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REVIEW ARTICLE

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A systemic review of hydrogen supply chain in energy transition

Abstract Targeting the net-zero emission (NZE) by 2050, the hydrogen industry is drastically developing in recent years. However, the technologies of hydrogen upstream production, midstream transportation and storage, and downstream utilization are facing obstacles. In this paper, the development of hydrogen industry from the production, transportation and storage, and sustainable economic development perspectives were reviewed. The current challenges and future outlooks were summarized consequently. In the upstream, blue hydrogen is dominating the current hydrogen supply, and an implementation of carbon capture and sequestration (CCS) can raise its cost by 30%. To achieve an economic feasibility, green hydrogen needs to reduce its cost by 75% to approximately 2 $/kg at the large scale. The research progress in the midterm sector is still in a preliminary stage, where experimental and theoretical investigations need to be conducted in addressing the impact of embrittlement, contamination, and flammability so that they could provide a solid support for material selection and large-scale feasibility studies. In the downstream utilization, blue hydrogen will be used in producing value-added chemicals in the short-term. Over the long-term, green hydrogen will dominate the market owing to its high energy intensity and zero carbon intensity which provides a promising option for energy storage. Technologies in the hydrogen industry require a comprehensive understanding of their economic and environmental benefits over the whole life cycle in supporting operators and policymakers.

Keywords hydrogen production, hydrogen transportation and storage, hydrogen economy, carbon capture and sequestration (CCS), technology assessment

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1 Introduction

The global energy demand is drastically rebounding after experiencing the largest decline of 4% since World War II due to the COVID-19 according to International Energy Agency (IEA) [1]. The rising supply of renewable energy and diminishing demand of fossil fuels not only diversify the energy sources from the supply side but also push the energy industry to the low-carbon fuels for the CO_2 mitigation purpose. Under the global goal of net-zero emission (NZE), the demand for hydrogen will rise from less than 90 Mt in 2020 to over 200 Mt in 2030. Especially, the demand of low-carbon hydrogen is predicted to rise from 10% to 70% by 2030 as shown in Fig. 1 [2]. The global average of 15% volumetric hydrogen blend can reduce the CO_2 emissions from gas consumption by 6%.

Hydrogen derived from fossil fuels was entirely meeting the global demand of 90 Mt in 2020, whereas 80% was directly produced from hydrogen plants and the rest was the by-product associated with other sources. The steam methane reforming (SMR) with the primary feedstock of natural gas dominates the hydrogen supply in the current industry, and corresponds to 900 Mt CO_2 emissions (2.5% of global emissions) in 2020 as shown in Fig. 2 according to IEA [3]. Therefore, the low-carbon hydrogen supply is projected to grow rapidly in the next few decades. The promising technologies include the hydrogen production from electrolysis and fossil fuel-based hydrogen with carbon dioxide capture and sequestration (CCS). By 2030, the NZE scenario will require 80 Mt of electrolytic H_2 and 60 Mt of H_2 from natural gas with CCS [3]. The strong policy support will prompt the sustainable development of the hydrogen market in the next few decades [4].

As the lightest, simplest, and most abundant chemical substance in nature, hydrogen is the most reliable renewable energy to address environmental problems [5]. The advantages of using hydrogen mainly include zero greenhouse gas (GHG) emissions and high energy

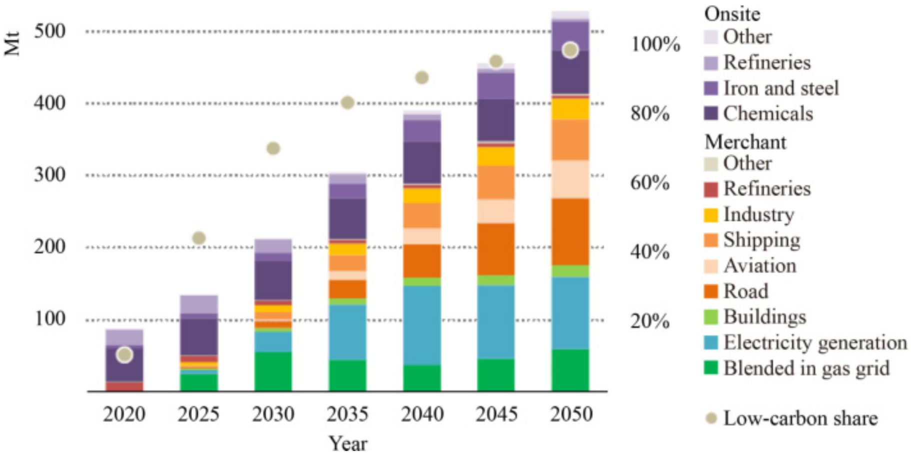

Fig. 1 Global hydrogen use in the NZE scenario (adapted from Ref. [2]).

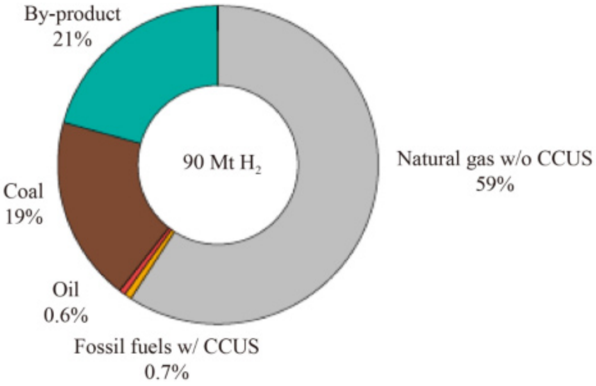

Fig. 2 Source of hydrogen supply (adapted from Ref. [3]).

density between 120 MJ/kg (lower heating value, LHV) to 142 MJ/kg (higher heating value, HHV). However, the current hydrogen industry is facing challenges from the production, transportation, storage, and utilization perspectives. This paper is keen to seek the answers for two questions by reviewing the state-of-the-art hydrogen development technologies in the current energy transition era. First, why the hydrogen supply chain will play an essential role in the clean energy transition? Then, to what extent will the technology assessment be focused on systematically estimating the hydrogen technologies over its supply chain as emerging technologies? Especially, the challenges and outlooks were addressed from the production, transportation, storage, and economic perspectives in the context of achieving the NZE goal by 2050. The remaining of this paper is structured as follows: First, Section 2 provided the general perception of the hydrogen spectrum. Second, Section 3 reviewed the hydrogen production technologies. Third, Section 4 discussed the development of hydrogen storage and tranportation. Fouth, Section 5 summarized the economic expansion of the hydrogen supply chain. Finally, Section 6 outlined the conclusion of this investigation.

