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Chapter 9

Feasibility Review of Hydrogen Production Options: Life Cycle Assessment and Economic Assessment

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As part of Singapore's international climate commitment to achieve net zero carbon emissions by 2050, the production and use of hydrogen is one of the nation's major decarbonisation pathways. Conventional technologies such as Steam-Methane Reforming (SMR) and Coal Gasification (CG) depend on fossil fuels for hydrogen generation. The usage of fossil fuels has led to environmental issues. To combat environmental impacts due to rising hydrogen demands, a review is done to identify and evaluate the sustainability of hydrogen production options based on environmental and cost indicators. The sustainable usage of SMR and CG can be potentially integrated with carbon capture and storage (CCS) or substituting fossil fuels with renewable energy. Electrolysis and Biomass Gasification (BG) show potential as alternatives to SMR and CG. Although the application of renewable energy has lower environmental impacts, the hydrogen production cost is higher than SMR and CG. Other promising hydrogen production options include white and aquamarine hydrogen. In the foreseeable future, further research and development are required for a judicious evaluation based on the environment and cost of advanced methods for hydrogen production.

1. Introduction

Conventional energy generation systems rely heavily on fossil fuels use, which leads to the release of atmospheric pollutants such as nitrogen oxides, sulfur oxides, particulate matter, and carbon dioxide. Climate change is the resulting environmental impact of carbon dioxide. Additionally, the use of fossil fuels accounts for 82% of the world's energy [1], and many efforts are spent investigating alternative energy resources to combat environmental problems associated with fossil fuels. Low-carbon energy pathways have since gained traction among scientific communities and industries. Hydrogen is a clean,

renewable, secondary energy source and is receiving significant attention as a versatile energy carrier. It has potential in energy generation, chemicals, transportation, and iron and steel production applications [2-5]. As part of Singapore's international climate commitment to achieve net zero carbon emissions by 2050, the production and use of hydrogen is one of the nation's major decarbonisation pathways [6]. The global hydrogen demand is projected to increase from 70 million tonnes in 2019 to 120 million tonnes by 2024 [5,7]. Hydrogen is also expected to become an important energy source in Japan, China, and the United Kingdom (Chapters 3, 5 and 6). With its growing requirement, one should consider the whole life cycle of hydrogen production options to evaluate its true sustainability in terms of environment and cost.

In this chapter, we review the conventional and emerging hydrogen production options. These include the thermochemical, electrolytic, direct solar water splitting and biological processes. The feasibility of these hydrogen production options via Life Cycle Assessment (LCA) and Economic Assessment i.e., Techno-Economic Assessment (TEA) and Life Cycle Costing (LCC) are also reviewed.

2. Hydrogen Production Options

Hydrogen production options are classified into different colour codes based on the production route's cleanness, without considering the entire life cycle [5]. Grey, blue, and green hydrogen are the main categories of hydrogen production options to be discussed in this book chapter. Grey hydrogen is produced from Steam-Methane Reforming (SMR) or Coal Gasification (CG). Blue hydrogen is formed by integrating carbon capture and storage with SMR or CG. Green hydrogen production routes include Electrolysis and Biomass Gasification, accompanied by power sourced from renewable energy sources [8]. This chapter provides an overview of various technologies for hydrogen production from renewable and non-renewable resources.

2.1. Steam-Methane Reforming (SMR)

Steam-Methane Reforming (SMR) is a developed technology pathway for worldwide hydrogen production (Figure 1). SMR has a process efficiency of 60 – 85% [9]. In 2021, 47% of the global hydrogen production is from natural gas [10]. Since hydrogen from this mainstream approach is produced from fossil fuels, it resulted in high carbon dioxide emissions [11]. SMR can be coupled with carbon capture and storage (CCS) for lower carbon dioxide emissions.

In the initial processing stage of SMR, sulfur is removed from the natural gas [12]. Next, methane reacts with steam under 3-25 bar pressure in the presence of a catalyst to produce syngas, as shown in Eqn. 1 [13].



