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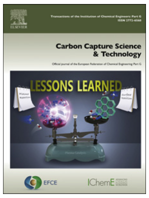

Review

Prospects of low and zero-carbon renewable fuels in 1.5-degree net zero emission actualisation by 2050: A critical review

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ABSTRACT

The Paris Climate Agreement seeks to keep global temperature increases under 2° Celsius, ideally 1.5° Celsius. This goal necessitates significant emission reductions. By 2030, emissions are expected to range between 52 and 58 $GtCO_2e$ from their 2016 level of approximately 52 $GtCO_2e$. This review paper explores a number of low and zero-carbon renewable fuels, such as hydrogen, green ammonia, green methanol, biomethane, natural gas, and synthetic methane (with natural gas and synthetic methane subject to CCUS both at processing and at final use) as alternative solutions for providing a way to rebalance transition paths in order to achieve the goals of the Paris Agreement while also reaping the benefits of other sustainability targets. The results show renewables will need to account for approximately 90% of total electricity generation by 2050 and approximately 25% of non-electric energy usage in buildings and industry. However, low and zero-carbon renewable fuels currently only contributes about 15% to the global energy shares, and it will take about 10% more capacity to reach the 2050 goal. The transportation industry will need to take important steps toward energy efficiency and fuel switching in order to achieve the 20% emission reduction. Therefore, significant new commitments to efficient low-carbon alternatives will be necessary to make this enormous change. According to this paper, investing in energy efficiency and low-carbon alternative energy must rise by a factor of about five by 2050 in comparison to 2015 levels if the 1.5 °C target is to be realised.

1. Introduction

The Paris Agreement of 2015 serves as the unifying document for global climate action to combat climate change. The Agreement's remediation objectives as outlined in Articles 2.1 and 4.1. 2.1 (a) highlights the temperature goal of "keeping the global average temperature increase to below 2 °C above pre-industrial thresholds and advancing measures to limit the temperature rise to 1.5 °C above pre-industrial thresholds, recognising that this would remarkably decrease the likelihood of climate change" (Rajamani and Werksman, 2018).

The energy industry presently is responsible for approximately three-quarters of greenhouse gas emissions and thus holds the key to limiting the most severe effects of climate change (Sokołowski, 2022). Limiting global CO_2 emissions to net zero by 2050 is coherent with attempts to curtail long-term average global temperature increases to 1.5° Celsius. This necessitates a complete overhaul of how we generate and consume energy. The growing political consensus on achieving net zero emissions is reason for substantial optimism about the world's progress, but the changes required to achieve net-zero emissions globally by 2050 are understudied or poorly understood (IEA, 2021b). An enormous amount of effort is required to make today's ambitious goals a reality, particularly considering the multitude of distinct situations between many countries and their varying capacities to effect the appropriate amendments.

To limit global warming to 1.5 °C above pre-industrial levels, transformative societal change must be combined with sustainable growth. Such a revolutionary change would require additional adaptation actions, such as pivotal adaptation, especially for trajectories that partially or completely exceed 1.5 °C. The recent national adaptation and mitiga-

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Nomenclature

ATR	auto-thermal reforming
BECCS	bioenergy with carbon capture and storage
CO_2	carbon dioxide
CCS	carbon capture and storage
CCUS	carbon dioxide capture, utilisation, and storage
CDR	carbon dioxide removal
DACCS	direct air capture with carbon capture and storage
EOR	enhanced oil recovery
FAOLU	forestry, agriculture, and other land use
GA	green ammonia
GHG	greenhouse gases
GT	gigatonnes
H_2	hydrogen
H_2O	water
IMO	international maritime organisation
LHV	lower heating value
MSW	municipal solid waste
MT	million tonnes
NZE	net zero emissions
NTP	normal temperature and pressure
PPAs	power purchase agreements
PEM	polymer electrolyte membrane
SDS	sustainable development scenario
SOEC	solid oxide cell electrolysers
WEO	world energy outlook

tion pledges are insufficient to keep temperatures below the Paris Agreement's limits and meet the agreement's adaptation objectives (Van Soest et al., 2021). Although many countries are making progress on energy efficiency, carbon effects of electrification, land-use transition, and fuels, limiting global warming to 1.5 °C will necessitate a larger scale and rate of change to transform industrial, urban, energy, and land systems worldwide (Kolb et al., 2021).

Wind energy, solar energy, and electricity storage technologies have improved dramatically in terms of social, political, technical, and economic feasibility in recent years, whereas nuclear energy and CO_2 capture and storage (CCS) in the electricity sector have not advanced at a commensurate rate (Huovila et al., 2022). Hydrogen (H_2), bio-based feedstock, electrification, and substitution, and, in some cases, CO_2 capture, utilisation, and storage (CCUS) (Hong, 2022), would result in the significant emissions reductions needed in energy-intensive industries to reduce global warming to 1.5 °C. Nevertheless, these opportunities are limited by economic, technological, and institutional constraints, which raise financial risks for many incumbent firms (high agreement, medium evidence). Energy efficiency in industry is more financially viable and aids in industrial system transitions, but it must be supplemented with carbon dioxide removal (CDR) or GHG-neutral processes to make energy-intensive industries consistent with 1.5 °C (Rogelj, 2018).

The most significant route to decarbonizing the power industry is to redevelop plants to allow for the use of zero and low-carbon fuels or to capture and store carbon using CCUS advanced technologies. This strategy would enable these thermal plants to continue operating as low-emission sources of firm capacity in the future while redeveloping existing facilities and their related facilities (transmission networks) and distribution networks. This would lower the cost while minimising the social and economic disruptions associated with large-scale energy industry transformation. Retrofitting for low-carbon fuels and CCUS also protects against the risk that cost decreases in newer generating technological advances such as offshore wind, advanced geothermal, or enhanced nuclear power do not actually occur.

The ability to decouple the generation system from the fuel enables these plants to receive feed from various sources. This presents a wide range of decarbonization prospects for the electricity sector while maintaining supply security, depending on the paths that appear to have the best chance of success. Co-firing, in particular, would allow for a gradual transition from fossil fuels while steadily expanding the production and transportation networks for zero-carbon and low-carbon fuels.

Increasing production and deployment of zero and low-carbon fuels, such as hydrogen, green ammonia, green methanol, biomethane, natural gas, and synthetic methane (with natural gas and synthetic methane subject to CCUS both at processing and at final use), will be required to decarbonize the gas and wider energy systems (Daniel et al., 2022) Table 5. Infact, Low-carbon renewable fuels currently contributes only 25% share in electricity but in the net zero scenario, the share needs to increase to 90% (IRENA, 2022). Locally made low and zero-carbon fuels can minimise dependency on fossil fuel supplies and enhance the security of energy supply in the foreseeable future, in addition to their environmental advantages. Given the critical need to accelerate the integration of low and zero-carbon fuels into energy systems, industries, technology, and government should begin making changes immediately to allow for their anticipated cost-effective deployment into the energy systems. Furthermore, a smooth transition from the existing energy schemes to one that integrates various fuels will necessitate careful market design from the start, taking into account the network transition challenging problem, the changing supply adaptability of low and zero-carbon fuels, as well as the risks for supply security (Buckingham et al., 2022).

According to Salmon and Bañares-Alcántara (2022), wind and solar sources of energy are set on a pedestral to replace the vast majority of energy needs globally, however, due to the seasonal varaiblity of wind and sun, and the fact that most regions have little to non of these renewable energy sources, renewable energy fuels still remain the pillars for a NZE from the energy sector, because they can serve as energy carries and store for wind and solar sources of power. Renewable fuels currently being developed all over the world can be classed into two categories zero-carbon and low-carbon. Although zero-carbon fuels, particularly hydrogen, is the most preferred, the importance of securing a constant uninterrupted supply chain and the urgency of the 2050 net-zero actualization, necessitates the harnessing of a wider range of fossil fuel alternatives that are cost effective, applicable wide range, storable long-time, and can also be locally sourced readily (Wu et al., 2022).

Different renewable fuels have been studied for the decarbonization of different sectors - aviation, shipping, road transport, construction, agriculture, and manufacturing, all geared towards achieving a net zero future. For example, Rahman and Wahid (2021) carried out an extensive review of the ongoing plans in Malaysia to slightly modify thermal power plants to establish interconnecting links that can secure a constant supply chain for zero-carbon fuels particularly green hydrogen and ammonia between Peninsular Malaysia and east Malaysia that will be complementary for both regions. Their study showed that a single region cannot achieve a net-zero future alone, thus, there is a need for more collaboration between regions and/or countries, as has been exemplified in Malaysia.

Additionally, finance seems to be an essential component required for the actualization of a net-zero future involving renewable fuels, although most studies have either negatively correlated financial development with CO_2 emissions levels with a stance that increased CO_2 comes with an increased financial development as it tends to necessitate unnecessary consumption patterns (Awan et al., 2020; Le and Ozturk, 2020; Tahir et al., 2021). However, as true as this may be, it pales in comparison with the huge benefits financial development can provide towards developing more renewable fuel options. Relatedly, Obobisa (2022) used an empirical study to show that financial development, renewable fuel consumptions, and CO_2 emissions were closely interlinked, highlighting their collective impart on the actualization of a net-zero future globally. The results show that a 5% increment in both financial development and renewable energy consumption on a global scale led to a respective increase (by 0.05%) and decrease (by 0.103%)

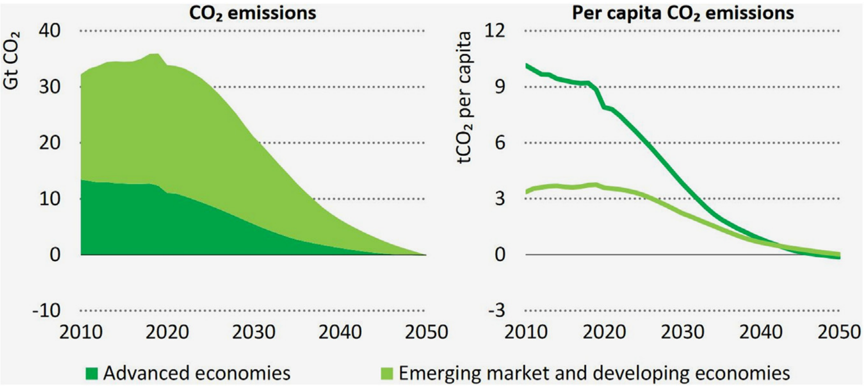

Fig. 1. The NZE's global carbon dioxide emissions (IEA, 2021a).

in CO_2 emission. They reiterated that the benefits of financial development on CO_2 emission reduction are doubled by 50% when compared to the detrimental effects. Furthermore, the study of Salmon and Bañares-Alcántara (2022) looked at bringing down the production costs for renewable fuels by exploring the option of green ammonia generation sites to be situated at sea where wind energy is surplus and this can be easily transportd to different regions via shipping vessels. This will hopefully motivates countries such as Saudi Arabia, Oman, Brunei Darussalam, Kuwait and Qatar, that are still 100% dependent on non-renewable fuel sources to decrease their fossil fuel dependancy (Dillinger, 2017).

Based on the above literature reviews that have assessed the contribution of different renewable fuels to the net-zero future ambitions, we have ascertained that no study yet has critically reviewed their collective prospects in 1.5-degree net-zero emission actualisation by 2050. The structure of this article is as follows: The carbon dioxide emissions are covered in Section 2. Selected low and zero-carbon fuels are covered in Section 3; the essential ideas and findings are summed up in Section 4.