2 Color of hydrogen

During a manufacturing process, rainbow color codes are often utilized to distinguish between the various forms of hydrogen synthesis and electricity consumption [6,7]. In the contemporary industry, there are ten colors of hydrogen that may be divided into three groups. First, white hydrogen identifies the subsurface geological hydrogen that occurs naturally. However, there is insufficient data to show the white hydrogen exploitation tactics. Second, the hydrogen derived from fossil fuels is the dominant source in the present hydrogen market [8–16]. Grey hydrogen describes the hydrogen generated by SMR from natural gas without CCS, while blue hydrogen describes the hydrogen produced by SMR from natural gas with CCS. The terms black and brown hydrogen refer to the hydrogen generated from black coal and lignite, respectively. The turquoise hydrogen represents the hydrogen generated by the pyrolysis of methane (MP) [17]. Finally, green hydrogen refers to the generation of hydrogen without GHG emissions using electrolysis [6,14,18–20]. Pink hydrogen refers especially to the creation of green hydrogen using nuclear energy. Orange and yellow hydrogen represent the green hydrogen powered by wind and solar electricity, respectively. As seen in Fig. 3, the path of future technological development is turning toward the use of renewable power sources and green hydrogen [8]. As a result, blue hydrogen will dominate the market in the near future with the matured production techniques associated with CCS technologies. Green hydrogen will be widely considered in the long-term with the significant penetration of renewable electricity to achieve the NZE goal at a large scale.

3 Hydrogen production

Hydrogen is manufactured mostly from fossil fuels and renewable resources through chemical processes, since the amount of naturally occurring hydrogen is limited. Production of gray hydrogen is the most resourceful commercialized technique in the current industry. With the successful commercial application of CCS, industrial-scale blue hydrogen is maturing into low-CO_2 hydrogen. As a result of robust legislative support for the development of renewable energy, green hydrogen has reached commercial scale in recent years. In this Section, the most advanced methods for producing blue and green hydrogen are discussed as summarized in Fig. 4.

3.1 Steam methane reforming (SMR)

Today, SMR is a mature large-scale technique for producing hydrogen by converting natural gas at a specified temperature and pressure [3,21–23]. Typically, a SMR process consists of four steps, removal of impurities, catalytically reforming or synthesis gas (syn-gas, Eq. (1)) production, water gas shifting (WGS, Eq. (2)), and methanation or gas purification [21,22]. The needed parameters for SMR are 700 to 900 °C of temperature, 0.3 to 3 MPa of pressure, and a steam-to-carbon ratio of 2.5 to 3.5 [12,23–27]. Using natural gas as a hydrocarbon feedstock typically necessitates a molar fraction of methane between 75% and 99% [28]. The yield efficiency can reach up to 75% and the estimated cost can be as low as 1.80 \$/kg H_2 [29]. To improve a hydrogen production rate, heterogeneous catalysts like non-precious metal nickel (Ni), precious metal platinum (Pt) or rhodium (Rh) and precious metal alloys like Ni/Al_2O_3 or ruthenium (Ru)/zirconium oxide (Ru/ZrO_2) are frequently utilized on an industrial scale [30–34]. In addition, natural gas can be composed of higher alkanes, inert gas, and acidic gases (i.e., CO_2 and H_2S). Consequently, a pre-treatment, such as hydrotreating or absorption on activated zinc oxide, is often necessary to remove hydrogen sulphide (H_2S) because of its detrimental effects on further processing. Pressure swing adsorption (PSA) units are often considered to filter the hydrogen generated by chemical processes. The primary chemical reactions of SMR are [35]

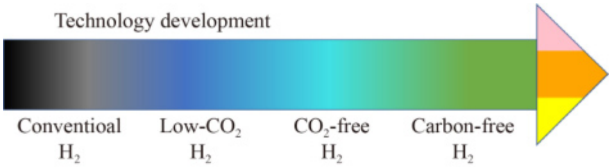

Fig. 3 Hydrogen color spectrum.

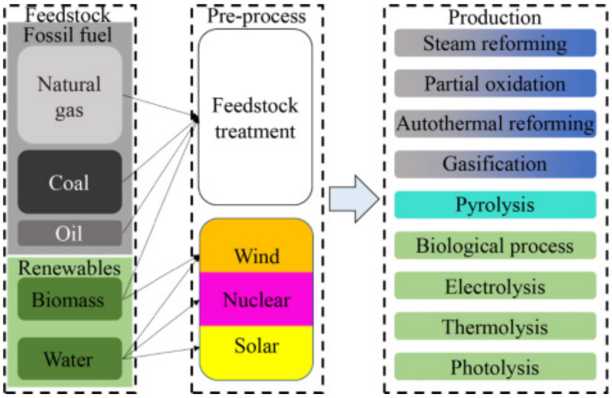

Fig. 4 Hydrogen production technologies with hydrogen spectrum.

Syn-gas generation:

$$C_nH_m + nH_2O \rightleftarrows nCO + \left(n + \frac{m}{2}\right)H_2. \quad (1)$$

WGS:

$$CO + H_2O \rightleftarrows CO_2 + H_2;\ \Delta H_R^0 = -41.2\ \text{kJ/mol}. \quad (2)$$

Methanation:

$$CH_4 + H_2O \rightleftarrows CO + 3H_2, \Delta H_R^0 = +206.3\ \text{kJ/mol}. \quad (3)$$

Both syn-gas generation and methanation are highly endothermic chemical processes. Therefore, external heat is necessary for these processes. In general, the reforming step may produce more than 10% of CO by volume. The WGS is an exothermic reaction. Regarding a temperature range and catalyst choice, a variety of catalysts selections of WGS can be categorized into two distinct directions. For example, a high-temperature shift occurs between 310 and 500 °C of temperature and 2.5 and 3.5 MPa of pressure when utilizing Fe/Cr or Co/Mo as catalysts [32]. A low-temperature shift for CuO/ZnO or brass catalysts occurs between 190 and 280 °C [8]. Both high-temperature and low-temperature operations need a two-stage reactor. The SMR procedure is shown in Fig. 5 [8]. SMR is a mature technology with a technology readiness level (TRL) of 9. The largest SMR plants have a production

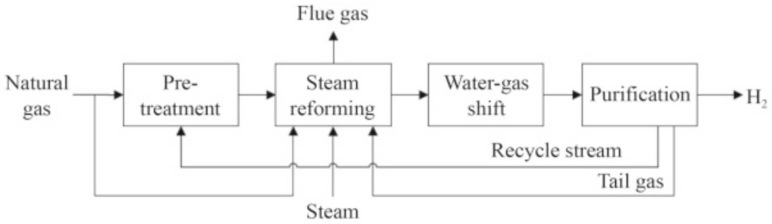

Fig. 5 SMR process (adapted with permissionfrom Ref. [8]).

capacity of 120000 Nm^3/h H_2 and are operating for downstream ammonia production [21]. Due to the excessive heat produced as steam by SMR, the by-product in the form of high-temperature steam may be utilized to power up the neighboring steam turbines for the electricity production. As SMR is a matured hydrogen production technology at large scale, the net-zero solution for SMR is capturing and sequestrating emitted CO_2 to geological formations (e.g., hydrocarbon reservoirs and saline aquifers) to offset the emissions to produce the zero-emission hydrogen over its lifecycle. The advantage of SMR is that it is a mature large-scale technology. However, the CCS would be required to reduce its CO_2 emissions.