Carbon monoxide and steam are then reacted in the presence of a catalyst to produce carbon dioxide and hydrogen, as depicted in Eqn. 2. This is known as the “water-gas shift reaction” [13].



In the final step, carbon dioxide is removed to obtain purified hydrogen [13].

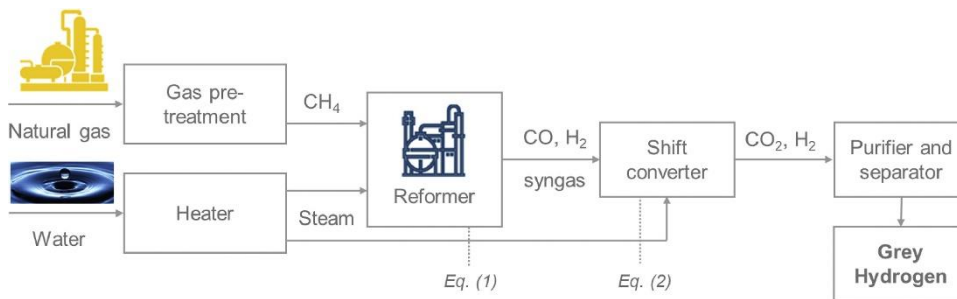


Figure 1. The schematic production process of Steam-Methane Reforming (SMR).

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2.2. Coal Gasification

Coal Gasification (CG) is another widespread hydrogen production technology, having a process efficiency of 74-85% (Figure 2) [9]. In 2021, coal contributes 27% of the global hydrogen production [10]. Similarly to SMR, this technology also results in high carbon dioxide emissions due to the usage of fossil fuels. CG consists of two phases. In the first phase, oxygen obtained from air separation is supplied into the gasifier to oxidise a fraction of coal into carbon dioxide (Eqn. 3) [14].



In the second phase, steam is injected to react with a fraction of coal to form carbon dioxide and hydrogen (Eqn. 4). After the heat is depleted to a certain threshold, oxygen is introduced into the gasifier again. These two steps alternate until coal is completely converted [14].

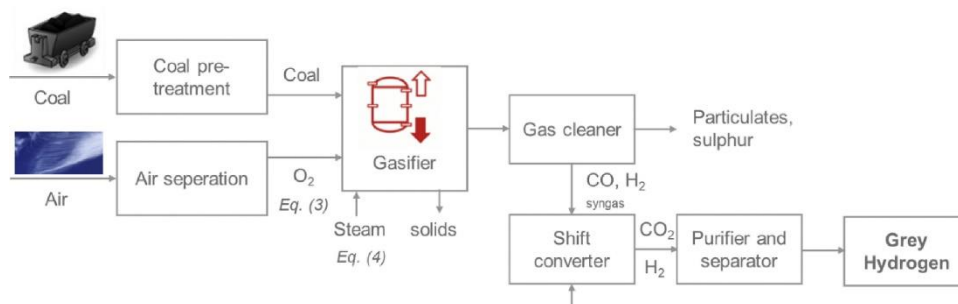


Figure 2. The schematic production process of Coal Gasification (CG).

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2.3. Electrolysis

Electrolysis separates water into hydrogen and oxygen using electricity. Electrolysis is a promising hydrogen production option which renders lower carbon dioxide emissions when renewable energy resources are employed. These renewable energy resources include wind, solar, nuclear and biomass [15]. Other advantages of electrolysis include high hydrogen purity > 99.95% and the absence of unwanted by-products such as sulfates, carbon oxides and nitrogen oxides that cause environmental pollution [6]. Although electrolysis shows capability as a renewable route, only 4% of global hydrogen demand comes from it [10,16]. This is due to challenges related to high capital costs, energy efficiency and operational issues [13].

Electrolysis can be grouped into three significant types – Polymer Electrolyte Membrane (PEM), Alkaline and Solid Oxide electrolysis [13]. PEM electrolysis is the most preferred option owing to its higher hydrogen production rate, better energy efficiency, compact and small design, easy integration with renewable energy and low maintenance [12].

Referring to Figure 3, the PEM electrolysis process is as follows: At the anode, water reacts and forms oxygen and positively charged hydrogen ions (protons) (Eqn. 5). At the cathode, hydrogen ions combine with the electrons to form hydrogen gas (Eqn. 6).