2. Status and projections of carbon dioxide emissions

Global energy and industrial process emissions of carbon dioxide (CO_2) in the NZE are projected to decline to about 21 Gt CO_2 by 2030, and to zero by 2050 as shown in Fig. 1. (IEA, 2021a) CO_2 emissions in developed and emerging economies as a whole will drop to net zero roughly by 2045, and these countries will jointly eliminate approximately 0.2 Gt of carbon dioxide from the air by 2050 (Iyer et al., 2021). Emission levels in various individual emerging economies will also drop to net zero well before 2050, but this group of countries will still have about 0.2 Gt of carbon dioxide emissions in 2050. These are mitigated by capturing carbon dioxide in developed economies, resulting in net zero emissions of CO_2 on a global scale.

Numerous developing markets and emerging economies with significant capacity for generating renewable bioenergy and electricity are important sources of carbon dioxide removal (CDR) (Godin et al., 2021). This includes using renewable energy sources to generate huge amounts of biofuels with CCUS, some of which may be exported, as well as performing direct air capture with carbon capture and storage (DACCS) (Apergis et al., 2020).

Advanced economies' per capita CO_2 emissions fall from roughly 8 tCO_2 in 2020 to about 3.5 tCO_2 in 2030, a level similar to the average in developing markets and emerging economies in 2020. In developing and emerging economies, per capita emissions are also falling, although from a significantly reduced starting point. By the early 2040s, both regions' per capita CO_2 emissions were roughly the same, at about 0.5 tCO_2 per individual (Fuss et al., 2020).

Total industrial process and global energy CO_2 emissions in the NZE amount to slightly more than 460 Gt. Presuming parallel steps to solve carbon dioxide emissions from forestry, agriculture, and other land use (FAOLU) from now until 2050, FAOLU will emit approximately 40 Gt of CO_2. This means that total CO_2 emissions from all sources—around 500 Gt CO_2 are in line with the CO_2 budgets included in the IPCC SR1.5, which states that the total CO_2 budget for 2020 is consistent with a 50% chance of reducing warming to 1.5° Celsius is 500 Gt CO_2 (IPCC, 2018). In addition to achieving net-zero CO_2 emissions, the NZE aims to minimize non-CO_2 emission levels from the energy sector. Methane emissions from the production and use of fossil fuels, for example, are expected to drop from 115 million tonnes (Mt) in 2020 (3.5 Gt CO_2 equivalent) to 30 Mt by 2030 and 10 Mt by 2050 (Hong, 2022).

The electricity sector subsequently observes the quickest and biggest decrease in global emissions in the NZE, as presented in Fig. 2. Electricity generation was the largest source of emissions in 2020, but projected emissions fell by nearly 60% between 2020 and 2030, owing primarily to significant reductions from coal-fired power plants, and the electricity sector became a small net negative source of emissions around 2040. Emissions from the building sector are expected to drop by 40% between 2020 and 2030 due to a transition away from using fossil fuel boilers and retrofitting existing facilities to enhance their energy efficiency. Emissions from various industrial sectors both drop by about 20% during this period, and the rate of reduction accelerates during the 2030s as low-emissions fuels and other reduced emissions options are scaled up. Even though there are a lot of aspects in transportation and industry where it will be hard to entirely remove emissions, such as aviation and heavy industry, both sectors will have a low level of residual emissions in 2050. These residual emissions are offset through the use of bioenergy with carbon capture and storage (BECCS) (Ahlström et al., 2022) and direct air capture with carbon capture and storage (DACCS).

Note: Other = fuel production, agriculture, transformation, direct air capture and related process emissions. BECCS = bioenergy with carbon capture and storage; DACCS = direct air capture with carbon capture and storage. BECCS and DACCS includes CO2 emissions captured and permanently stored (IEA, 2021a).

The NZE involves a systematic preference for all new assets and infrastructural facilities to be as efficient and sustainable as feasible, accounting for half of total emissions reductions in 2050. Addressing emissions from current infrastructure accounts for a further 35% of reductions in 2050, while behavioral changes and avoided demand, such as material efficiency gains and modal shifts in the transportation sector, account for the remaining 15% of reducing emissions. The NZE employs various technologies and methods to curb emissions from current facilities, such as industrial facilities, power plants, networks, buildings, appliances, and equipment. The NZE is proposed to reduce stranded capital where feasible, for example, cases where the initial investment is not recouped, but in many scenarios, early retirements or lower utilization, or early retirements lead to stranded value, i.e., a decrease in revenue.

As shown in Fig. 3, effective employment of more energy-efficient advanced technologies, electricity generation, and rapid growth of renewables all play important roles in emissions reduction in the NZE across all sectors. Renewables will account for approximately 90% of

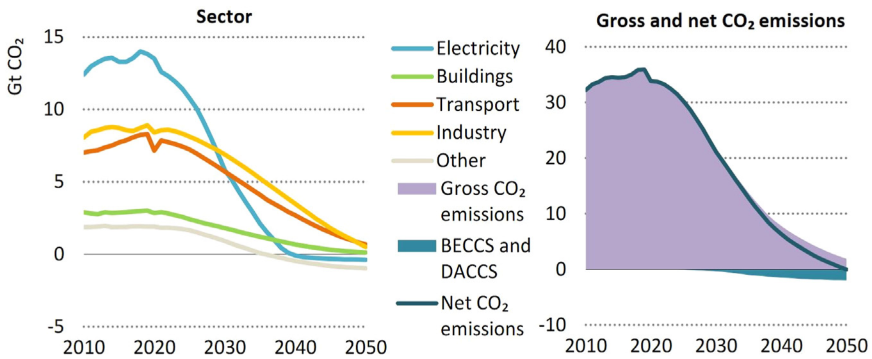

Fig. 2. The global CO_2 emissions by sector, as well as net and gross CO_2 emissions in NZE.

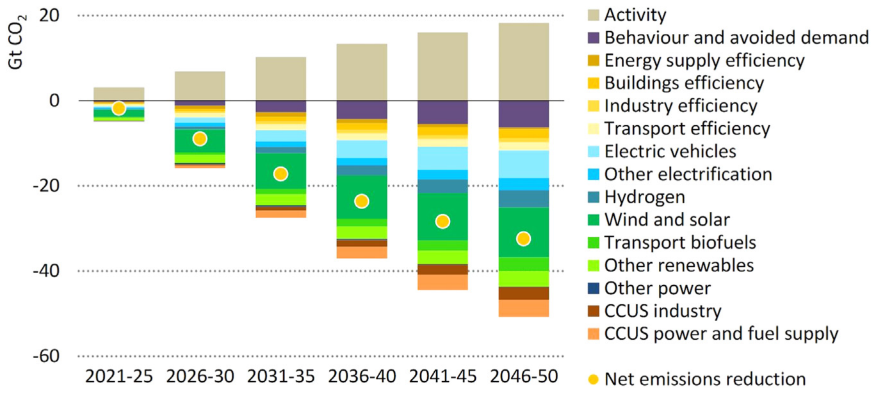

Fig. 3. Estimated annual CO_2 reductions in the NZE starting in 2020. Activity = changes in energy service demand from population and economic growth. Behavior = change in energy service demand from user decisions, e.g. changing heating temperatures. Avoided demand = change in energy service demand from technology advancements, e.g. digitalisation (International Energy Agency, 2021).

total electricity generation by 2050 and approximately 25% of non-electric energy usage in buildings and industry. Emerging technologies and fuels, particularly bioenergy, H_2-based and H_2 fuels, and CCUS (Ahlström et al., 2022), play an essential role, particularly in sectors where emissions are frequently challenging to reduce (Slorach and Stamford, 2021).

3. Low carbon fuels

Low-carbon fuels are important for the energy transitions. Supportive policies should be implemented to exploit the full potential of biomethane and biogas. To facilitate the energy transitions, multiple fuels and technological advances will be needed, with low-carbon gases led by biomethane and zero-carbon H_2 playing key roles. Although electricity's 20% share of global final consumption is increasing, electricity cannot handle energy transitions on its own in the face of growing energy demands (Witcover and Williams, 2020). In the period horizon of the World Energy Outlook (WEO) cases, biomethane is the major contributor to low-carbon gas sources. The biomethane and biogas industries will develop differently in each country, depending on the sectoral focus, feedstock accessibility, market trends, and policy initiatives. Realizing the numerous advantages of biomethane and biogas, on the other hand, necessitates integrated policymaking across transportation, energy, agriculture, waste management, and the environment (Sanchez et al., 2021).

3.1. Concept of biogas and biomethane

3.1.1. Biogas

Biogas is a gas mixture composed of methane, carbon dioxide, and trace amounts of other gases generated by the anaerobic digestion of organic matter in an O_2-free environment. The accurate composition of biogas is determined by the nature of the feedstock used and the production pathway, which includes the following major technologies (Golmakani et al., 2022):

- Biodigesters: this is an airtight technology (such as tanks or containers) in which naturally occurring microorganisms break down organic material diluted in H2O. Prior to using the biogas, moisture and contaminants are often eliminated.
- Landfill gas extraction mechanisms: When municipal solid waste (MSW) decomposes in anaerobic environments, biogas is produced at landfill sites. This can be recovered by inducing flow to a central collecting point using extraction wells and pipes, as well as compressors.
- Wastewater treatment plants: These facilities are capable of extracting organic matter, sediments, and nutrients such as phosphorus and nitrogen from sewage sludge. Sewage sludge could be used as a feed into an anaerobic digester to produce biogas after further processing.

Biogas is typically 45–75% methane by volume, with CO_2 accounting for the majority of the remainder. Because of this variance, the energy content of biogas varies; the lower heating value (LHV) ranges from 16 to 28 MegaJoules per cubic metre (MJ/m^3). Biogas is used directly to generate heat and electricity, as well as a cooking source of energy. Its applications and economic strength vary depending on local conditions, but one common factor is that biogas provides a sustainable solution to satisfy community energy demands, particularly in areas where access to national grids is difficult or where there is a high demand for heat that cannot be achieved by renewable electricity. Biogas reduces the dependency on solid biomass as a cooking fuel in developing nations, improving both health and economic outcomes. According to the Sustainable Development Scenario (SDS), biogas will provide clean cooking to an extra 200 million people by 2040, as shown in Fig. 4, with half of them living in Africa. By eliminating CO_2 and other impurities, biogas can be upgraded to generate biomethane (Golmakani et al., 2022).

3.1.2. Biomethane

Biomethane is a relatively pure methane source that is generated by either biogas upgrading (a method that eliminates any CO_2 and other

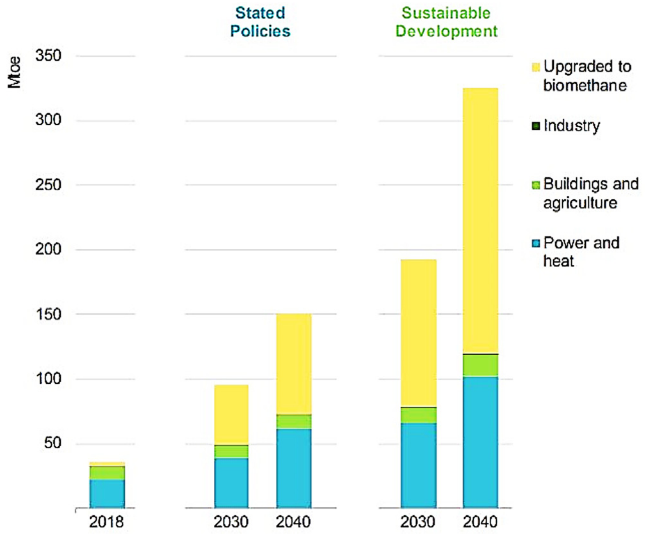

Fig. 4. The sectoral forecast for worldwide biogas usage (IPCC, 2018).