3.2 Partial oxidation (POX)

A POX process (Fig. 6) is categorized as either catalytic or non-catalytic [36]. Catalytic POX can operate at a lower temperature (950 °C) with feedstocks ranging from methane to naphtha [37,38]. Non-catalytic POX is more sulfur tolerant and can take a wider range of feedstocks than SMR, but requires a much higher temperature (i.e., 1150 to 1135 °C) [36]. The primary feedstock for non-catalytic POX is methane from natural gas, although other hydrocarbons, such as heavy oil and coal, may also be used [39]. In general, oxygen is used to partially oxidize hydrocarbons and produce syn-gas, as shown in Eqs. (4) and (5), and complete oxidization occurs for a small portion of hydrocarbon feedstock as shown in Eq. (6) [40, 41]. This exothermic reaction generates sufficient heat to supply the WGS reaction to increase a hydrogen production rate [28]. Similar to SMR, desulfurization is necessary as a pre-treatment procedure before proceeding hydrocarbons with a restricted quantity of oxygen to a high-pressure reactor to produce syngas. Controlling an oxygen-carbon ratio in this stage is crucial since it has a direct effect on maximizing a syn-gas production rate and preventing coke formation [28]. POX is the most suitable method for producing H_2 from heavier hydrocarbon feedstocks like heavy oil and coal. Furthermore, an implementation of WGS generates significant CO_2 emissions [42]. Thus, the contemporary industry is using a CCS technology to transform hydrogen from gray to blue. According to previous studies, the use of CCS may raise the cost of producing hydrogen from 1.34 to 1.63 \$/kg but mitigate CO_2 emissions at a significant level [43]. Although POX has a lower cost compared to SMR, its high temperature requirement is a severe concern for operators.

$$\text{Catalytical POX}: \mathrm{C}_n\mathrm{H}_m + \frac{1}{2}n\mathrm{O}_2 \rightarrow n\mathrm{CO} + \frac{1}{2}m\mathrm{H}_2. \tag{4}$$

$$\text{Non-catalytical POX}: \mathrm{C}_n\mathrm{H}_m + n\mathrm{H}_2\mathrm{O} \rightarrow n\mathrm{CO} + \left(n + \frac{1}{2}m\right)\mathrm{H}_2. \tag{5}$$

$$\text{Complete oxidization}: \mathrm{C}_n\mathrm{H}_m + \left(n + \frac{1}{4}m\right)\mathrm{O}_2 \rightarrow n\mathrm{CO}_2 + \frac{1}{2}m\mathrm{H}_2\mathrm{O}. \tag{6}$$

3.3 Autothermal reforming (ATR)

An ATR process describes a merged SMR and POX procedure [5]. POX is exothermic while SMR is endothermic, as explained in Sections 3.1 and 3.2. In ATR, the heat from POX is used to provide thermal energy to SMR, hence enhancing hydrogen production and achieving thermodynamic equilibrium [39]. In its operation, high-temperature steam and oxygen/air are fed to a reformer, where reforming and oxidation reactions occur simultaneously [30]. A reactor is specially designed with a ceramic-lined, fixed-bed catalytic and combustion zone so that hydrocarbons can react with steam and oxygen at temperatures between 900 and 1100 °C [36,44,45]. Its chemical process is described by Eq. (7), and the flow diagram is illustrated in Fig. 7 [46]. An oxygen-carbon ratio and inlet temperature can be optimized to maximize the hydrogen yield. Additionally, large-scale ATR plants will generate a substantial quantity of CO_2. Consequently, appropriate capturing methods will also be required. The cost of H_2 is typically approximated at 1.48 \$/kg [47]. Both POX and ATR can be implemented at industrial scale with an estimated TRL of about 7–8 currently, but the disadvantage is that a significant amount of thermal energy would be required.

$$\text{ATR}: \mathrm{C}_n\mathrm{H}_m + \frac{1}{2}n\mathrm{H}_2\mathrm{O} + \frac{1}{4}n\mathrm{O}_2 \rightarrow n\mathrm{CO} + \left(\frac{1}{2}n + \frac{1}{2}m\right)\mathrm{H}_2. \tag{7}$$

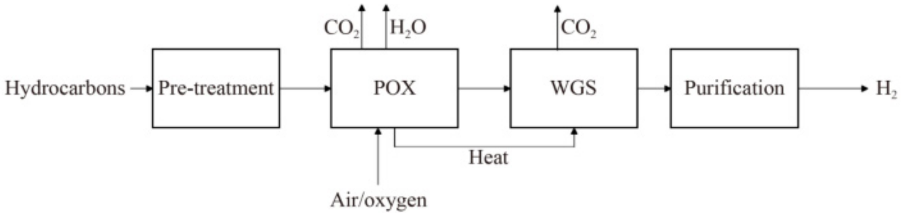

Fig. 6 Flow diagram of POX process.

3.4 Coal gasification

A process of coal gasification explains the transformation of carbon into gas [48]. Gasifiers can be characterized in three types including fixed bed, fluidized bed, and entrained flow gasifiers [49]. To increase hydrogen yield, high temperature entrained flow is often chosen by industrial operators. Equation (8) describes a reaction and Fig. 8 describes the process of coal gasification to produce H_2, in which syn-gas is generated and H_2 is extracted. CO is proceeded to a WGS process to maximize H_2 production. This is also an endothermic process that requires thermal energy input. The capital investment in a coal gasification process is usually much higher than that in ATR, POX, and SMR [47]. Moreover, the underground coal gasification (UCG) is an alternative pathway for converting coal to syngas *in situ* by the injection of oxidants, as presented in Fig. 9 [36,50–52]. As coal seam is combusted underground, syn-gas is produced and collected from a producer [36]. Recent development of UCG incorporated directional drilling technologies to drill two boreholes in deep coal seams. By injecting the oxidant for the purpose of *in situ* combustion, the syngas can be produced without generating a large amount of GHG emission [52]. The coal gasification technology is not as mature as SMR with an estimated TRL of around 5–7 currently. The UCG process can be considered as a zero-emission hydrogen production route as the CO_2 produced is immediately sequestrated to coalbed subsurface [52]. However, since the process requires a high temperature (i.e., > 500 °C), its feasibility still needs to be addressed.

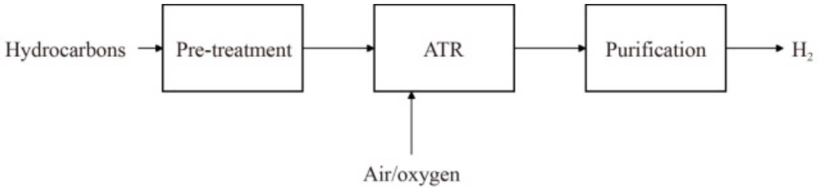

Fig. 7 Flow diagram of ATR process.

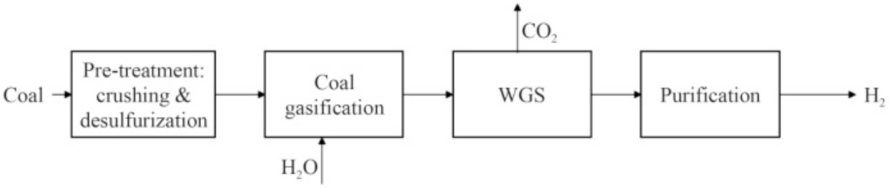

Fig. 8 Flow diagram of coal gasification process.