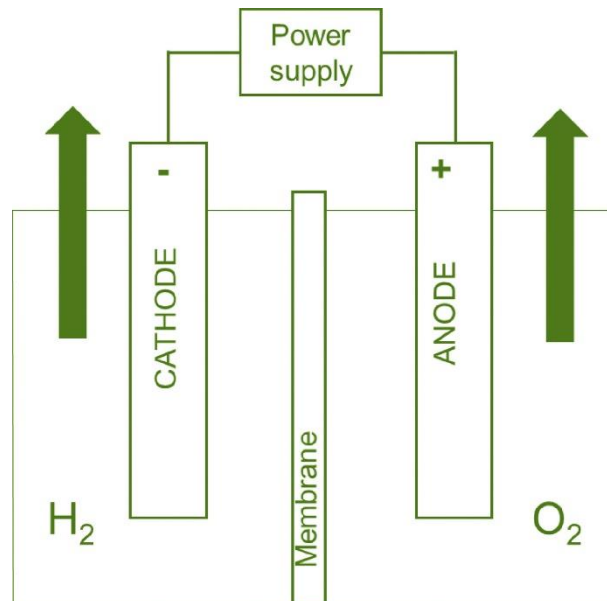
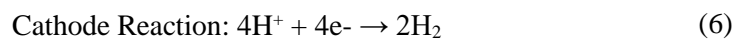
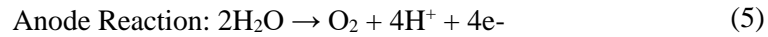


Figure 3. The schematic production process of Polymer Electrolyte Membrane (PEM).
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2.4. Biomass Gasification

Biomass Gasification (BG) is a potential hydrogen production technology since biomass is an abundant and renewable energy resource. Furthermore, net carbon dioxide emission is lower than SMR and CG since plants consume carbon dioxide while they make biomass. However, only around 1% of the global hydrogen demand is produced by biomass [16]. This may be associated with limitations such as lower efficiency, higher capital costs and biomass feedstock costs [13,16,17].

Other reasons include aggressive molten slag, tar formation at low temperatures and potential biomass supply issues [18]. Sources of biomass include sustainable wood waste, agricultural residues, organic municipal solid waste, and animal waste [13,19].

The process of BG is very similar to CG; however, biomass does not gasify easily compared to coal. As a result, other hydrocarbon compounds are produced. These hydrocarbon compounds must undergo reforming with a catalyst to yield clean hydrogen, carbon monoxide and carbon dioxide. The water-gas shift reaction will then convert carbon monoxide to carbon dioxide. Purified hydrogen is then obtained with the adsorbers or special membranes [13].

3. Life Cycle Assessment (LCA)

To achieve near-zero carbon emissions, a systematic environmental tool is needed for evaluating the list of hydrogen production options. LCA helps identify the environmental impacts and ascertain environmental feasibility by considering the entire life cycle of the process chains. The suitability of using emerging hydrogen production options is assessed.

Antonini *et al.* [20] perform a cradle-to-gate Life Cycle Assessment (LCA) of natural gas reforming and biomethane-based hydrogen production with and without the integration of carbon capture and storage (CCS). Global Warming Potential (GWP) is lowered by 45-85% with the addition of CCS in different natural gas reforming-based hydrogen production configurations. However, other environmental impacts worsen due to higher electricity consumption, carbon dioxide transport and storage requirements. Alternatively, in all investigated cases of biomethane-based hydrogen production, the addition of CCS leads to net-negative emissions. With soil carbon sequestration, bio-based hydrogen achieves net-negative life cycle greenhouse gas emissions without CCS. The authors also deemed electrolysis an equally valid option to reforming-based hydrogen with CCS if electricity is generated from abundant intermittent renewables.