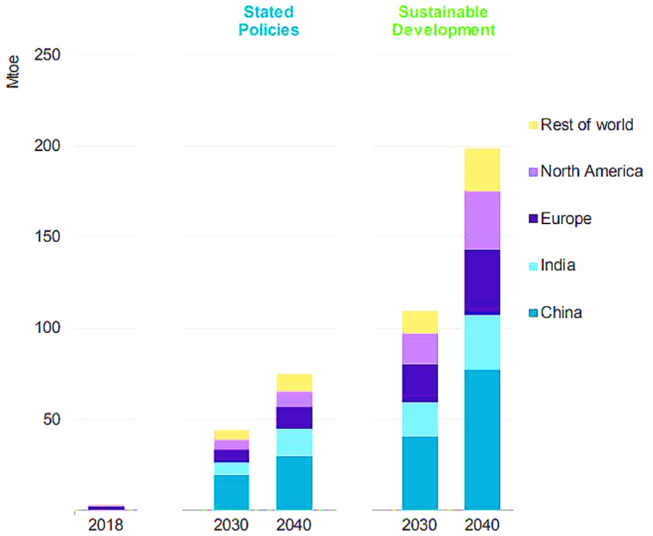

Fig. 5. The sectoral forecast for worldwide biomethane usage (IEA, 2021b).

pollutants existing in the biogas) or by gasifying solid biomass followed by methanation (Dar et al., 2021).

- Upgrading biogas: This equates to roughly 90% of the total biomethane produced globally today (González-Arias et al., 2022). Upgrading techniques use the distinct features of the different gases embedded within biogas to detach them, with H2O scrubbing and membrane separation accounting for nearly 60% of global biomethane production today (Obaideen et al., 2022).
- Thermal gasification of solid biomass, followed by methanation: In a low-oxygen environment, woody biomass will be broken down at high pressure and temperature (700–800 °C). Under these circumstances, the biomass is converted into a gas mixture, primarily carbon monoxide, hydrogen, and methane (sometimes referred to as syngas). This syngas is cleaned to remove any acidic or corrosive components before being converted into a pure stream of biomethane (Gabbrielli et al., 2022). A catalyst is then utilised in the methanation system to enhance the reaction between carbon monoxide and hydrogen or CO_2 to generate methane. At the end of this process, any remaining H_2O or CO_2 is removed.

The lower heating value (LHV) of biomethane is approximately 36 MJ/m^3. Because it is indistinguishable from natural gas, it can be deployed without any modifications to distribution and transmission systems or equipment end-users, and it is completely compliant with natural gas automobiles. Biomethane helps consumers limit emissions levels in difficult-to-abate industries such as freight transportation and heavy industry. The sectoral forecast for worldwide biomethane utilisation is shown in Fig. 5. Moreso, it contributes to making some current gas facilities more compliant with a low-emissions future, enhancing the cost-efficiency and safety of energy transitions in several parts of the world. In 2040, biomethane in the SDS saves approximately 1000 million tonnes (Mt) of GHG emissions. This involves the carbon dioxide emissions that would have existed if natural gas had been utilised instead, as well as the methane emissions that would have occurred due to feedstock decomposition (Ghafoori et al., 2022).

3.2. *The prospect of gas technologies and biomethane*

Biomethane and other low-carbon gases' opportunities are intertwined with broader considerations concerning the gas system's future involvement in decarbonisation in numerous ways. Long-term plans must consider the ability of current and new systems to supply a wide variety of gases in a low-emissions era and their involvement in guaranteeing energy security (Koornneef et al., 2013). Interactions and potential synergies between electricity, liquids, and gas distribution systems must also be considered.

The opportunity for electricity to play a significant active role in the energy system at some point has been frequently underlined by WEO studies (IEA, 2021b). However, most profound decarbonisation approaches envision a low-carbon energy infrastructure in which low-carbon electricity generation is supported by extensive electrification of industrial operations, electric heating replaces natural gas in houses, and electric transportation is widely available.

Global electricity demand has increased by two-thirds faster than total final consumption since 2000. Global investment in electricity storage, generation, and networks exceeded USD750 billion in 2018, outpacing overall expenditure on oil and gas delivery.

On the other hand, electricity is not adequate to offer energy decarbonisation solutions to all sectors. Hence, there are constraints to how widely and rapidly electrification may occur. Even if all of the current electrification capacity was used, there would still be areas that require other energy sources (given current technology). Most aviation, heavy-duty trucks, shipping, and industrial processes, for instance, are not yet "electric-ready." While some industries may be able to employ electricity-generated fuels (such as hydrogen or synthetic fuels) in the future, most of these fuels will require their own technology that facilitates the delivery.

The importance of overlapping technology for energy security might also be a factor for lawmakers to consider. As opposed to a method that depends just on electricity, sustaining a parallel gas technology infrastructure offers a layer of robustness. This was evident in Japan following the closure of its nuclear reactors in 2011. Gas-fired generation moved in and provided power. It also serves as a good buffer against the danger that electrification and the building of new electricity systems do not progress at the rate required to displace old fuels while satisfying energy demand. Gas infrastructure, on the other hand, will need to deliver really low-carbon energy sources if it is to play a part in a low-emissions network (Ghafoori et al., 2022).

In the SDS, as shown in Fig. 6, electricity's proportion of final consumption increases from 19% now to 30% by 2040, while supply is simultaneously decarbonized through a major expansion of renewables, mainly wind and solar PV, but also nuclear power, biofuels, and hydropower (Koornneef et al., 2013). Gas and liquids will continue to supply half of the energy needed in 2040, with low-carbon sources accounting for 14% of liquids in some places around the world. Recreating the services provided by gas grids using low-carbon electricity may be feasible, particularly in areas with abundant renewable energy resources, relatively low winter heating demands, and an electrifiable economic

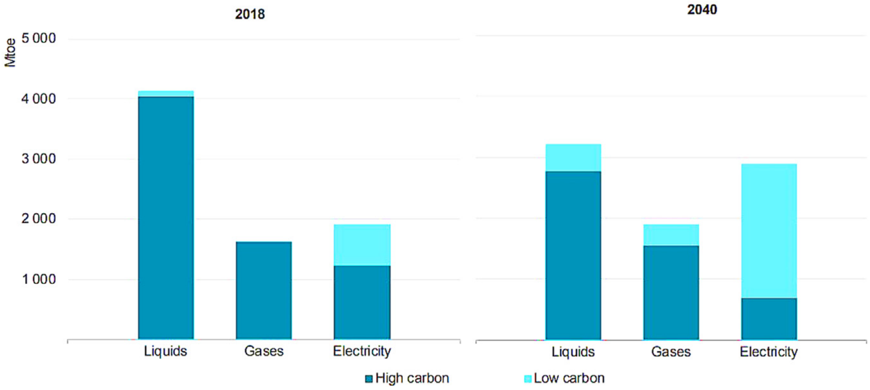

Fig. 6. SDS final energy consumption by carrier between 2018 and 2040 (IEA, 2021b).

base (services as well as certain industrial subnetworks). However, in other areas, switching from gas to electricity as a means of providing services to end-users is anticipated to be far more difficult and costly.

Both the residential and industrial sectors face practical challenges when adopting electric heating on a large scale. The size of the infrastructure investments needed to balance peak loads with variable supplies is a substantial impediment to full electrification. Although batteries are becoming more affordable and well-suited to controlling short-term changes in electricity demand and supply, they are unlikely to be a cost-effective option for dealing with significant seasonal swings. If the current infrastructure can be used to distribute decarbonised gases appropriately, these systems might be utilised throughout the energy transition and even beyond. Gas networks are the primary means of delivering energy to customers in many countries. In the United States and Europe, for instance, gas systems deliver significantly more energy to target consumers than electricity networks. They work in tandem with gas storage facilities to provide a vital source of flexibility, ramping up delivery as required to meet demand spikes.

Zero-carbon H_2 and biomethane are the two primary possibilities for decarbonizing the gas supply. In recent times, there has been a boom in interest in zero-carbon H_2, even though it is still quite expensive to create. Incorporating zero-carbon hydrogen into gas grids would reduce carbon dioxide emissions while also helping to significantly increase hydrogen production and lower prices (IEA, 2021b). Furthermore, because there is currently no extensive infrastructure for specialised H_2 transport, many countries' existing natural gas grids might be used to carry H_2 at significantly cheaper unit costs than if new separate H_2 pipes were required.

Transmission systems could possibly handle H_2 blends of approximately 15–20% with modest changes, depending on the local circumstances. However, today's H_2 blending restrictions are usually derived from natural gas supply tolerance or the specifications of the grid's most sensitive piece of equipment. As a result, just very low levels of blending are permitted: today, no more than 2% H_2 mixing is permitted in many nations (IEA, 2019). Biomethane, a near-pure source of methane, is indistinct from natural gas and may thus be used without requiring any adjustments to transmission and distribution systems or end-user equipment, unlike H_2.

3.3. Effects on industry and policymakers

3.3.1. Low-carbon investments

Presently, biomethane and biogas projects account for a small portion of the total global gas spending. Over the last decade, investments have averaged less than USD 4 billion per year, roughly the same amount that the natural gas industry spends every week (Lepitzki and Axsen, 2018).

According to Stated Policies Scenario (STEPS), total expenditure on biomethane and biogas will more than triple to around USD 14 billion by 2040. By the late 2020s, rising biomethane spending will have surpassed direct biogas use investments. However, the proportion of biogas and biomethane in total gas investment spending continues to remain below 5%, as shown in Fig. 7.

According to the Sustainable Development Scenario (SDS), this trend has upside potential. As natural gas investment falls, total capital spending on low-carbon gases increases to capture more than a quarter of total investment in global gas supply, as biomethane and biogas are scaled up and H_2 and CCUS are added to the mix of low-carbon gases (Lepitzki and Axsen, 2018). Biogas and biomethane projects continue to be the most popular destination for low-carbon gas investment, accounting for 40% of total investment. By 2040, around USD 30 billion will be spent on biomethane infused into gas grids each year, roughly the same amount invested in shale gas advancement in the US today. These developments are directed specifically toward Asia's developing economies, especially India and China, which account for roughly 40% of total global expenditure.

Investing in the SDS assumes that a number of financing obstacles are resolved. Biomethane and biogas projects are currently facing some of the same funding problems as other small-scale, distributed renewable energy projects (particularly in developing economies). Nonetheless, loan criteria are frequently too small to attract investment projects and, in some cases, too large for individual investors to raise the necessary equity. The latter is typically between 20 and 25% of the initial capital costs (which, for a medium-sized biogas plant producing roughly 2 million cubic metres per year (1.7 kilotonnes of oil equivalent), ranges between USD 1.5 million and USD 2 million).

From a financial services standpoint, there is frequently a lack of technological expertise in the field, as well as a scarcity of benchmarks to accurately examine the return/risk profile of specific projects. There are a few risks that can be hard to determine, such as the ability to secure constant feedstock or, in the case of biomethane, to reach the stringent gas quality standards for injection into national distribution systems. These challenges can raise debt costs and risk perceptions, and shorten loan terms for investors. Several models are now being assessed to overcome these challenges; for instance, project sponsors like energy firms or larger-scale agricultural firms can present a comprehensive business model to the agricultural sector to reap the benefits of fixed feed-in tariffs or other types of subsidies, which ordinarily have a lower risk of obtaining finance (Lepitzki and Axsen, 2018). Agricultural cooperatives or other models that pool feedstock sources are also good alternatives for increasing output. Both biomethane and biogas projects could gain from the increasing availability of financial measures geared toward renewable energy, such as green bonds or other targeted institutional investor funds.