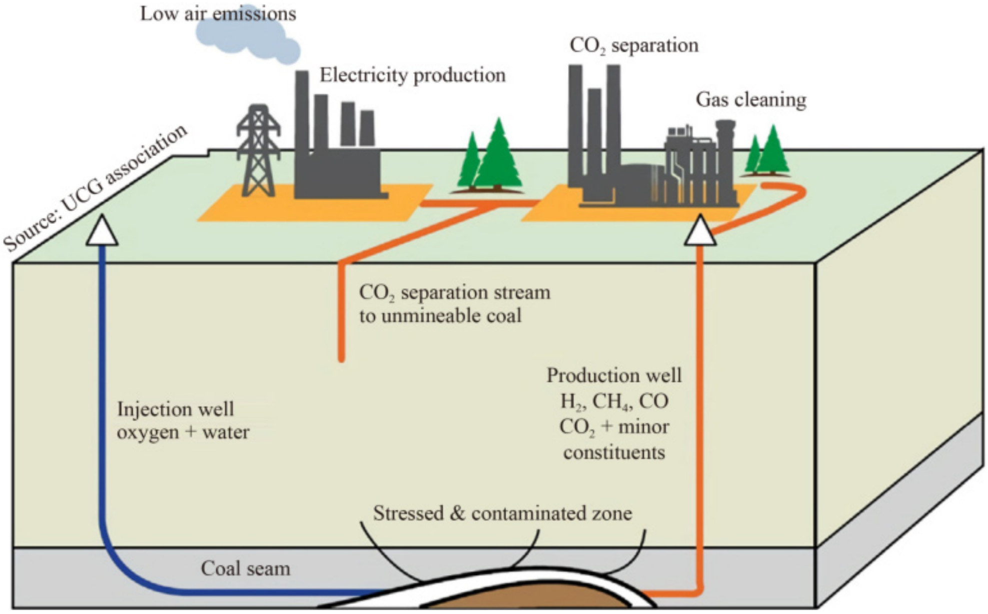

Fig. 9 Schematic of UCG (adapted from Ref. [52] under the terms of CC BY).

Although numbers of pilot test projects have been conducted around the world since 1935, the low gas production rates and gas quality suggest that the development of the UCG technology is still at the early stage [53].

$$\text{Coal gasification}: \mathrm{C(s)} + \mathrm{H_2O} \rightarrow \mathrm{CO} + \mathrm{H_2}. \quad (8)$$

3.5 Methane pyrolysis (MP)

MP, also known as thermal cracking, directly splits methane into carbon and hydrogen as demonstrated in Eq. (9) [54]. The turquoise hydrogen is generated in this process because no CO_2 is released directly and the WGS is not required [17]. Figure 10 depicts a MP flow diagram [8]. In this process, considerable quantities of methane are delivered to a reactor to convert into solid carbon and hydrogen gas [54]. This method is in its infancy at the industrial scale, and the ongoing studies are investigating the reaction mechanism, kinetics, and appropriate catalysts for scaling up the laboratory concept [55–58]. According to the literature, a high temperature is primarily required to upscale MP owing to the stable chemical properties of CH_4 [59–61]. For example, a catalytic process requires a temperature of over 800 °C, a non-catalytic process requires the temperatures of above 1000 °C, and a plasma-based process requires a temperature of above 2000 °C to assure a high yield rate as it is proportional to temperature [36,62]. With a right choice of a catalyst, the temperature requirement can be reduced to 500 °C [63]. Recent studies have suggested several reactor concepts, such as plasma, packed bed, circulating fluidized bed, monolithic, liquid bubble column, and moving bed reactors [64–77]. However, these concepts are still in their infancy without proof of industrial applications. To improve the methane conversion rate and H_2 selectivity, metal catalysts primarily based on nickel, iron, and cobalt, as well as carbonaceous materials and molten media, have been investigated [78–99]. However, a catalyst must be regenerated periodically because of an adverse impact by deposition of solid carbon [100–107]. The H_2 selectivity at moderate temperatures is the most important factor to consider when choosing appropriate catalysts [108–110]. The carbon by-product generated from a MP process is recognized as a carbon black that can be used in the production of merchandise [111–113]. MP is the cleanest method of producing hydrogen from fossil fuel as no CO_2 is directly emitted. However, the TRL of the MP process still lies in a research and development stage with a TRL of 2–4 and the process still present obstacles from three angles. First, there is no mature design of large-scale reactors and the proper strategies for catalysts selection to reduce the required temperature. Second, there is no clear understanding of the effects of methane purity on the production of hydrogen. Lastly, the current research lacks an economic and environmental evaluation of MP as the emerging technologies to compete with established hydrogen production technologies.

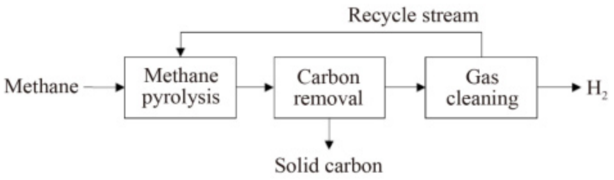

Fig. 10 Flow diagram of MP process (adapted with permission from Ref. [8]).

$$\text{MP}: \mathrm{CH_4} \rightleftarrows 2\mathrm{H_2} + \mathrm{C(s)};\ \Delta H_\mathrm{R}^0 = +74.9\ \mathrm{kJ/mol}. \quad (9)$$

3.6 Role of CCS

The methods outlined in Sections 3.1 to 3.4 yield gray hydrogen. To achieve the global NZEs goal, CCS is the only solution to the gray hydrogen sector shifting to blue hydrogen [2,3,11,114–116]. During a CCS process, CO_2 is captured from either a pre-combustion or post-combustion stage and either permanently sequestered to the subsurface porous media (i.e., hydrocarbon reservoirs and saline acquifers) or used in the production of commercial goods [117–133]. Currently, 26 commercial scale CCS facilities with a total annual capture capacity of 40 Mt are in operation around the world [1,10,114,134–137]. Six of the 26 projects are devoted to geological storage, while the other 20 are employed for CO_2 enhanced oil recovery [135]. Additionally, there are also 34 pilot CCS projects in a demonstration or development phase. To minimize global warming to 1.5 °C, the global capture capacity must exceed 1200 Gt annually [2,138,139]. Thus, CO_2 capture is extremely important to the existing hydrogen production plants owing to its large emissions [140]. As shown in Fig. 11, five main processes have been used to the CO_2 flue gas capture facilities over decades [141,142]. Capturing CO_2 from flue gas is a mature technology with a TRL of 7–9 [137,143–148]. The capture rate at the industrial scale ranges from 53% to 95%, and the greatest efficiency achievable with a cryogenic separation technique is 99.99% [142,143,145,146,149–154]. However, an increased capture rate will result in higher expenses [137,149,155–158]. The current cost of flue gas capture is estimated between 70 and 100 $/t [141,142]. In recent years, direct air capture (DAC) has been researched with a TRL of 6 to 7 [159–166]. However, the CO_2 capture from DAC plants requires a much higher cost between 300 and 600 $/t [161,166,167]. The CCS market is a policy-driven market in which operators cannot gain profits directly. The establishment of a higher carbon price will give operators possibilities to earn additional revenues and promote the industries transforming toward the NZEs target by 2050. According to the United States current carbon pricing policy, carbon credits may only be issued if the collected CO_2 is effectively utilized or sequestered. If CO_2 is emitted, the carbon tax will be charged. Industrial emitters can avoid the carbon tax by adopting a CO_2 capture technology, while downstream operators can gain carbon credits by sequestering or utilizing captured CO_2. The price of carbon will increase dramatically in the future. For instance, the US 45Q indicates that the price would rise from 31.77 to 50 $/t by 2050, and Canada will increase its carbon price from 40 to 170 CAD per ton [168,169]. SMR-CCS is an industrially validated technology that has reached maturity (TRL 8 to 9). As shown in Fig. 12, CO_2 emissions may be collected by three options during SMR [170].