Amaya-Santos *et al.* [21] evaluated the LCA of biohydrogen, blue hydrogen and green hydrogen production technologies. In current and future scenarios, biohydrogen production shows potential with its negative climate change impacts when CCS and biogenic carbon content are considered (Figure 4). The team established that environmental impacts are greatly dependent on electricity sources. Biohydrogen is a more sustainable option if electricity is sourced from renewables (e.g., solar or wind). The benefits of achieving decarbonisation via solar hydrogen are illustrated in Chapter 5.

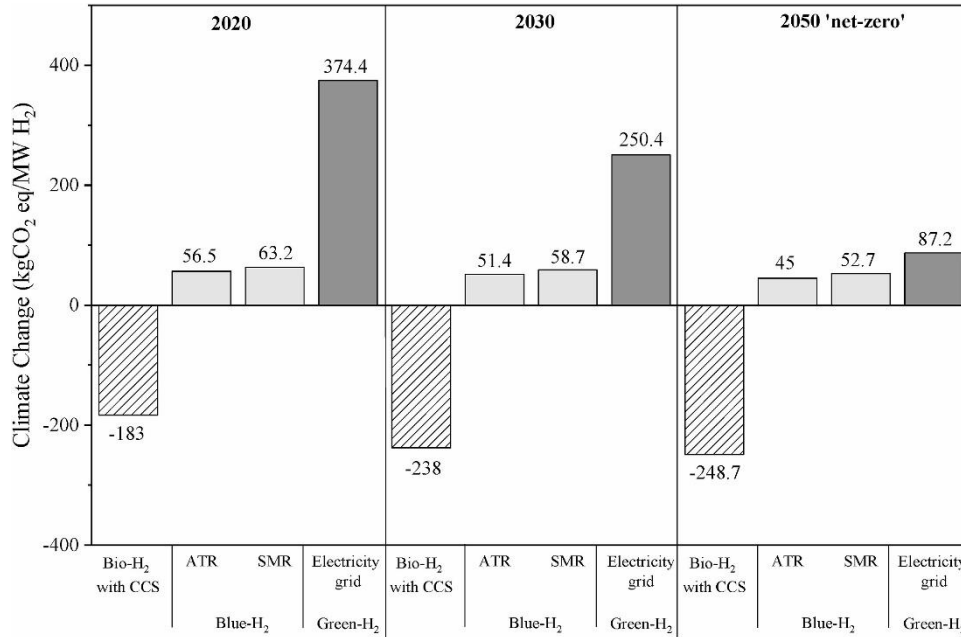
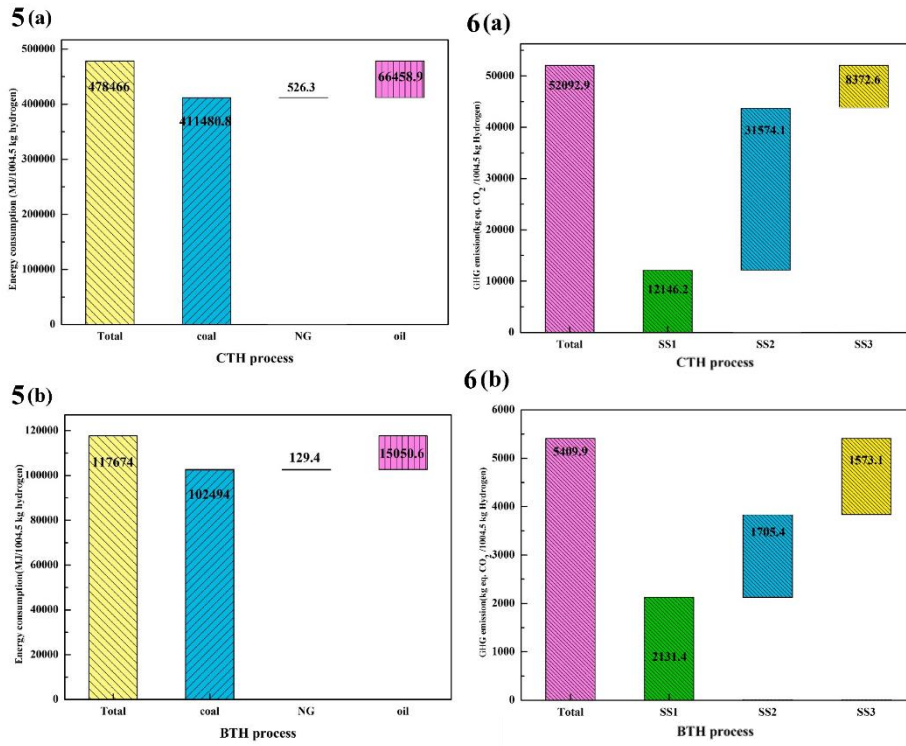