3.3.2. Carbon dioxide and methane reductions

Biomethane and biogas assist in decreasing carbon dioxide emissions by replacing polluting fuels and facilitating the advancement of other renewables. The ability to reduce CO_2 emissions using biomethane or biogas depends on how these gases are generated and where they are

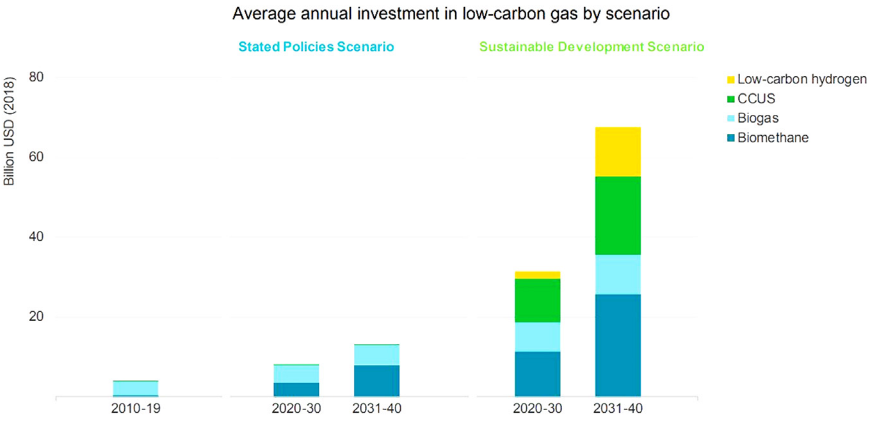

Fig. 7. Average yearly investment in low-carbon gas scenarios (IEA, 2021b).

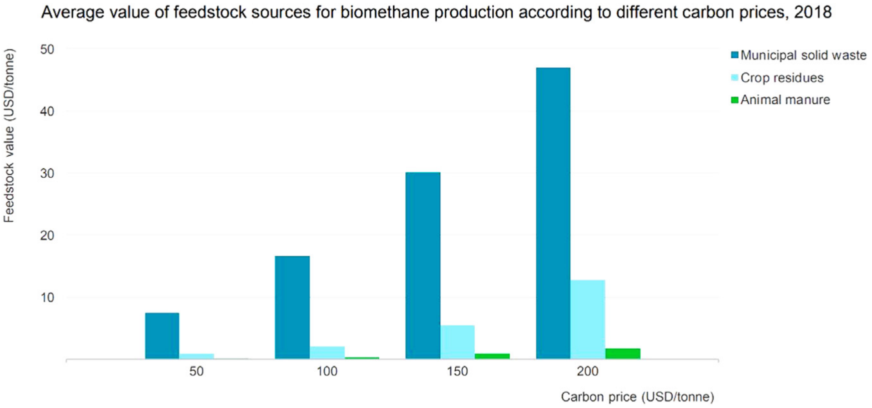

Fig. 8. The 2018 average price of feedstock supplies for biomethane generation, based on various carbon prices (IEA, 2021b).

used in the value chain. From a policy standpoint, it is critical that biogas production results in net life-cycle carbon dioxide emissions reductions.

In theory, a 10% volume mixture of biomethane in a natural gas pipeline would limit carbon dioxide emissions in the gas used by 10%. Nevertheless, emissions from the processing, transport, and collection of biogas feedstock must be weighed against carbon dioxide emissions from natural gas processing, production, and transportation. These indirect emissions can vary significantly between natural gas and biomethane sources and, if not minimised, could reduce the CO_2 emissions earnings from biomethane use. This is also true for low-carbon H_2: a 10% volume mix in a natural gas pipeline reduces emissions by 3–4% (for a specified energy level). However, because of the various possible energy inputs and conversion techniques used in H_2 production, a cautious life-cycle emissions method is required to guarantee it is low-carbon. Biomethane production provides another opportunity to eliminate CO_2 emissions. Biogas upgrading creates an efficient, concentrated carbon dioxide by-product stream that can be acquired for around USD 20 per tonne of carbon dioxide (tCO_2).

Carbon pricing makes biomethane use more economically viable, encouraging plant development in places where feedstock is plentiful and, in many situations, offering extra sources of revenue to rural areas (see Fig. 8). The value of each feedstock type is decided mainly by the product yield of each tonne of waste collected, as well as the costs of collection and handling the waste. A tonne of MSW utilised for biomethane generation, for instance, would be worth roughly USD 10 at a carbon price of USD 50/tCO_2, as it can be used to provide carbon-neutral energy and heat (Van Tran et al., 2022). To generate the same value from a tonne of agricultural residue, carbon prices would have to more than triple. Low-carbon biomethane and hydrogen integrated into the gas line in the SDS prevent approximately 500 Mt of carbon dioxide emissions that would have happened if natural gas had been used instead in 2040.

Today, there is approximately 30 MTOE of biomethane capacity that can be produced at a cost that is lower than the regional price of gas. As previously stated, if CO_2 costs are introduced to natural gas combustion, a significantly higher amount of biomethane becomes a viable offer. If policy additionally considers the value of prevented methane emissions from feedstock decomposition, a bigger quantity would indeed be cost-competitive. Because methane is such a powerful greenhouse gas, assigning a monetary value to these averted emissions has a significant impact on its entire supply cost profile.

If not adequately controlled, a few of the feedstocks used to make biomethane will breakdown and emit methane emissions. This is especially true of animal waste and the organic percentage of MSW at landfills. Anaerobic digestion can occur spontaneously in both circumstances, resulting in methane emissions. All other types of possible biomethane feedstocks, such as agricultural residues, break down in the presence of oxygen (rather than anaerobic environments) and hence do not often result in methane emissions.

By contrast, biomethane production can prevent methane emissions from several organic wastes by acquiring and handling them instead. Even if these emission levels happen outside of the energy sector, they should indeed be attributed to biomethane. This has been the case under California's Low Carbon Fuel Standard, which considers biomethane's entire life-cycle GHG emissions and credits prevented methane.

However, calculating the size of this credit is difficult because it is based on a reasonable case for what stages of methane emissions would have existed if the feedstock had not been converted into biomethane, which varies by region and over time. For instance, how methane generated within landfill sites is currently handled varies significantly across the country. Most locations in Europe have capture facilities, and the captured methane (known as "landfill gas") is either flared or used to generate electricity. In the United States, approximately 55% of the methane produced in landfills is captured. Approximately 20% of the remaining portion degrades before entering the atmosphere, implying that nearly 35% of the methane produced in landfills is released into the atmosphere. Most emerging economies lack credible data on landfills, but the proportion of methane captured is likely to be much lower than in developed economies.

There are several policy methodologies for how "prevented" methane emissions should be managed or credited (e.g., the Clean Development Mechanism), but there is presently no globally acknowledged or widely recognised framework. Various methods of dealing with these emissions can significantly impact the apparent cost-effectiveness of using biomethane to lower overall GHG emissions. For instance, if no credit is given for mitigating methane emissions but a credit is given for the carbon dioxide prevented by displacing natural gas, then about 60 Mtoe of biomethane production would be economically viable at a USD 50/tonne GHG price. If prevented methane emissions were also included, more than 120 Mtoe would be economically feasible at a GHG price of USD 50/tonne.

3.3.3. Recommendations for lawmakers

Both biomethane and biogas have significant potential to assist in meeting various energy-related Sustainable Development Goals (SDGs) and support clean energy transitions. Previous surges of interest in these gases have subsided, but they now only supply a small portion of total energy demand. This is because they are costlier than natural gas and do not receive the same level of legislative assistance as renewable energy sources like solar PV and wind. If biomethane and biogas are to play a significant part in the future energy mix, it will be important to understand both the advantages they offer over natural gas and the long-term relevance of gaseous energy sources (Fuss et al., 2020).

This paper discusses several potential measures for governments and policymakers to consider to help the biogas and biomethane markets thrive. Any legislative framework should have two fundamental features:

- Support biomethane and biogas' competitiveness against natural gas, coal, and oil by using CO_2 or GHG pricing mechanisms. This should include acknowledging biogas/large biomethane's GHG emissions mitigation capability to prevent direct methane emissions into the atmosphere from feedstock degradation. There are numerous current and prospective regulations that achieve this around the world, like California's Low Carbon Fuel Standard.
- To establish a comprehensive approach that promotes the biomethane and biogas sectors, it is necessary to provide integrated policymaking across energy, agriculture, transportation, and waste management. Developing a biogas business has several benefits, including enhanced gender equality, increased employment and income for rural people, decreased deforestation risk, increased resource efficiency, health advantages from lower air pollution, and proper waste management. These benefits go across multiple government agencies' responsibilities, necessitating a holistic approach that appropriately values these benefits and encourages private and public investment in their development (González-Arias et al., 2022).

Selected potential policy concerns and initiatives in three areas are highlighted:

A. Accessibility of viable biomethane and biogas feedstocks

Strategies for increasing the supply of viable feedstocks for the production of biomethane and biogas include the following:

- Implement sustainable waste management standards and procedures to improve MSW pre-treatment, collection, and sorting, resulting in a suitable biomass feedstock for urban biogas production.
- Improve food waste collection by prohibiting landfill disposal and instituting separated collection.
- Encourage sequence cropping experiments and initiatives to maximise feedstock resources from a specific area of agricultural land while minimising the impact on food production.
- Use a relevant and integrated sustainable development process to ensure that only sustainable feedstocks are used in biomethane and biogas production.
- Initiate GHG reporting and monitoring for large-scale biomethane and biogas production units.
- Conduct comprehensive regional and national feedstock cost and availability analyzes, including a screening of the best locations for biomethane and biogas plants and an assessment of municipal potential.
- Carry out feasibility studies at existing landfills and water treatment plants to evaluate potential sewage or landfill gas production.

B. Encourage the use of biomethane and biogas

Policy initiatives or strategies which might result in increased biomethane and biogas utilisation include:

- When establishing biomethane/biogas policy support, take into account the wider positive externalities, as the advantages of biomethane and biogas go beyond the availability of renewable electricity, heat, and transportation fuels.
- Promote the growth of biomethane and biogas sector jobs in rural areas through promotional programmes and skill training.
- Promote the use of biogas facilities for clean cooking in remote communities by providing subsidies that cover a portion of the capital cost or microfinance initiatives that allow households to pay off the investment costs over time using the financial benefits generated by the biogas plant.
- When establishing biogas and biomethane policy support, take into account the wider positive externalities, as the advantages of biomethane and biogas go beyond the availability of renewable electricity, heat, and transportation fuels.
- Increase the number of jobs in the biomethane and biogas sectors in rural areas through promotional programmes and skill training.
- Encourage the use of biogas facilities for clean cooking in remote communities by providing subsidies covering a portion of the capital cost or microfinance initiatives that allow households to pay off the investment costs over time using the financial benefits generated by the biogas plant. Create renewable electricity sale structures for power purchase agreements (PPAs) that reward biogas systems' flexible generation potential.
- Create directories to monitor and balance the amount of biomethane injected into and consumed by the gas network. These are an integral part of policy support implementation and are already in use in 14 European countries.
- Implement renewable energy quotas in transportation, including sub-targets for sophisticated bioenergy production from waste and byproducts, such as the European Union (EU) Renewable Energy Directive sub-target of 3.5% of transportation energy needs from such fuels by 2030.
- Construct biomethane/natural gas fueling stations along major road freight routes to facilitate biomethane utilization, as mandated by the EU Alternative Fuels Infrastructure Directive.
- Promote public procurement of biomethane-powered vehicles that serve as captive fleets, such as municipal waste disposal vehicles and public buses.
- Use pricing modules that allow for comparison with other transportation fuels, such as gasoline components.

- Create a system for using anaerobic digesters as soil fertilizers, such as through appropriate certifications, regulations, and standards.
- Consider establishing stringent renewable gas standards based on quotas tied to total gas consumption.
- Create more targeted incentives for renewable energy sources capable of providing baseload services.