3.7 Green hydrogen from biomass

Biomass can be used to produce green hydrogen. Its technologies can be classified into two categories (i.e., thermochemical and biological) with a variety of biomass feedstocks [48,171–174]. The thermochemical process is comprised of the pyrolysis and gasification conversion processes, which convert biomass to hydrocarbons before proceeding to the hydrogen production unit detailed in earlier sections [130,175,176]. The use of feedstocks and catalysts may have a direct effect on a hydrogen yield. Figure 13 depicts a process flow diagram. The biological processes include three fundamental mechanisms: bio-photolysis, photo and dark fermentation, and biological WGS responses. The mechanisms for direct and indirect bio-photolysis are shown in Figs. 14 and 15, respectively. Fermentation operations may occur with or without oxygen and include the microbial transformation of organic feedstocks into alcohols, acetone, H_2 and CO_2. These technologies can convert waste into bio-hydrogen. In the near future, however, bio-hydrogen pathways

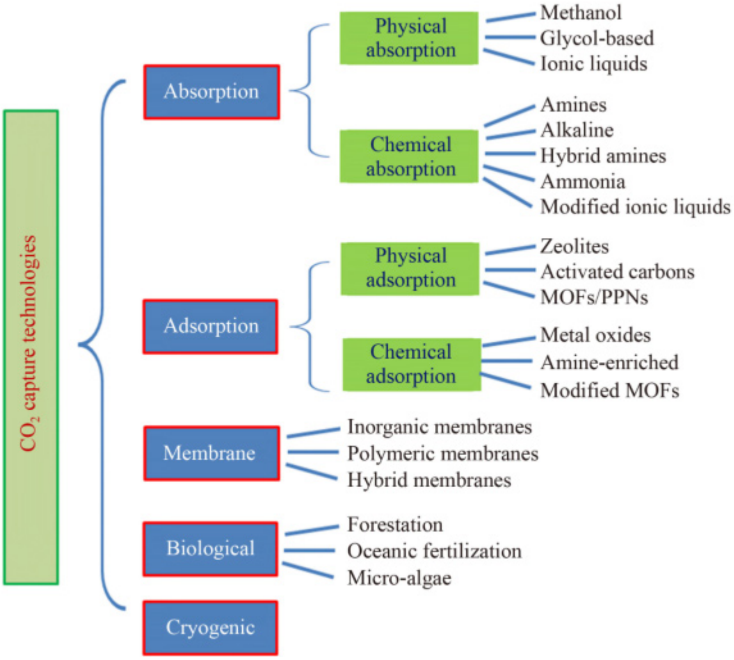

Fig. 11 CO_2 capture mechanisms (adapted from Ref. [142] under the terms of CC BY).

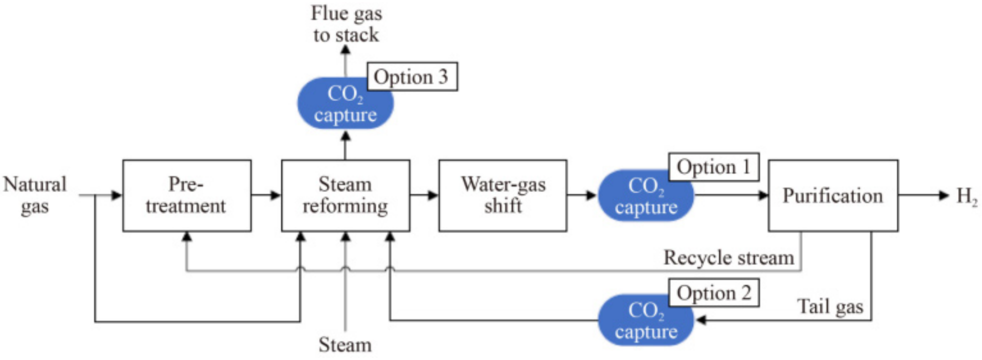

Fig. 12 SMR-CCS options (adapted from Ref. [170]).

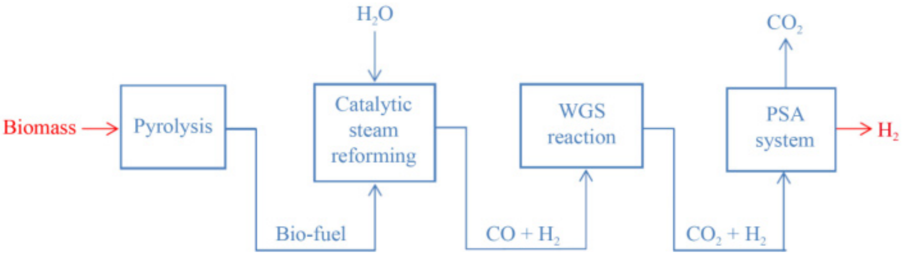

Fig. 13 Flow diagram of thermochemical biomass conversion (adapted with permission from Ref. [28]).

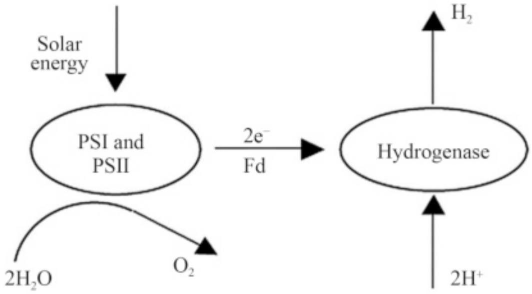

Fig. 14 Direct bio-photolysis (adapted with permission from Ref. [177]).

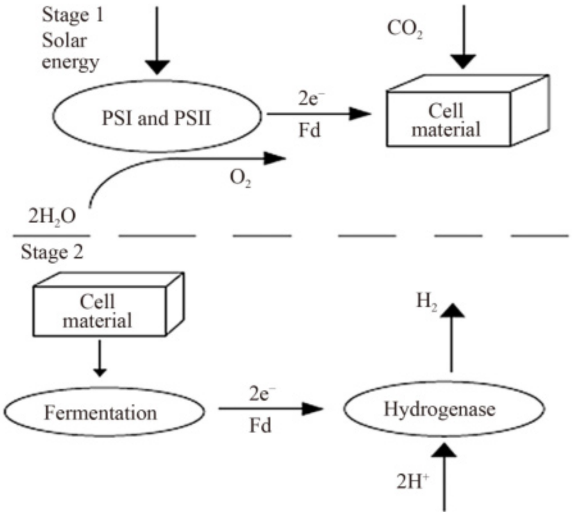

Fig. 15 Indirect bio-photolysis (adapted with permission from Ref. [177]).

cannot compete with fossil fuel-based hydrogen routes due to their low yield rate and extensive biomass consumption [5].