Figure 4. Climate Change impacts of current (2020) and future (2030 and 2050) electricity grid mix scenarios. *Source:* Taken from Ref. [21] with permission from Elsevier.

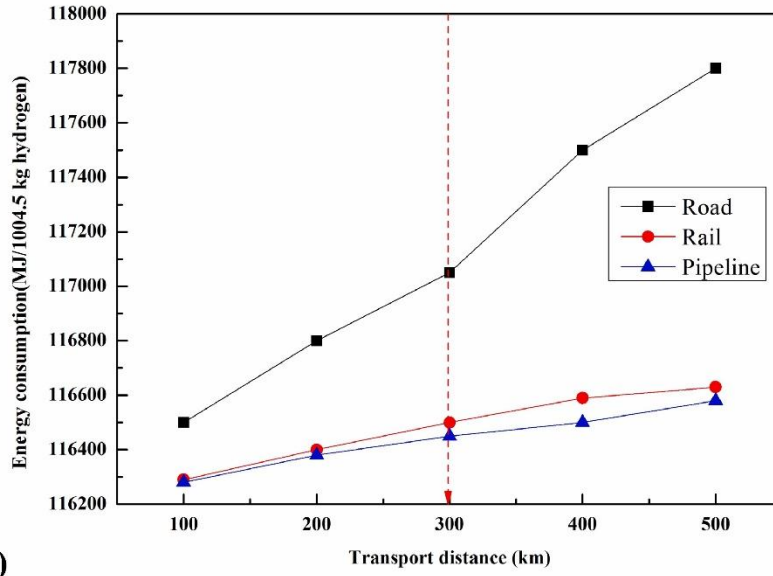
A comparative LCA of coal-to-hydrogen (CTH) with biomass-to-hydrogen (BTH) processes were performed by Li *et. al.* [22]. Results revealed that energy consumption and greenhouse gas (GHG) emissions are respectively 75.4% (Figure 5) and 89.6% (Figure 6) lower in the BTH process in comparison with the CTH process. To further lower GHG emissions and improve energy efficiency, the authors suggest gasification temperatures ranging from 1400-1500°C and pipeline transport. Energy consumption of pipeline transport increases at a slower rate as compared to rail and road (Figure 7). Hence, the pipeline is the desired transport mode. The sustainability benefits of hydrogen from biomass and waste were also described in Chapter 6.



Figures 5 and 6. Energy consumption and GHG emissions of (a) CTH process and (b) BTH process.

Source: Taken from Ref. [22] with permission from Elsevier.

(a)



(b)

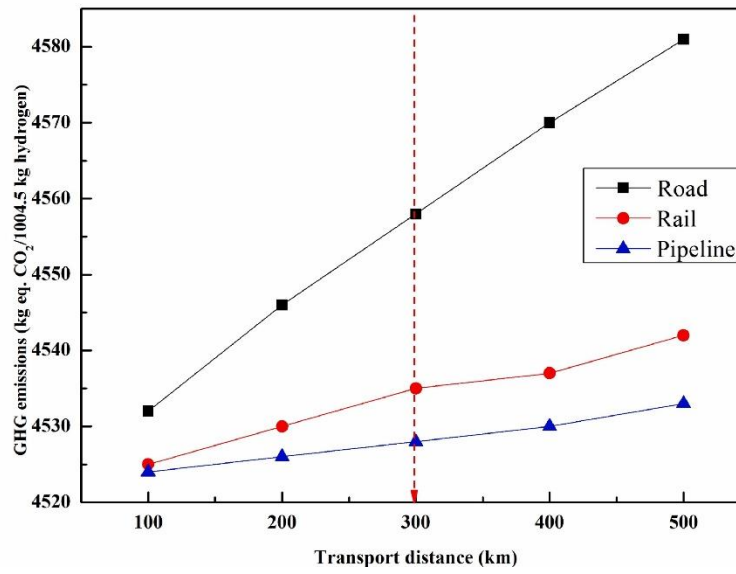


Figure 7. Effects of hydrogen transport mode and hydrogen transport distance on energy consumption and GHG emissions.