C. Encourage biomethane and biogas supplies

Government initiatives or strategies that could result in the increased supply of biomethane and biogas include the following:

- Implement incentives and low-carbon renewable gas standards, considering the viability of feed-in premiums, feed-in tariffs, or auction-based renewable gas support programs.
- Based on relevant feedstock accessibility and industry condition assessments, set targets for biomethane production, biogas electricity generation capacity, and infusion into natural gas channels.
- Offer fiscal incentives such as accelerated depreciation for biogas production accessories and duty exemptions for imported biomethane fuels and equipment.
- Create structures for collaborative infrastructure and applications for biomethane advancement and gas network infusion, lowering capital and operation costs for numerous biogas manufacturers in the same geographical area, such as multiple farm digester units.
- Promote technology transfer, capacity building, and financing from advanced nations through efficient and effective mitigation actions in developing countries.
- Use international economic aid to help developing countries fund market-based community and household biogas systems.
- Raise awareness of the potential of biogas in key industries such as beverages, food, and chemicals.

3.4. Hydrogen

Hydrogen is critical to achieving net-zero emissions by 2050 and limiting global warming to 1.5 °C. Clean H_2 (zero-carbon and renewable) is the only scalable, cost-efficient, and long-term alternative for profound decarbonization in industries such as maritime, steel, ammonia, and aviation, complementing other decarbonization systems such as renewable power, biofuels, or increased energy efficiency (Tashie-Lewis and Nnabuife, 2021). Between now and 2050, H_2 can save 80 gigatonnes (GT) of carbon dioxide emissions. With a yearly abatement possibility of 7 GT in 2050, H_2 has the capability to improve 20% of the overall abatement required in 2050. This requires the use of 660 million metric tonnes (MT) of low-carbon and renewable H_2 by 2050, which is equal to 22% of worldwide final energy consumption. Hydrogen is essential to achieving a low-carbon energy economy. Since H_2 can store energy, provide adaptability, and transport large amounts of energy over vast distances through the use of piping systems and vessels, it enhances the integration of renewable energy (El-Emam and Özcan, 2019). Hydrogen enables energy companies to access highly competitive renewable energy that would otherwise be "trapped" in remote areas (Nnabuife et al., 2022). This speeds up the energy transition by allowing more renewables to be established. Finally, because H_2 can be generated from electricity and utilised as, or transformed into, power, fuels, and chemicals, H_2 production from electricity will link and distinctly transform the existing markets for gas, power, fuels, and chemicals (El-Emam and Özcan, 2019).

Hydrogen has the potential to play a critical role in helping countries and sectors of the economy achieve net-zero emissions reduction targets by 2050. While H_2 is not a complete solution for reducing all emissions across industries, it supports and facilitates other decarbonization channels such as biomass-based fuels, direct electrification, and energy-saving measures (Blanco et al., 2018). Table 1 shows the estimated greenhouse gas emissions for various H_2 production methods. Estimates thus cover a wide range of comparable greenhouse gas emissions for each production method. Few manufacturing techniques have the ability to minimise emissions to zero or less.

Table 1
GHG emissions from techniques for producing H_2 (Susmozas et al., 2016).

Production techniques	GHG emission equivalent estimates (gCO_2/kWh of H_2)
SMR with CCS	23–150
Coal gasification with CCS	50–180
Low-carbon electricity-powered electrolysers	24–178
Biomass gasification with CCS	- 371
Natural gas for heating	230–318 (CH_4)

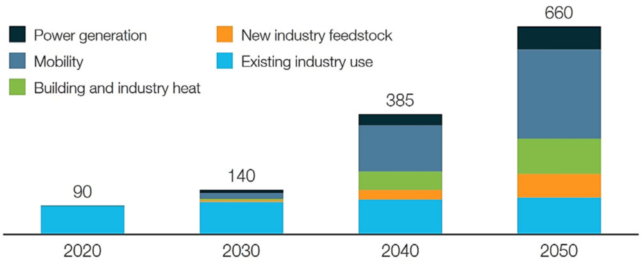

Fig. 9. Global demand for hydrogen by sector until 2050. 660 MT hydrogen required p.a. in 2050 for net-zero. 22% of global final energy demand (IEA, 2021).

In a net-zero globe, access to clean H_2 could attain 660 million metric tonnes (MT) in 2050, accounting for 22% of global final energy consumption (Fig. 9) and preventing annual carbon dioxide emissions of 7 gigatonnes (GT). If the world continues on its current global warming trajectory, this yearly abatement possibility of 7 GT in 2050 is equal to about 20% of existing emissions. Clean H_2 could save 80 GT of CO_2 by 2050, which is approximately twice the current yearly anthropogenic emissions. The cumulative CO_2 abatement potential of 80 GT by 2050 represents about 11% of the reduced emissions required to stay within the 420 GT carbon budget required to limit carbon emissions to 1.5–1.8 °C (Blanco et al., 2018).

The key purpose of H_2 in the energy transition is that of a cost-effective decarbonization vector in several industries, especially those less suitable for direct electrification. Hydrogen applications include a wide range of feedstock uses, such as ammonia synthesis for fertiliser production and iron reduction for steel; fuel for mobility, including direct utilisation of H_2 in heavy-duty vehicles and liquid H_2 or H_2-based fuels for use in aviation and maritime applications; heating, including high-grade heat in buildings and industries; and power applications, such as backup generators, seasonal balancing, and blending in established baseloads (French, 2020).

3.4.1. The role of hydrogen in the energy system

Hydrogen (H_2) is instrumental in supporting greater electrification and penetration of renewable power generation in a to develop decarbonized energy sources. Because of its flexibility, H_2 can store energy for long periods of time as well as provide energy system robustness by allowing for system balancing (Rosa and Mazzotti, 2022). It can potentially assist in transmitting clean energy over lengthy ranges, mostly through piping systems and shipping, thereby unlocking untapped renewable resources (French, 2020). Moreover, it has the potential to transform existing chemical, fuel, and metal production sectors as well as connect them to the power industry. Hydrogen's system-wide role enables broad, and thus faster and more cost-efficient, decarbonization across regions and sectors.

Hydrogen sector coupling: Hydrogen, in addition to this system functionality, links industry sectors in distinctive ways. Since H_2 can transform electricity into gas and other byproducts, it has the capability to facilitate and, eventually, transform the existing power, gas, fuel, and

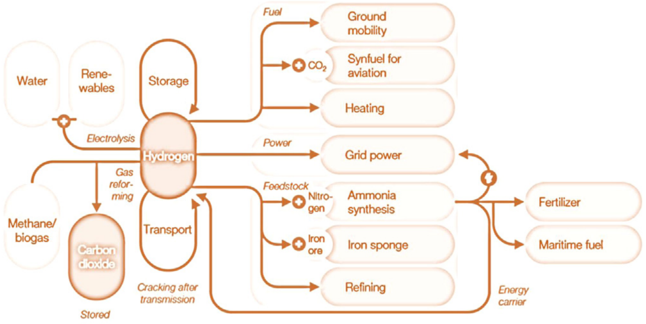

Fig. 10. The energy system's hydrogen pathways (IPCC, 2018).

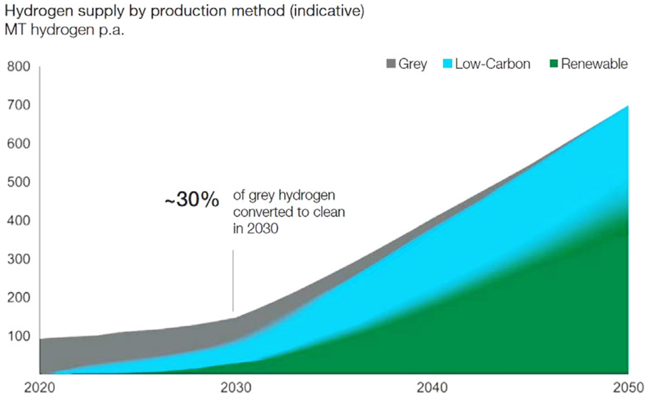

Fig. 11. The advancement of the hydrogen supply mix (IEA, 2021).

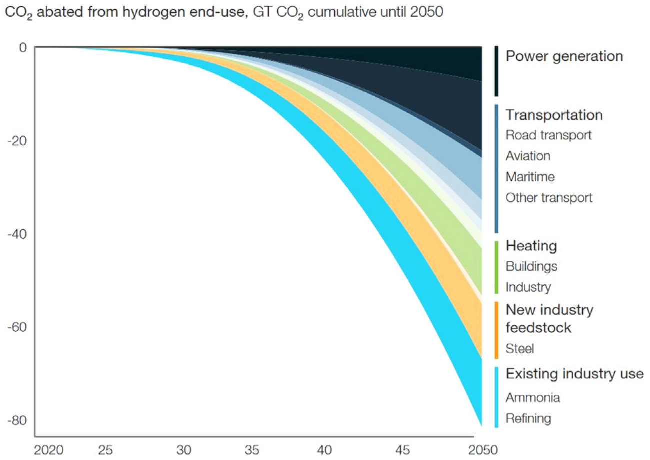

Fig. 12. Hydrogen reduces global emissions until 2050. 80 GT cumulative reduction by 2050. 7 GT p.a. reduced in 2050, with ~4GT CO_2 p.a. in 2040 (IEA, 2021).

chemical markets, with clean energy as the source of these applications (Fig. 10) (Pollitt and Chyong, 2021). Clean H_2, for instance, used in steel production or aviation fuel, is subsequently derived from renewable energy, biogas, or natural gas, with carbon capture. Hydrogen links the clean energy and power markets with the fuels, metals, petrochemicals, and chemical industries, finding a balance between previously distinct industries. For example, ammonia, which is currently utilised for fertiliser production and other commercial uses, could play a significant role as a fuel for power generation or maritime, or as a clean energy source for the worldwide transmission of clean electrons in the pattern of clean molecules (Pollitt and Chyong, 2021).

Long-term H_2 consumption should attain 660 MT in 2050 to accomplish net-zero goals. In 2050, the major end sectors for H_2 will most likely be mobility and industrial applications of H_2, including heating, feedstock, and building heating, making up for 90% of the total demand of 660 metric tonnes. The majority of the development comes from new H_2 applications, which will contribute to more than 540 metric tonnes of demand in 2050. There are several significant sub-sectors (Hanley et al., 2018):

Steel: Steel is one of the most carbon dioxide-emitting sectors worldwide, responsible for roughly 8% of annual global emissions due to the deployment of coking coal in the blast furnace system. Steelmaking is one of the most difficult industries to decarbonize because there are few substitute decarbonization processes and full decarbonization requires H_2. Steel decarbonization necessitates 35 MT of H_2 demand in 2050, giving rise to a 12 GT reduction in emissions through 2050 (Slorach and Stamford, 2021).

Mobility: Mobility, which accounts for approximately 19% of total emissions presently, will be the single largest H_2 end-use sector in 2050, with 285 metric tonnes of H_2 demand. Hydrogen (H_2) applications in aviation, ground mobility, and maritime are included in this sector. Some mobility end-uses, such as long-distance containerships and flights, are among the most difficult to decarbonize, and H_2 in combination with biofuels provides the only scalable path to fully decarbonizing these (Hanley et al., 2018).

Currently available feedstocks: Hydrogen now plays an important role in feedstock applications such as methanol, ammonia, and clean hydrogen, and refining is needed for decarbonization. These uses account for approximately 2-3% of total emissions. Clean H_2 to decarbonize these applications will make up around 15% of demand in 2050 (approximately 105 metric tonnes), down from more than 90% presently (Rosa and Mazzotti, 2022).

Aviation and maritime: Aviation and maritime, which account for approximately 4% of total emissions presently, are both high-power, long-distance end-applications that will rely in part on H_2-based fuels to reduce carbon emissions cost-effectively. The most viable clean fuels for full emissions reductions in the maritime sector are liquid H_2 or H_2-based fuels such as e-methane or methanol, and ammonia. Aviation is becoming a significant consumer of e-kerosene (synthetic fuels), which are based on H_2 mixed with CO_2 from biogenic source materials or captured directly from the atmosphere, as well as liquid H_2 for intra-continental short-range flights. These two end-applications will account for 110 MT of H_2 demand, reducing CO_2 emissions by 13 GT by 2050.

