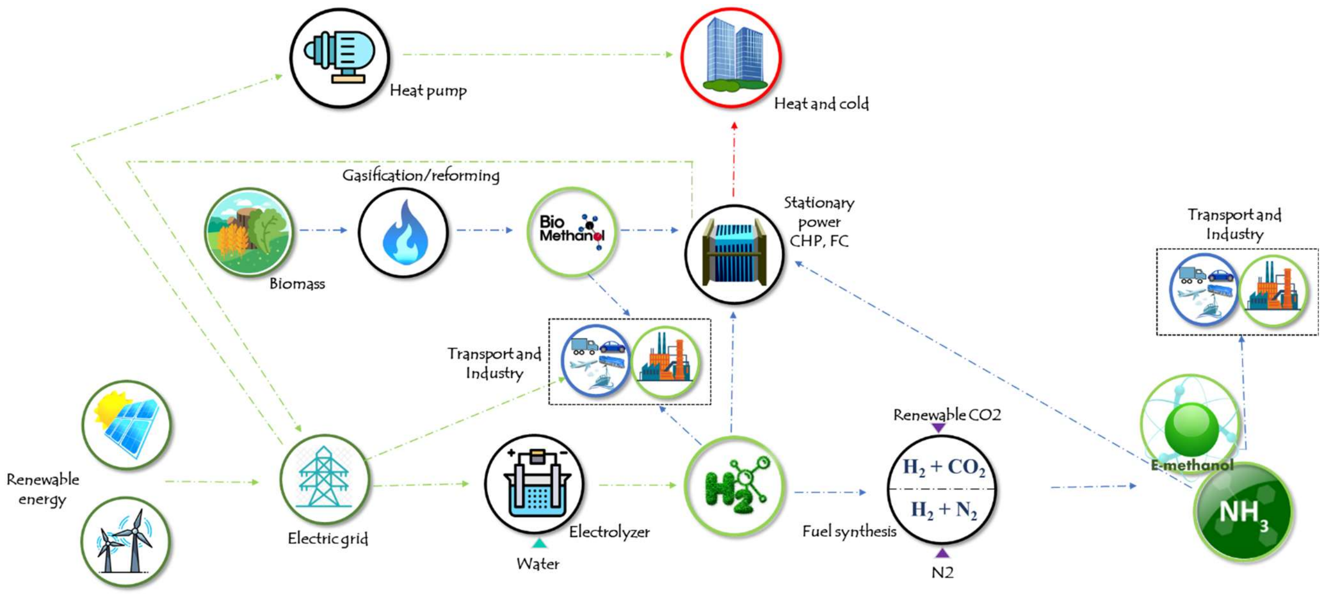


Figure 10. General production pathways of various carbon-neutral fuels and their key sector of application.

4. Challenges, Future Perspectives, and Conclusions

The three fuels presented in this perspective have a critical role to play in the world's quest of reaching carbon neutrality by mid 21st century. However, there are still some challenges that pose a potential threat to the realization of net zero carbon emissions via carbon-neutral fuels. Some of the common barriers to the up-scaling of all three fuels are summarized as follows. The main and universal challenge facing all three fuels concerns their investment costs when compared to fossil fuel-based processes. For instance, the price of renewable hydrogen is at least two times more expensive than that of grey hydrogen. One of the critical reasons for the discrepancies in fuel pricing between carbon-neutral fuels and their traditional counterpart stems from the fact that the latter is well-developed and already at hundreds of MW to GW capacities, and as such can negotiate for feedstocks at lower prices whiles most carbon-neutral fuels are still in kW to low MW capacities. Furthermore, the price variations between fossil-based and renewable-based fuels can be attributed to the high initial investment of renewable energy projects and the requirement for large electricity for the production of carbon-neutral fuels. Going forward, the cost of renewable energy technologies and clean electricity generation should decrease whiles simultaneously making the fossil-based pathways economically unattractive to pursue. Mechanisms such as carbon pricing, phasing out fossil fuel subsidies, private sector involvement in renewable energy development, and the establishment of production tax credits and investment tax credits for promoting wind and solar energy projects, respectively, could be instituted to make renewable electricity-based fuels cost-competitive against their fossil fuel alternatives. Since all three carbon-neutral fuels depend largely on renewable electricity (except bio-methanol), there is the issue of the intermittent and fluctuating nature of sources such as wind and solar energy. The power plants for producing carbon-neutral fuels need to be in operation frequently, and as such future developments should consider providing a stable and dependable electrical grid via the combination of both dispatchable and non-dispatchable sources of electricity as well as storage. To build a huge global market for carbon-neutral fuels, huge investments are required to develop a range of infrastructure for transportation and storage, especially in the case of hydrogen. There is a need to establish a well-functioning infrastructure that can handle the fuels after production, transport, and cost-effectively store them. The lack of sectorial coupling is another issue that curtails the upscale of carbon-neutral fuels. Currently, the fuels are most applied in the industrial sector, and to rapidly achieve the 1.5 °C goal, they should also be widely used in sectors where their application is currently limited such as transport, heating, and power generation. The coupling of the various energy sectors creates additional demand for these fuels and maximizes the technical penetration of solar and wind energy without causing challenges to the grid network. In other words, the Power-to-X through the interactions of the different sectors will create the needed balance in the grid network at high shares of solar and wind electricity generation. At the moment, it is also difficult to tell the difference between fossil-based fuels and their carbon-neutral counterparts—for instance, grey and green hydrogen will look the same to consumers after production. Immediate regulation, standardization, and certification could help resolve this challenge. Figure 11 summarizes some critical challenges facing the development of carbon-neutral fuels.

Figure 11. Critical challenges facing the development of carbon-neutral fuels.

In summary, the current paper presents a brief perspective on three different carbon-neutral fuels i.e., green hydrogen, green ammonia, and renewable (green) methanol which are the 'hot' fuels for tomorrow's energy system in light of climate goals. We have shown that these fuels have a critical role to play if net zero carbon emissions are to be possible by mid 21st century. Their most important contributions will be witnessed in hard-to-decarbonize sectors like long-range transport, energy-intensive industry, and part of residential heating where it is difficult to directly electrify. The realization of carbon neutrality via carbon-neutral fuels is possible but only after some critical challenges are resolved, especially in making the entire process cost-effective and competitive against existing processes that are dominated by fossil fuels.

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