Source: Taken from Ref. [22] with permission from Elsevier.

Barei *et al.* [23] performed an LCA comparison study of proton exchange membrane water electrolysis and SMR. A carbon emission reduction of up to 75% is obtained from the electrolytic system when electricity is generated from renewable energy sources. Wulf *et al.* [17] reported that PEM and Alkaline electrolysis has the lowest impacts on Climate Change (Figure 8). Apart from Climate Change, other environmental impact categories are investigated, i.e., Eutrophication, Particulate Matter, Photochemical Ozone Creation and Acidification (Figures 9-12). Further studies have shown that switching from fossil fuel-based electricity mix to renewable sources can reduce the global warming impact [23,24].

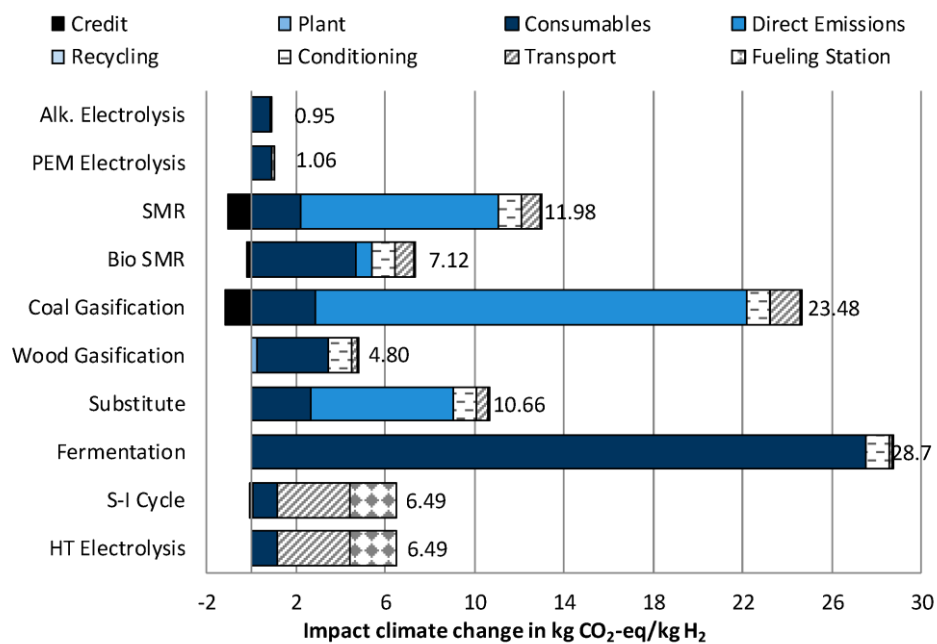


Figure 8. Impact on Climate Change.