3.4.2. Hydrogen as an emission reduction vector

To fulfil the net-zero goals, hydrogen's position as an emission reduction vector will necessitate a considerable rise in clean H_2 supply by 2050. Due to resource chain shortfalls such as conversions to or from carriers, boil-off or pipe leakage from liquid H_2 distribution or storage, the industry requires 690 MT of renewable and low-carbon H_2 sources to achieve H_2 demand of 660 MT in 2050 (Hanley et al., 2018).

Most H_2 today is fossil-based (grey); in the long run, this potential will be taken out of service or transitioned to low-carbon or renewable H_2 (Fig. 11). Low-carbon H_2 would be the most cost-effective mid-term workable alternative in a variety of areas, accounting for the majority of capacity built over the next 10–15 years (Rosa and Mazzotti, 2022). In the long run, renewable power generation potential will have increased, and renewable H_2 will be the most productive supply of H_2 across most territories. Renewable H_2 will most likely account for the vast majority of capacity, respectively, in 2040 and 2050 (Schulthoff et al., 2021).

Clean H_2 has substantial emission reduction prospects through 2050. Between now and 2050, H_2 could prevent 80 gigatonnes (GT) of cumulative carbon dioxide emissions, which is up to eight times what China released in 2019, or approximately 11% of the emissions reductions required to keep global warming to 1.5–1.8° Celsius (Fig. 12). If the world continues on its current path, the yearly carbon reduction from clean H_2 in 2050 would be about 7 GT, or roughly 20% of the yearly anthropogenic emissions (El-Emam and Özcan, 2019). Reducing 7 GT of CO_2 emissions equates to taking away all passenger vehicles, buses, and trucks from the road, as well as the aviation industry, or alleviating net emissions from the United States, Germany, and Japan in 2019.

The majority of these prospects will be accounted for by industry and mobility, with over 6 GT of CO_2 reduced in 2050, or a total emission reduction of 70 GT of carbon dioxide by 2050. Hydrogen-based fuels are the only feasible at-scale emissions reduction alternative for the aviation and maritime industries, with promising prospects for H_2 to effectively reduce 13 GT of CO_2 through 2050. Chemicals and steel will contribute another third of total H_2 emission reduction prospects by 2050, decarbonizing 20 and 35% of discharged CO_2 in 2050, respectively, on the current trajectory (Schulthoff et al., 2021).

Low-carbon H_2 will make up approximately 20–40% of supply in 2050, equating to 140–280 MT of supply. This is roughly twice today's grey capacity and would necessitate infrastructure able to store 1–2.5 GT of CO_2 per year (Ozawa et al., 2018).

Renewable H_2 will provide 60–80% of the total, or 400–550 MT of H_2. A volume of this size will necessitate 3–4 TW of electrolysis capacity and 4.5–6.5 TW of renewable capacity committed to H_2 production (Brändle et al., 2021). This is roughly twice the total renewable generation capacity installed globally through 2020 (2.8 TW) (Griffiths et al., 2021). A significant increase in renewable generation facilities is needed not only for H_2 production but for societal electrification. In 2050, a net-zero economy would demand approximately 27 TW of renewable power; the approximate electrolyzer infrastructure would need approximately 20% of this capacity (Ozawa et al., 2018).

Developing both supply processes will allow for the use of the most appealing resources to reduce carbon emissions in industries and territories in a cost-effective and rapid manner. If all of the H_2 were generated by renewable energy, approximately 5.5 TW of electrolysis would be needed, with approximately 8 GW of renewables. Conversely, supplying the demand only with low-carbon H_2 would necessitate approximately 5.5 GT of annual carbon storage capacity (Brändle et al., 2021). Using both sources will result in lower total energy system costs and a faster transition. Focusing on a single clean H_2 supply path may slow the required scale-up because it necessitates an even faster ramp-up of project development and value chains, impeding the required emission reductions to meet net-zero objectives (Ozawa et al., 2018).

Carbon-free hydrogen: A quantity of 45–55 MT of low-carbon H_2 is required to meet the needed clean H_2 uptake and the annual CO_2 reduction capacity of 730 MT in 2030. Because existing facilities can be rebuilt with extra carbon capture facilities, a more rapid phase-out of grey H_2 is possible with low-carbon H_2. The implementation of low-carbon H_2 necessitates the installation of technology to transport captured CO_2 to underground storage sites (See Tables 2 and 3). Scaling up low-carbon H_2 supports renewable H_2 and facilitates the expansion of renewable power generation capacity; if only renewable H_2 were utilised, the required electrolyzer volume would be approximately 600 GW, supported by approximately 1 TW of renewable generation potential (Ozawa et al., 2018).

3.4.3. Low-carbon hydrogen production

There are various methods for producing H_2, each with a different carbon footprint. In Fig. 13, we look at the low-carbon H_2 production possibilities.

1 Blue Hydrogen (H_2): Blue H_2 is created by using a fossil fuel, primarily natural gas, along with CCS. Although conventional SMR could be used, technological advances are being investigated, such as autothermal reforming (ATR), which provides energy by incorporating oxygen (O_2) to burn a portion of the feedstock rather than separately burning natural gas. While not a 100% net-zero technique, it is expected to capture up to 95% of carbon emissions. This, of course, is dependent on CCS development and implementation. Many novel membranes, catalysts, solvents, and adsorbents are being researched.

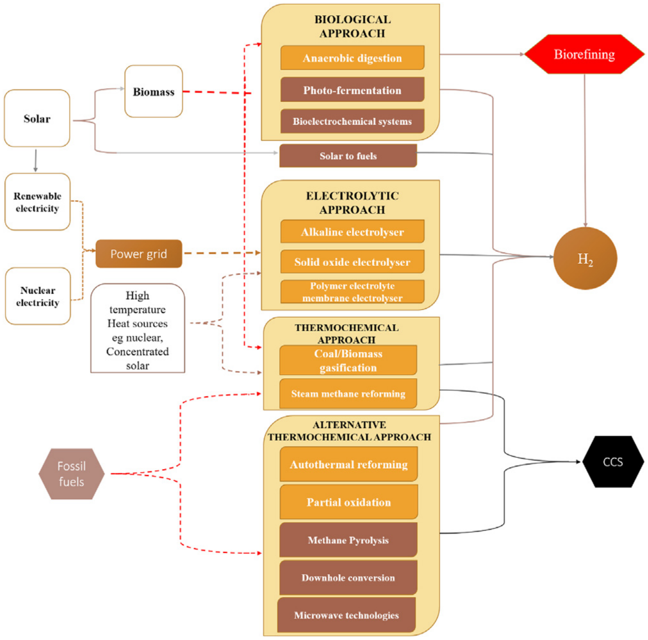

Fig. 13. A diagram of low-carbon H_2 production options (The Royal Society, 2018).

2 Green Hydrogen: Green H_2 is a zero-carbon route that uses renewable electricity to split H_2 from H_2O via electrolysis. The most fully developed technique is alkaline electrolyzers, but they do not work well with intermittent renewable energy sources. Relatively new polymer electrolyte membrane (PEM) electrolysers respond quickly to renewable energy fluctuations and are in early deployment. Solid oxide cell electrolysers (SOEC), which operate at higher temperatures, are less developed but have the potential to be more efficient. Green H_2 needs renewable electricity and thus may be limited by the availability of renewable capacity. For example, if all of the H_2 used today were produced via electrolysis, it would necessitate 3,600 terawatt-hours (TWh) per year, which is more than the EU's total generation.

3 Other options: Other options typically involve "turquoise" H_2 produced by methane thermal pyrolysis (heating in an O_2-free atmosphere), which produces solid carbon instead of CO_2 as a by-product, and "pink" H_2 produced by nuclear energy electrolysis. Nuclear power could also provide zero-carbon heat for either high-temperature steam electrolysis (higher thermal efficiency) or SMR high-temperature requirements with CCS. Other alternatives include biological methods with lower operating temperatures centered on anaerobic digestion and 'solar to fuels', in which H_2O is directly split into H_2 and O_2 utilising solar energy (Griffiths et al., 2021).

3.5. Ammonia

Ammonia's use as fertiliser has a vital impact on the world's agricultural systems. The foundation of all mineral N_2 fertilisers is ammonia (NH_3), which serves as a link between the nitrogen in the atmosphere and the food we eat. Ammonia is used for a variety of industrial purposes, including synthetic fibres, plastics, and explosives. Fertilizers account for around 70% of ammonia's usage. The use of NH_3 as a fuel indicates promise in the area of sustainable energy transitions. However, this use is still in its infancy. So, the current agricultural and industrial applications of NH_3 are the main emphases of this strategy.

The world will require more NH_3 in the future, but with reduced emissions. A growing and more privileged global population will drive up NH_3 demand at a time when governments worldwide have announced that emissions from the energy source must fall to zero.

Table 2
A few initiatives to boost the deployment of low-carbon hydrogen in industries via ammonia (IEA, 2021).

S/N	Project	Technology	Capacity	Status	Date	Location
1	Coffeyville fertiliser	Carbon dioxide captured from the production of oil-based NH_3, which is employed in EOR.	$1\ Mt\ CO_2/year$	In operation	2013	USA
2	PCS N_2	Carbon dioxide captured from the production of gas-based NH_3, which is employed in EOR.	$0.7\ Mt\ CO_2/year$	In operation	2013	USA
3	Nutrien fertiliser	Carbon dioxide captured from the production of gas-based NH_3, which is employed in EOR.	$0.3\ Mt\ CO_2/year$	In operation	2020	Canada
4	Olive Creek	The pyrolysis of CH_4 to produce NH_3	-	Currently under development.	2021	USA
5	Iberdrola /Fertiberia	Solar PV-derived H_2 production for NH_3 production	Stage 1 – 20 MW Stages 2-4 – 810 MW	Stage 1 - Currently under development. Stage 2 – 4 - feasibility analysis	Stage 1 – 2021 Stages 2-4 – 2027	Spain
6	Green NH_3 from Western Jutland	Production of electrolytic NH_3 from renewable sources	10 MW	-	2023	Denmark
7	CF industries	Production of NH_3 electrolytically using grid electricity	20 MW	Final investment decision (FID)	2023	USA
8	Porsgrunn green fertiliser project	Production of NH_3 electrolytically using grid electricity	Approximately 25 MW	FID	2023	Norway
9	Engie Yara Pilbara	Production of electrolytic NH_3 from renewable sources	10 MW	FID	2023	Australia
10	HyEx	Production of electrolytic NH_3 from Solar PV	50 MW	Feasibility analysis	2024	Chile
11	Yara Sluiskil	Production of electrolytic NH_3 from renewable sources	100 MW	Feasibility analysis	2025	Netherlands
12	Blue NH_3 Barents	Carbon dioxide captured and stored from the production of gas-based NH_3	$1\ Mt\ NH_3/year$	Feasibility analysis	2025	Norway
13	Green $NH_{3\ \text{Esbjerg}}$	Production of electrolytic NH_3 from offshore wind	1GW	Feasibility analysis	2027	Denmark
14	CF Fertilisers Ince	Carbon dioxide captured and stored from the production of gas-based NH_3	$0.3\ Mt\ CO_2/year$	Feasibility analysis	-	UK

Table 3
A few initiatives to boost the deployment of low-carbon hydrogen in industries via methanol (IEA, 2021).