3.8 Green hydrogen from water electrolysis

Given the abundance of water and the growth of renewable energy, the production of green hydrogen by splitting water or even sea water is gaining attention and becoming a renewable power storage alternative for the energy sector [178–180]. Three promising methods are commonly applied to split water: electrolysis, thermolysis, and photo-electrolysis [181–183].

The most well-established and effective approach is electrolysis [184–187]. A typical electrolyzer consists of a cathode and an anode [36]. As shown in Eq. (10), green hydrogen is generated by using a significant amount of electricity with water as a feedstock. Currently, there are three common electrolysis approaches being studied [36,178]. They are alkaline water electrolysis (AEL), polymer electrolyte membrane water electrolysis (PEM), and solid oxide water electrolysis (SOEL). Recent advancments proved that H_2 can be produced from seawater, but its economic feasibility needs to be addressed at the large scale [180,188]. The commercialized AEL is capable of producing 380 tonnes of green hydrogen per year at a maximum efficiency of 73% while consuming 53.4 kW·h/kg of electricity [189,190]. Therefore, the choice of an electricity source considerably influences the carbon intensity and cost of H_2 delivery [43]. Electrolysis costs vary from 4.15 \$/kg to 10.49 \$/kg of H_2 supply, which is much more than blue hydrogen. Green hydrogen from electrolysis is one of the most promising solutions for storing renewable energy due to the exceptionally low carbon intensity of renewable power.

$$2H_2O \rightarrow 2H_2 + O_2. \tag{10}$$

The thermolysis or thermochemical technology describes a process that splits water into hydrogen and oxygen by heating water to high temperatures until it breaks down into hydrogen and oxygen [44,191]. In order for its Gibbs function to reach zero and hydrogen to be produced, this process requires a high temperature of approximately 2500 °C. The thermochemical cycles consist of a series of chemical reactions that can reduce the required temperature lowest to 550 °C [192,193]. Cu–Cl and Mg–Cl are the two most promising cycles that also do not release GHG. A high temperature needs strong heat sources such as solar or nuclear energy [194]. The cost of green hydrogen via thermolysis is cheaper than electrolysis, ranging between 2.17 and 8.20 \$/kg [192, 195–197].

Photo-electrolysis, also known as photolysis absorbing visible light, is associated with photo-catalysts to trigger an electrolysis process. In general, semiconducting materials are often used to absorb sunlight. The electrodes material selection for cells has been studied to improve the conversion efficiency. The average cost of hydrogen production by potho-electrolysis is estimated to be about 10.36 $/kg [198–205].

4 Hydrogen transportation and storage

The rising demand and productivity of hydrogen need the development of efficient transport and storage systems. Safe, trustworthy, and cost-effective strategies are required as the hydrogen sector continues to face obstacles. Due to the unique properties of hydrogen, such as a low density and a small molecular size, transportation, and storage are remaining challenges to industry. In this Section, the methods of hydrogen transportation and storage are discussed [206].

4.1 Transportation

The techniques for transporting hydrogen are divided into two categories: direct and indirect transportation. The direct transporting approach entails transporting hydrogen without altering its chemical composition. Common transport techniques include containers and pipelines [207–209]. Hydrogen is compressed at a high pressure (up to 20 MPa) and transported by gas cylinders, hydrogen vehicle tanks, and pressure vessels [210]. The optimal container design materials should possess three characteristics: high tensile strength, low density, and not reacting with hydrogen or allowing diffusion. However, their ineffectiveness is questioned by the industry due to their poor carrying capacity and expensive price. As the most efficient route for the direct transfer of hydrogen, pipeline networks are being investigated and constructed in recent years. The indirect transport techniques explained the process of transporting H_2 utilizing liquid organic hydrogen carriers [211,212]. In this process, H_2 reacts with an organic material to generate a new compound, which dehydrates back into H_2 once the liquid carrier reaches its destination. As carriers, cycloalkanes, N-heterocycles, B-N-based heterocycles, and formic acid have been studied [211, 213–221]. However, the carrying capacity is quite low (usually less than 6 wt.%), and the dehydration process often requires a high temperature. Using ammonia and related chemicals (e.g., ammonia borane, liquid ammonia, and 35 wt.% ammonia solution) as the hydrogen carriers can reach a carrying capacity of up to 19.6 wt.%. The carrying capacity can meet the US Department of Energy (DOE) target (9 wt.%), but the cost is relatively inaffordable [212]. The most common process is named the Haber-Bosch process shown in Eq. (11). Haber won the Nobel Prize in 1918. In this process, ammonia is synthesized from hydrogen and nitrogen in a reactor designed with a pressure of 20 to 35 MPa and a temperature of 300 to 500 °C with two to four catalysts [222]. Since ammonia is unstable and decomposes at over 200 °C, the decomposition process as depicted in Eq. (12) is usually required when the ammonia is transported to a destination as a hydrogen carrier.

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g); \Delta H = -92\ \mathrm{kJ/mol}. \tag{11}$$

$$2NH_3(g) \rightarrow N_2(g) + 3H_2(g). \tag{12}$$

Additionally, long distance transportation of hydrogen from an offshore wind farm is needed in the future owing to the rising installed capacity of wind energy. A high grid connection cost makes the green hydrogen one of the most promising options for energy storage. However, transportation and distribution of H_2 offshore is facing economic challenges owing to its high cost. Liquid H_2 (LH_2) is commonly transported by a ship to onshore storage tanks, and distributed to end-users via tube trailers or LH_2 semitrailers, which are mature technologies [223]. Pipelines are not commonly used owing to the corrosion of seawater and challenges of long-distance construction in the ocean. In 2019, the first LH_2 carrier ship in the world was launched in Japan with the capability of 75 t and longest ferrying distance of 5600 m [224].

In brief, hydrogen can be transported directly or indirectly via pipelines, ground transportation, marine transportation, and liquid hydrogen carriers. However, the hydrogen industry lacks an understanding of the impact of interfical reactions of hydrogen and carrier materials such as hydrogen embrittlement and corrosion. Liquid hydrogen carriers need to improve the transportation efficiency by improving their carrying capability and reducing their cost.

4.2 Storage

Hydrogen can be stored both on the surface and underground [38,206,225]. There are three potential solutions to store hydrogen on the surface [226–228]. First, compressing hydrogen at a high pressure is presently the most popular and mature technology for surface storage. Due to the extraordinarily low density of hydrogen in the atmosphere (i.e., 0.09 kg/m^3), a high pressure of up to 77 MPa is necessary to compress it [226]. Another solution is to store liquid hydrogen (also named the cryogenic hydrogen) in a cryogenic tank, which needs temperatures below its boiling point of −253 °C [210]. Lastly, solid-state storage is being considered as an effective large-scale storage option based on the hydrogen adsorption and desorption mechanisms especially in recent years [229, 230]. The advantages of solid-state storage include high storage capacity, high purity, and high safety [5,231]. For instance, metal hydrides have an ability to absorb and desorb hydrogen molecules with a high capacity for the storage purpose [232,233]. In general, a desorption procedure requires the temperature in a range between 120 to 200 °C. Another potential material is carbon nanotubes. Due to their complex porous structure, hydrogen can be, therefore, stored and extracted through adsorption and desorption, respectively [234–238]. The storage capacity of a carbon nanotube varies according to the processing uncertainties during preparation and synthetic purity when manufacturing the materials. Metal-organic frameworks (MOFs) are another type of material for hydrogen storage purpose [239–246]. MOF is a synthetic material with a high porosity and specified surface area that has a high hydrogen absorption capacity and has garnered considerably more interest in recent years. MOF materials are still difficult to synthesize, and their characteristics have a significant influence on hydrogen storage capacity.