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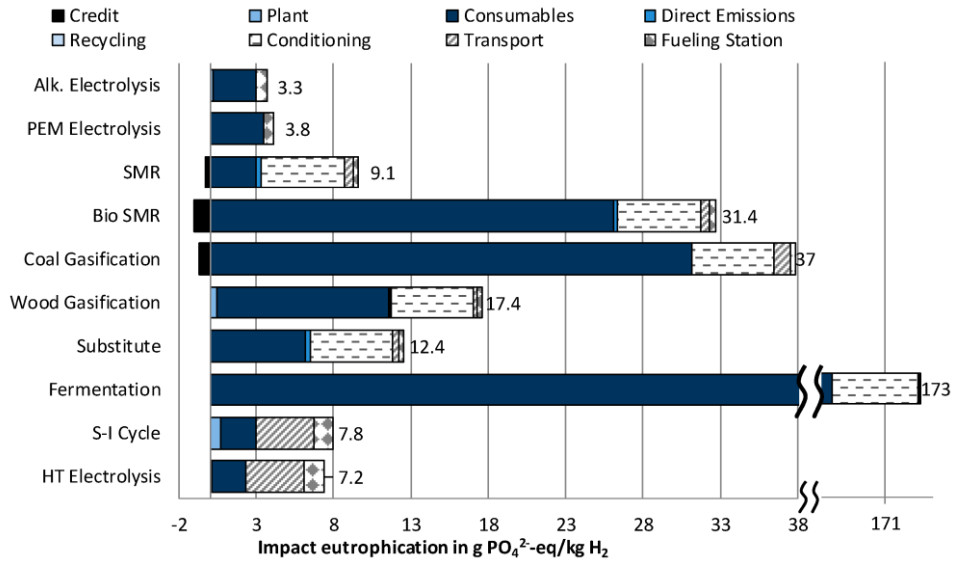


Figure 9. Impact on Eutrophication.

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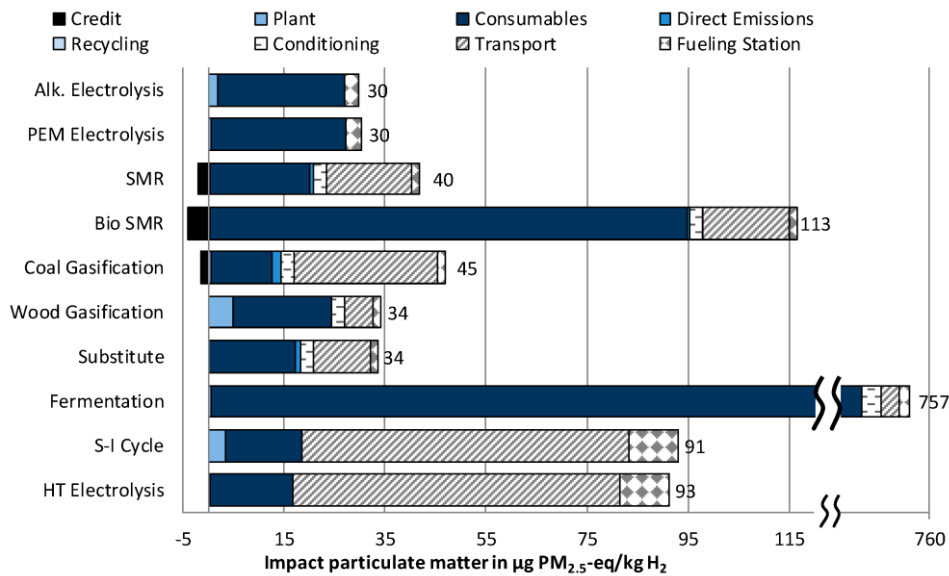


Figure 10. Impact on Particulate Matter.

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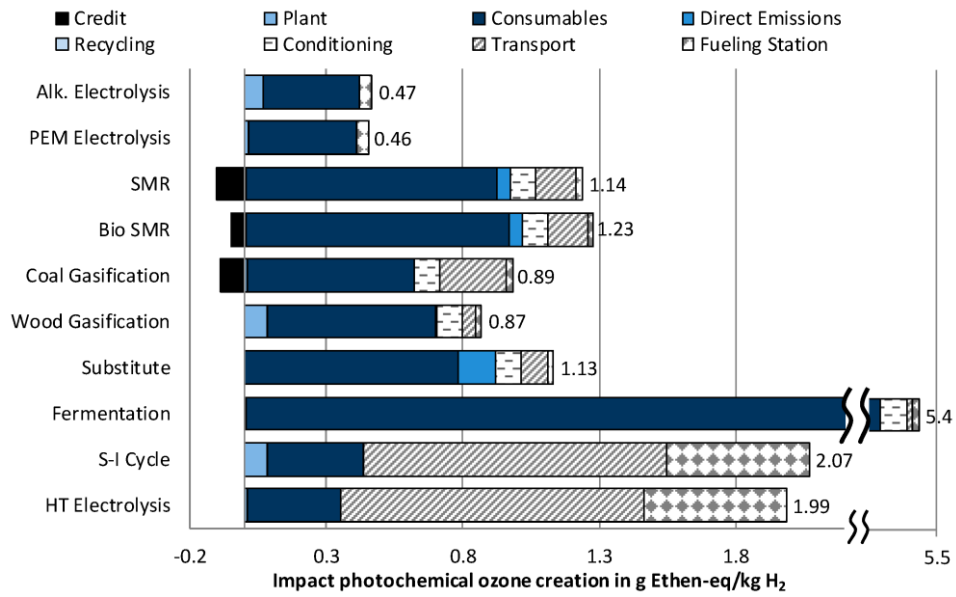