S/N	Project	Technology	Capacity	Status	Date	Location
1	Svartsengi commercial plant	Production of electrolytic CH_3OH from renewable sources	6 MW	In operation	2011	Iceland
2	Karamay Dunhua Oil Technology CCUS EOR	Carbon dioxide captured and stored from the production of CH_3OH, which is employed in EOR	$0.1\ Mt\ CO_2/year$	In operation	2015	China
3	$MEFCO_2$	Production of electrolytic CH_3OH	1 MW	In operation	2019	Germany
4	Power2Met	Production of electrolytic CH_3OH	0.25 MW	In operation	2020	Denmark
5	Park of Lanzhou Fine Chemical Industry	Production of electrolytic CH_3OH from renewable sources	4.5 MW	In operation	2020	China
6	Skive Green lab	Production of electrolytic CH_3OH from renewable sources	12 MW	Currently under development	2022	Denmark
7	DJEWELS Chemiepark	Production of electrolytic CH_3OH from renewable sources	20 MW	Feasibility assessment	2022	Netherlands
8	Lake Charles Methanol	The CH_3OH and H_2 production from gasification of petcoke with CCUS	$4.2\ Mt\ CO_2/year$	Feasibility assessment	2025	USA
9	North-C- CH_3OH	Production of electrolytic CH_3OH from renewable sources	Stage 1 – 63 MW Stage 2 – 300 MW	Stage 1- Feasibility assessment. Stage 2 – Early phase	2024 2028	Belgium
10	Power-to-CH_3OH	Production of electrolytic CH_3OH from renewable sources	10 MW 100 MW	Stage 1- Feasibility assessment. Stage 2 – Early phase	2023	

This strategic plan investigates three potential NH_3 production future prospects. The industry appears to follow recent trends in the Declared Policies Scenario, making gradual gains but falling well short of a feasible trajectory. The sector implements the techniques and policies needed to put it on a route consistent with the overall Paris Agreement in the Sustainable Development Scenario. The Net Zero Emissions by 2050 report aims to explore an NH_3 industry trajectory that is compliant with the energy infrastructure and achieves net zero emissions worldwide by 2050.

3.5.1. Ammonia as an emission-free fuel

Burning NH_3 produces no carbon dioxide. Ammonia is becoming more popular in the worldwide maritime sector as a result of this and the fact that it is derived from available resources. It can be used in both internal combustion engines and fuel cells. The potential is great, but there is a need for infrastructure, regulatory frameworks, and technological development to facilitate a widespread deployment (Xing et al., 2021).

It will be necessary to make a quick and widespread switch from fossil fuels to green alternatives in order to meet both international and national commitments for emission reductions. By 2050, the International maritime organisation (IMO) predicts that NH_3 and H_2 will be the most popular substitutes for conventional fossil-based fuels. According to a 2019 prediction from DNV, practically all newly built ships would run on NH_3 as of 2044. Ammonia might account for 25% of the maritime fuel mix by that time.

Hydrogen and N_2 combine to form NH_3. Around 180 million tonnes of NH_3 were produced globally in 2020, the majority of which went

Table 4
Comparison of different internal combustion engine fuels and ammonia (Cardoso et al., 2021).

Parameter	Fuel				
	Ammonia (NH_3)	Hydrogen (H_2)	Gasoline	Diesel	Liquefied Petroleum Gas (LPG) (Propane)
Density (kg/m^3)	0.73	0.08	720 - 780	850	495
Boiling point (K)	239.80	20.28	310 - 477	455 - 633	231
Freezing point (K)	195.50	13.99	215	219	85
Energy content, lower heating value (LHV)	18.80	120	43.50	45	45.50
Octane number	130	130	86 - 94	8 - 15	120
Auto-ignition temperature (k)	930	773	643	527	728
Latent heat of vaporization (kj/kg)	1371	461	380	375	428
Autonomy – 500 km range (litres)	107.30	279.50	39.20	34.50	53.10

toward the creation of fertilisers. As a single producer, Yara sends approximately 20 million tonnes of NH_3 by sea each year, and 130 ports around the world have NH_3 loading, handling, and storage facilities. Ammonia is a good candidate for long-distance transportation because it has long been used in shipping and has a higher energy density than both batteries and H_2 (Xing et al., 2021).

3.5.2. Green ammonia (GA)

Green ammonia is considered the key to a sustainable net-zero energy future free of carbon not only because it contains no carbon atom but has in place an already established storage infrastructure and transport network. Also, it has multiple applications for different energy sectors and releases only water and nitrogen gas as by-products of its combustion (Valera-Medina et al., 2018a; MacFarlane, 2020). It also, has recently received renewed interest in the energy sector because of the several challenges associated with the sustainable application of the 'golden gas' green hydrogen, as detailed below.

3.5.3. Green ammonia as an energy vector for hydrogen

Although hydrogen has a high gravimetric energy density (e.g., at pressured form, hydrogen contains approximately 39,405-Watt hours of energy per kg which is approximately 15,000% higher than what is obtainable from commercial batteries such as lead-acid or lithium-ion), at normal temperature and pressure (NTP) its volumetric density is incomparable to that of a natural gas (Cinti et al., 2017; Osman et al., 2022; Sinha and Pakhira, 2022). Therefore, it requires a high amount of energy for its transportation from production site to point of use, because it must be cooled down to a liquid state at extremely low temperatures (-253 °C) or converted to a pressurised form at 100–300 atmospheric temperature and pressure for it to be stored and moved from place to place (Kim et al., 2020; MacFarlane, 2020; Osman et al., 2022). Ammonia has no carbon atoms, so when it burns, it does not produce any carbon dioxide, soot, hydrocarbons, or carbon monoxide. Table 4 compares the primary combustion properties of ammonia with various transportation-related fuels (Cardoso et al., 2021).

Moreso, liquified ammonia is more energy dense (0.011308 MJ/l) than liquified hydrogen (0.008491 MJ/l), plus it liquefies readily at -33 °C and can be changed to its pressurised form at just 10 ATP (MacFarlane, 2020). According to Jeerh et al. (2021) a liter of GA is more than 100% higher than that green hydrogen, although the later releases energy values (lower heating value) that is approximately 500% (142 MJ/kg) higher than that of GA (22.5 MJ/kg), this golden quality is however dwarfed by green ammonia's ability to contain more hydrogen atoms per unit volume (3:1 H_2 and N_2 ratio) making its cost effective for storage and transport since a higher number of H_2 atoms (3) are present in one molecule of GA and thus occupies very small volume in comparison with green hydrogen with contains just 1 atom per unit volume (Ahlgren, 2012; Al-Aboosi et al., 2021) as shown in Fig. 15. In addition, the highly reactive nature of green hydrogen makes it very corrosive not only for the pressurized steel cylinders needed for its transportation but also spontaneously explosive at 520 °C (Aziz et al., 2020; Osman et al., 2022).

As opposed to oil and gas, which are easily stored long-term and transportable long-range, most renewable gases such as hydrogen are not. Therefore, the greatest industrial interest is now about storing and transporting hydrogen in the form of green ammonia, which is a safe and efficient way that employs the established ammonia transport infrastructure that are in existence all over the world. However, taking advantage of pre-existing transport infrastructures requires overcoming the initial hurdle of converting the hydrogen into green ammonia in an efficient and cost-effective way. As a result, lots of efforts are being put into finding sustainable ways of converting these gases into green NH_3 for easy storage and transport (Chehade and Dincer, 2021; Nayak-Luke et al., 2021).

The so-called 'sustainable Haber-Bosch' Fig. 14 process has been employed but is not 100% sustainable as the process still partly employs non-renewable sources of electricity and requires excessive amounts of energy and pressure (Chen et al., 2021). Thus, more sustainable methods for green ammonia production that involves the green-electrical redox dissociation of water to release hydrogen and a subsequent reaction step of the hydrogen with nitrogen are being intensively researched upon (MacFarlane et al., 2014). This involves the use of electrochemical reverse fuel-cells powered by electricity (from renewable sources such as solar, wind etc.,) and catalysts (usually electro-microbial enzymes like nitrogenases or metal-based catalysts such as Fe and Mo) to dissociate hydrogen protons from water at a location called the anode and join it to nitrogen atom at the cathode to form the green NH_3 (Service, 2018; Simanaitis, 2018; Dutta and Pati, 2022). Although the reverse fuel-cell technique is a process that is 100 % green and considered an efficient alternative because it excludes the very high amount of heat and pressure normally used in the sustainable Haber Bosch process of ammonia production, however at normal temperature and pressure (NTP), ammonia forms very slowly making its scalability a big challenge (Ye et al., 2017; MacFarlane, 2020).

To achieve a speedier process, Sun et al. (2021) developed a seminal hybrid electrocatalytic nitrogen reduction reaction (NRR) technique involving a nitrogen fixating approach, using a non-thermal plasma technology coupled to an electrocatalytic process. In their approach, they worked with a combination of air and water, using the fourth state of matter (plasma) to activate nitrogen present in air and water into highly reactive forms (NOx), and these activated nitrogen solutions were subsequently electrochemically converted into NH_3 by electrocatalytic reduction. The approach was shown to be approximately10^3 more efficient than earlier methods which were limited by the low reactive nature of Nitrogen that slows that the overall electrochemical reduction process. In addition, the overall process uses 10^3 less energy making it more efficient when compared to earlier methods. One unique advantage this non-thermal process has over previous electrocatalytic methods is that it bypasses the hydrogen cleaving step (Al-Aboosi et al., 2021).

Following this plasma route of green ammonia production, Indumathy et al. (2022) adopted an anti-aging technique that employs the conversion of nitrogen gas into its plasma form to reduce water into ammonia while exclude g the use of a catalyst. Although this technique

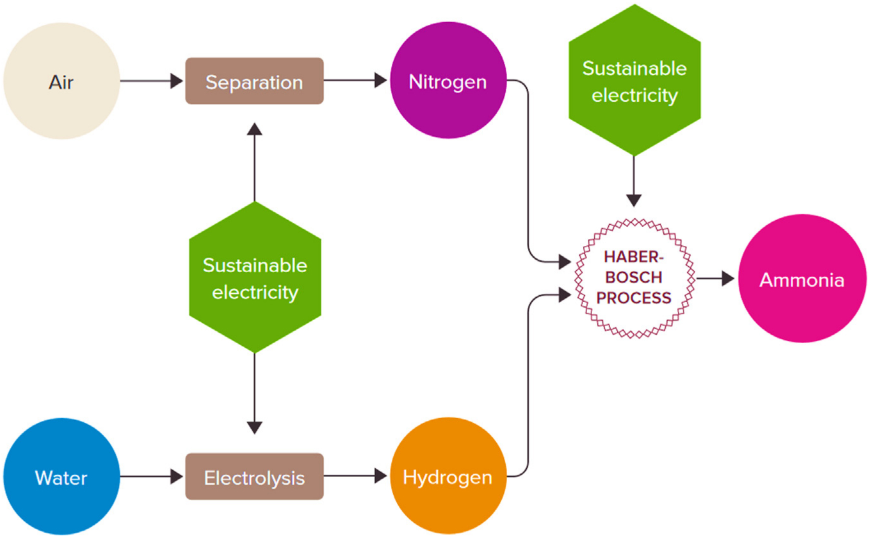

Fig. 14. The Green ammonia production schematic is based on hydrogen production via water electrolysis and complete decarbonization of the Haber-Bosch process (The Royal Society, 2018).