Underground hydrogen storage (UHS) has been proposed as a large-scale option to store hydrogen to geological porous media [225,247–251]. Potential candidate formations include empty salt caverns, deep aquifers, depleted hydrocarbon reservoirs, and coal seams. This is a novel application to the energy industry and the feasibility of this approach has been studied in recent years. Therefore, there is not sufficient industrial application data up to date. However, owing to the different fluid properties of hydrogen compared with CO_2 and natural gas, the evaluation schemes are different. Additionally, geological properties such as rock properties, fluid properties, and solid-fluid interactions can significantly impact the performance of UHS. On the operational side, the storage efficiency poses another challenge to industry as it is easier for hydrogen to leak than other molecules.

5 Hydrogen economy

Hydrogen economists analyze production, transportation, and storage systems primarily from two perspectives: techno-economic and environmental effects. To achieve the cost-effective and sustainable development goals, a variety of technologies have been evaluated [10,16,29]. During the manufacturing phase, matured blue hydrogen technologies have been successfully evaluated, and costs have decreased to an economical level (less than 2 $/kg) over the past decades [252–254]. The cost of green hydrogen routes is still relatively expensive compared to blue hydrogen pathways, posing an economic obstacle. Other emerging H_2 production methods are still in the progress of development, and an industrial-scale techno-economic assessment will be required in the near future. The feedstocks used to produce hydrogen will be a crucial factor in determining the cost, since they will directly influence the selection of technologies (Fig. 16) [187]. Current research lacks evidence of the economic assessment of transportation and storage because the demand for these technologies has been relatively low in the past years but is expected to increase considerably in the near future [254–257]. Figure 17 depicts the future hydrogen market supply chain [258]. Similar to the market for fossil fuels, the whole value chain can be divided into upstream production, midstream transportation and storage, and downstream use.

In the downstream utilization phase, hydrogen can be directly utilized as a clean fuel because it is a zero GHG emission energy source. Its applications include hydrogen fuel vehicles in ground transportation, retrofitting hydrogen plants in electricity generation and heating supply, and high energy intensive fuel for aviation and space crafts [259,260]. Although using hydrogen fuel in space crafts has been successfully deployed, the aviation sector still requires further investigations in terms of the safety, economics, and retrofitting feasibility. Similarly,

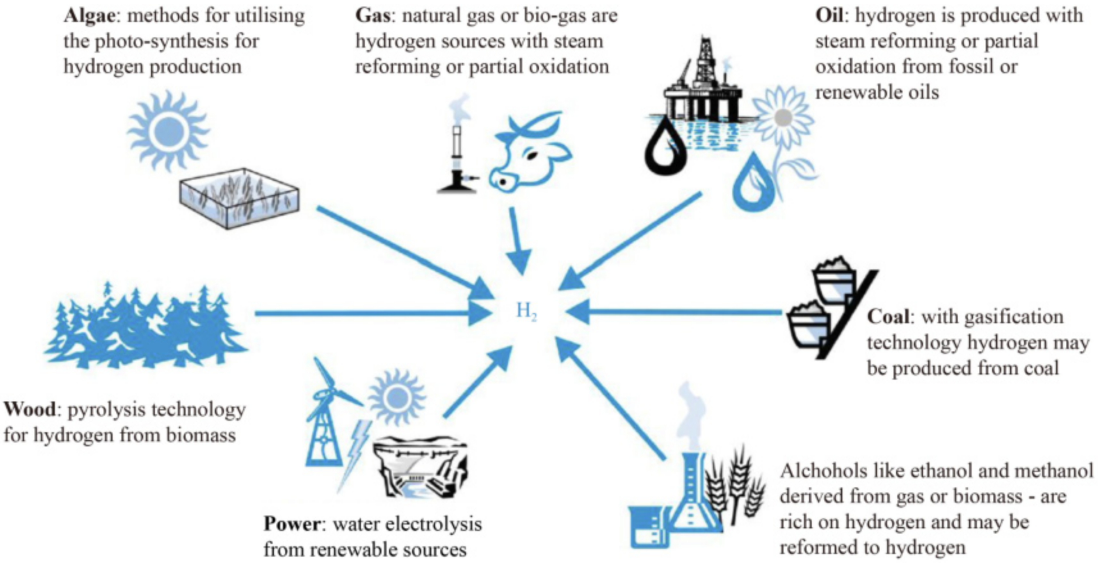

Fig. 16 Feedstocks of hydrogen production (adapted from Ref. [187] under the terms of CC BY).

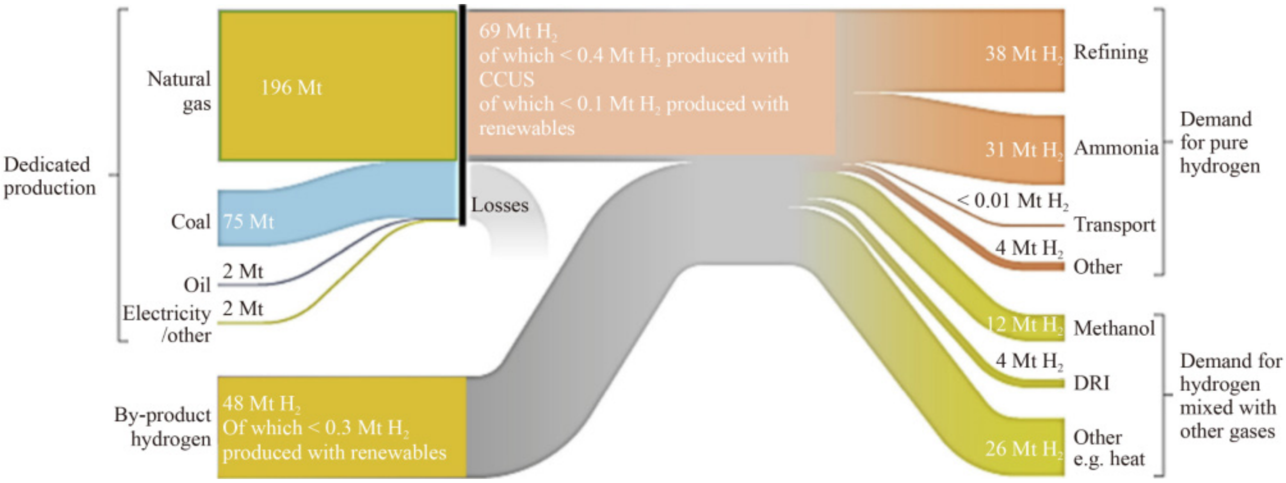

Fig. 17 Hydrogen value chain (adapted from Ref. [258]).

the retrofitting feasibilities of internal combustion engines and coal and natural gas plants need to be estimated economically and technically. The utilization of hydrogen fuel cells can potentially improve the energy conversion efficiency for transportation and heavy-duty applications. Hydrogen can also be indirectly used to produce value added chemical products, such as ammonia, methanol, and carbon-free fuels. Additionally, using hydrogen as a feedstock in petroleum refinaries can remove sulfur and other impurities as well as in other industries such as plastic material production, manufacturing of vacuum tubes, the glass industry, and the food industry [259]. The demand of different colors of hydrogen will be a challenge in the short-, mid- and long-terms. As stated in the previous sections, blue hydrogen accounts for about half of current hydrogen supply, where most of them are used in the chemical industry in purposes of producing value added products. In the mid-term, the market will diversify its supply by incorporating the blue and green hydrogen while the large-scale industrial applications will be employed toward the clean energy transition, such as constructing hydrogen plants and energy cogeneration. In the long-term, green hydrogen will dominate the market and industrial utilization including transportation, fuel cells, and energy storage [261,262].

The cost of producing hydrogen will be a major problem for industrial-scale production, and policy-driven incentives will be advocated. A learning curve suggests that with adequate research and development, the long-term cost of green hydrogen may be reduced to an affordable level [263–265]. Prior to that, fossil fuel-based hydrogen plus CCS is the best choice in the immediate and medium future (Fig. 18) due to its cheap cost and potential capability to offset CO_2 emissions [266].

As upscaling a low-carbon green hydrogen technology is still a challenge for industry, the environmental effect of blue hydrogen must be carefully evaluated in order to achieve the NZE goal in a short future. The environmental performance of the whole hydrogen supply chain must be evaluated using the approach of life cycle assessment (LCA) in order to determine the lifetime carbon emissions of hydrogen [267–270]. The selection of low-carbon electricity is essential for low-carbon technologies, and each unit process must be included in the detailed examination of the environmental effect [16,271–275]. The adoption of LCA can facilitate rational decision-making and assess the environmental implications of emerging technologies over time. Challenges associated with LCA for emerging technologies include a lack of data, scale-up, a lack (in some cases) of incumbents against which to compare, and uncertainties with respect to both how an emerging technology will be deployed and the market conditions into which it will be deployed [275]. An early-stage assessment can help set targets for technology development, influence design, and ensure that environmental goals of innovation are met [276]. The cradle-to-gate global warming potential of hydrogen generation ranges between 3.94 and 34.85 $kgCO_2eq/kg$ H_2 [8]. However, several parameters, such as a carbon intensity of power, the selection of catalysts, and the manufacturing process design, might alter this estimate.

6 Conclusions

The growth of the hydrogen industry, comprising production, transportation and storage, and the economy, was reviewed, based on which, the following conclusions, as well as future outlooks, are given.

For the hydrogen production sector, efforts in the research and development sector will be required to upscale green hydrogen technologies to meet the long-term increasing hydrogen demand. Over the years, fossil fuel-based hydrogen has dominated the market. However, the GHG emissions cannot be ignored owing to its

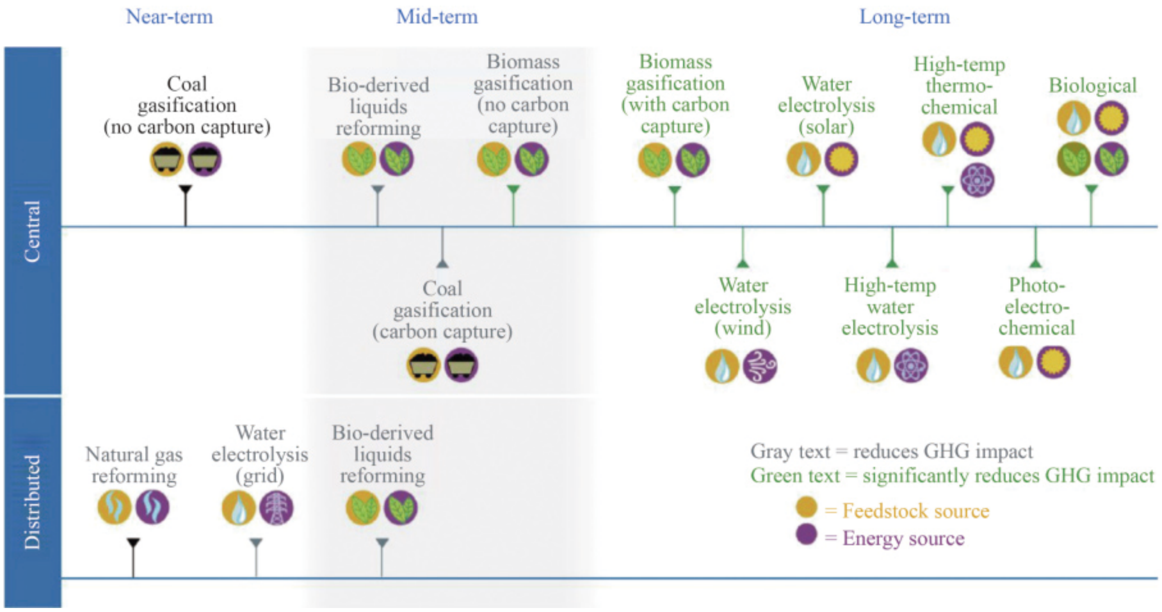

Fig. 18 Projection of hydrogen production technologies (adapted from Ref. [266]).

significantly adverse impact on global warming. CCS will be the only solution to the current gray hydrogen generation routes to fulfill the NZE target. Turquoise hydrogen generation is a promising method to obtain hydrogen as the transitional substitute from “blue” to “green”. The majority of the research efforts will be focused on reactor designs and catalyst selections so that the process may be efficiently scaled up. Successful adoption of CCS can guarantee the blue hydrogen production to meet the increasing hydrogen demand in a short-term. With the renewable electricity and green hydrogen production technologies, the industry can achieve the NZE goal in a long-term. The cost-effective hydrogen production will pose a major challenge to the hydrogen industry, while the CCS can raise the blue hydrogen cost by 30%. The current blue hydrogen production processes are economic feasible, but the green hydrogen technologies need to reduce their cost by 75% to 2 $/kg in the coming decades so that it can be competitive with blue hydrogen to meet the future market demand. Future research needs to focus on upscaling the green hydrogen by discovering cost effective catalysts and diversifying feedstocks and electricity usage. Techno-economic analysis is recommended associated with the proposed emerging technologies.

Due to a rising market demand, hydrogen transportation and storage have actively been developed in recent years. However, pipeline network transportation could be an effective strategy but will considerably differ from CO_2 and natural gas pipelines due to the different properties of hydrogen. Additionally, addressing the challenges will be a crucial milestone in future research. For instance, quantifying the impacts of embrittlement, contamination, and flammability can provide a solid support in the selection of materials for the transportation safety and development of new materials for transportation and storage. The research and development sector should concentrate on solid-state hydrogen storage feasibility studies on the surface and feasibility investigations of UHS to assure storing hydrogen on a large scale.

The hydrogen market is confronted with two biggest barriers, particularly in terms of technology assessment. First, precise techno-economic appraisals of new technologies must be conducted to guide the development of cost-effective blue hydrogen and green hydrogen production techniques. Second, a cradle to grave LCA at various TRLs must be conducted to estimate the carbon footprint of a hydrogen supply chain in order to achieve the NZE goal by 2050.

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