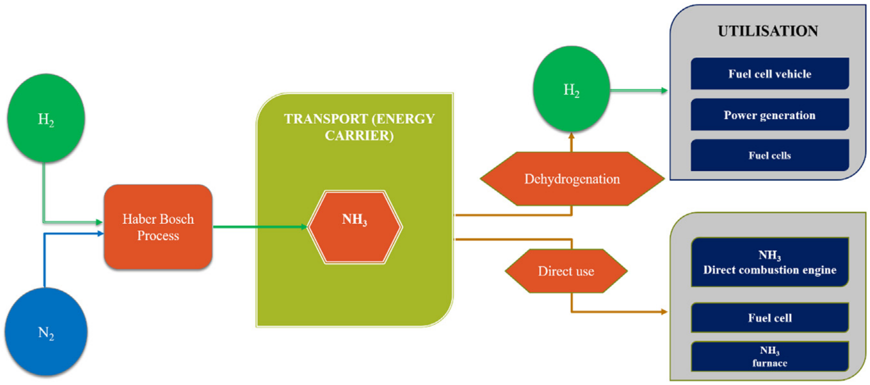

Fig. 15. Ammonia as a source of energy (The Royal Society, 2018).

Table 5

Percentage energy consumption and emission by sectors.

Energy consumption sectors	Energy source	% Energy consumption	% Emission	Substitute low/zero carbon energy	% Reduction required for Net-Zero	Refs.
Transport (road, rail air & water)	90% fossil fuels, 10% others	25.60	37	Green electricity, hydrogen, ammonia, methanol, methane	20	Rodrigue (2020), IEA (2021c), EIA (2022)
Industry (manufacturing, construction, agriculture & mining)	88% fossil fuels, 12 % others	31.67	38	Green electricity, hydrogen, ammonia, methanol, methane	-	Liu and McMillan (2018), EIA (2021, 2022), González-Torres et al. (2022)
Buildings (Commercial & residential)	61% electricity 34% fossil fuels	42.74	28	Green electricity, hydrogen, methane	-	EIA (2018, 2022), González-Torres et al. (2022)

required no catalyst as seen in traditional electrolytic NRR processes nor an excess of energy characteristic of the well-established Haber-Bosch process, the resulting energy efficiency (0.03 g-NH_3/kWhr ≈) was approximately 400% lower than that achievable with the Haber-Bosch system (0.03 g-NH_3/kWhr), thus will require more research to achieve optimization to become adopted for large scale production.

Taken together, the aforementioned novel carbon-free green ammonia production techniques are very promising for the envisioned net zero future. Much uncertainty still exists about the consistency of the supply chain for green ammonia. Despite the seemingly overwhelming odds surrounding the potential scale-up of green ammonia, there is still a way to augment such an apparent and possible shortage in the supply chain. For instance, the deployment of carbon-neutral means of green ammonia production can serve as complementary production routes. Also, the production of green ammonia from the Nitrogen rich biomass such as algae has also been investigated for green ammonia production by Nurdiawati et al. (2019), with a 63.8% production efficiency.

Thus, green NH_3, is a vital tool necessary for achieving 1.5 net zero carbon emission, because it is a gas generated from sustainable processes and is considered a valuable carbon free fuel 'energy vector' for hydrogen gas in the transportation of shipping vessels, fuels for powering jets, turbines, and heavy-duty trucks (Cesaro et al., 2021).

3.5.4. *Green ammonia applications in various energy-intensive sectors*

History has nature as the first known producer of NH_3 via the joint plant-microbe nitrogen-fixation process that gave rise to the large-scale industrial synthetic NH_3 production for primarily agricultural development purposes (Aziz et al., 2020; Sun et al., 2021). However, industrial NH_3 production via the Haber-Bosch process directly accounts for 1.2% of global CO_2 emissions, not to mention the indirect impacts from natural gas exploration (Al-Aboosi et al., 2021). So, adopting green production techniques that includes the production of ammonia onsite, where it can be directly applied to the farm as fertilizer has been on the forefront of research globally. (Service, 2018; Simanaitis, 2018; Sun et al., 2021).

The potential scope of GA application has exceeded its primary function as just a fertiliser feedstock or even as a hydrogen carrier because it has up to half of the energy density of fuels used for driving the engines of jets and even heavy-duty trucks (MacFarlane et al., 2014). Therefore, it is now considered a powerful tool for achieving a total net zero future in the shipping industry as it is regarded as a direct bunker (fuel) for powering ships (Ahlgren, 2012; Brown, 2017). The very board environmental and economic prospects for green NH_3 have set up a global race between governments and stakeholders for who will emerge as a major producer and exporter of green ammonia. In fact, by 2030, Japan projects to run its ships with 100% green NH_3 (Aziz et al., 2020; Brown, 2021). And because of its versatility, it has the capacity to displace 80% of fossil fuel applications (Ahlgren, 2012).

Moreover, world-leading bunker engine manufacturers have set targets to release newer models of engines adapted to NH_3 internal combustion, and Maersk's green NH_3 engines will become fully commercialised by the year 2023. Also, billions of monetary funds have now been invested globally into green ammonia projects globally with high scale up capacity in the very near future (Valera-Medina et al., 2018b; Hansson et al., 2020; Kim et al., 2020). More so, green ammonia has great application in the driving of power turbines and can be a suitable substitute in jet engines, however, because NOx gases are released when NH_3 is combusted at the high temperature of power turbines, the enthusiasm about its application in this area is very low (Valera-Medina et al., 2017; Aziz et al., 2020). Turbines are majorly employed in the aviation sector for driving jet engines.

3.5.5. *Green methanol*

Methanol is a fuel that takes up the liquid state of matter at ordinary room temperature and atmospheric pressure and have been traditionally generated from natural gas which is not a renewable feedstock nor a sustainable means (Räuchle et al., 2016). That is why the focus for the synthesis of methanol has now been shifted to greener methods mainly by employing renewable energy sources such as solar and wind for the hydrogenation CO_2, and it is termed a green production because it is a neutralizer process that utilizes the CO_2 captured from air or that are generated from organic waste management processes that results in bio-renewable products such as bio-hydrogen, biogas, bio-ethanol, ethylene glycol and other platform chemicals (Bos et al., 2020). This has a pronged benefit of creating a circular economy since the CO_2 waste from other sustainable processes is used as raw material for a high energy as well as a net carbon neutral process, especially when the CO_2 employed is captured from the atmosphere. This CO_2 is captured and catalytically reacted with green hydrogen to generate methanol (Räuchle et al., 2016; Verhelst et al., 2019; Zappa et al., 2019; Bos et al., 2020).

Moreover, methanol has a high ignition resistance in addition to its research octane number (RON) that can withstand higher compression values in internal combustion engines which promotes knock resistance and now being studied to serve a dual purpose as potential hydrogen storage and decarbonization route for CO_2 utilization with advantage of having the highest hydrogen to carbon ratio of 4:1 and no presence of carbon-to-carbon bonds (Ahlgren, 2012; Wang, 2019; Aziz et al., 2020). More recently, several attempts have been made by the global scientific community in response to the global call for more greener process of methanol production. One technique that has drawn the attention of many stakeholders in the shipping industry involves the e-methanol method which uses renewable sources to drive the electrocatalysis of water for hydrogen proton generation and reduction of CO_2 from carbon captured from the environment and from biomass (Ahlgren, 2012; Delikonstantis et al., 2021).

Traditionally, internal combustion engines of ships and heavy-duty vehicles are adapted to fossil fuels sources such as diesel, gasoline, etc.. Therefore, the application of green methanol has been typically in combination with the varying compression ratios with these hydrocarbon fuels sources to help cut done on emissions and improve combustion efficiencies, however there is now in place a global development of dedicated methanol advanced combustion engines (Verhelst et al., 2019). In fact, Maersk - the world largest integrated marine logistics company has announced that by 2023 they will release their first carbon neutral container ship vessel on waterways and the vessel will run on carbon neutral methanol thereby reducing their SOX emissions by 99% and NOX by 60%. Also, many Governments such as Demark, Japan, China, Nerthalands, Norway, and Iceland have set in motion the production of vehicles with spark ignition engines that will run solely on methanol and most are now at the stage of engine testing (Verhelst et al., 2019; Bos et al., 2020; Prevljak, 2020; Thygesen, 2021). All these efforts are highly ambitious, and rightly so if they are to march the equally ambitious demands of achieving a 1.5 °C net-zero emission by 2050.

Of all the carbon-neutral fuels considered in this study, bio-menthane is the most economical although the least safe, whilst green ammonia wins on 3 counts by being economical due its ease of storage and transport, zero-carbon content, and versatility of application (Zhao et al., 2019). Although green hydrogen remains the best option for a clean future due to its broad range of energy applications, its high storage and transport cost as well as low density compared to green ammonia places a limit on practicalities of it addressing the goal 7 of the UN Sustainable Development Goal which is not just about making energy clean but affordable for all. Green methanol, on the other hand, contains carbon and has a narrower application compared to green hydrogen. Also, has a lower energy density compared to the others and its cost of production is still high when compared to green ammonia. However, considering the urgency of the climate situation that requires an immediate reduction of global warming to 1.5 °C, each of the understudied fuels will collectively play vital roles in the actualisation of the Paris Agreement.

4. Conclusion

- Achieving net-zero emissions by 2050 is a pivotal and daunting goal that will necessitate an unprecedented transformation of how energy is generated, transmitted, and used.
- The path to net-zero depends on the immediate and huge implementation of all accessible, reliable and sustainable energy technologies, as well as increased clean energy innovation.
- Low-emission fuels, such as biogas, help to decarbonize sectors where direct electrification is difficult.
- Biogases provide more than just energy; they also aid in waste management, greenhouse gas reduction, and the creation of jobs and income opportunities, particularly in rural areas.
- NetZero Emissions (NZE) by 2050 outlines the steps required for the global energy sector to achieve NetZero CO_2 emissions by 2050. This, combined with a significant reduction in GHG emissions from sources other than the energy sector, is consistent with limiting global warming to 1.5°C with a 50% probability of temperature overshoot. To achieve this, all governments would have to raise their ambitions beyond their present net zero pledges and Nationally Determined Contributions.
- Global CO_2 emissions from energy and industrial processes are expected to drop by roughly 40% between 2020 and 2030 in the NZE, before reaching net zero in 2050. By 2030, universal access to renewable energy is likely to be achieved. Furthermore, by 2030, methane emissions from the usage of fossil fuels will have decreased by 75%. These shifts occur as the global economy more than doubles by 2050 and the world's population grows by 2 billion people.
- At around 2020 and 2030, total energy supply in the NZE falls by 7%, and it stays at this point until 2050. Prior to 2030, solar PV and wind power were the world's leading sources of electricity, accounting for roughly 70% of global generation by 2050. By 2030, conventional bioenergy use will be phased out.

- In 2050, coal demand falls by 90% to less than 600 Mtce, oil demand falls by 75% to 24 mb/d, and natural gas demand falls by 55% to 1750 bcm. The remaining fossil fuels in 2050 are employed in the production of non-energy goods in which the carbon is incorporated into the product (such as plastics), in plants with carbon capture, utilization, and storage (CCUS), and in sectors where high technological opportunities are limited.
- Energy efficiency, solar, and wind account for roughly half of the NZE's emissions savings through 2030. They help to lower emissions after 2030, but the period to 2050 sees increased electrification, hydrogen use, and CCUS usage, for which not all technological advances are commercially available, and this offer more than half of the emissions savings between 2030 and 2050. In 2050, the NZE will remove 1.9 Gt of CO_2 and demand 520 million tonnes of low-carbon hydrogen. Citizens' and businesses' behavior changes reduce CO_2 emissions by 1.7 Gt by 2030, limit energy demand growth, and promote clean energy transitions.
- The NZE takes advantage of all the possibilities to reduce carbon emissions in the energy sector, including all technologies and fuels. However, the road to 2050 is fraught with uncertainty. If behavioral changes are more restricted than anticipated in the NZE, or if sustainable bioenergy is less readily accessible, the energy transition will be costlier. Inability to build CCUS for fossil fuels might slow or inhibit the growth of CCUS for process emissions from production of cement and carbon removal techniques, making net zero emissions by 2050 much more difficult.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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