Figure 11. Impact on Photochemical Ozone Creation.

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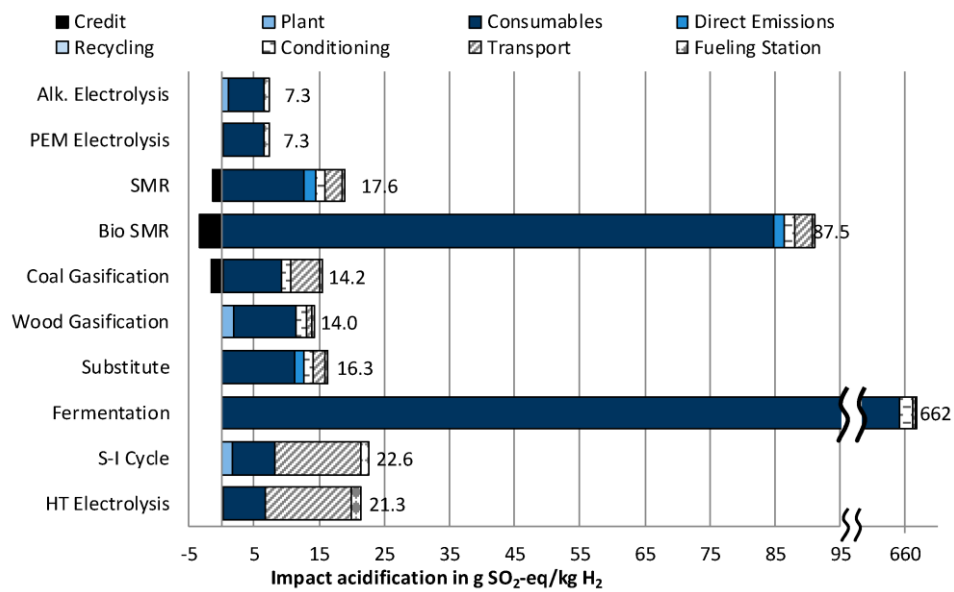


Figure 12. Impact on Acidification.

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4. Economic Assessment

Besides the environmental concerns of hydrogen production, other sustainability indicators involve cost or economic aspects. Techno-Economic Assessment (TEA) and Life Cycle Costing (LCC) are different methods to analyse the economic performance of hydrogen production options. Herein, we assess conventional and emerging hydrogen production options based on economic costs.

Currently, conventional technologies (SMR and CG) have lower costs of hydrogen production without carbon dioxide capture [17, 25-28]. Khan *et al.* [29] developed a spatial techno-economic framework to evaluate SMR with Carbon Capture, Utilization and Storage (CCUS). Natural gas contributed the highest to hydrogen production costs, followed by CCS capital costs. Conversion of carbon dioxide emissions into formic acid via carbon dioxide electro-reduction decreases costs associated with carbon storage and hydrogen production costs by 4–9%. Reduction in natural gas and emission mitigation costs can lower blue hydrogen costs.

Yan *et al.* [30] investigated the techno-economic performance of Sorption-enhanced steam methane reforming (SE-SMR) processes. The economic performance is comparable with SMR integrated with CCS. As seen in Figure 13, fuel costs are the hot spot in influencing economic performance, followed by net efficiency, total direct equipment capital costs and carbon dioxide storage costs.

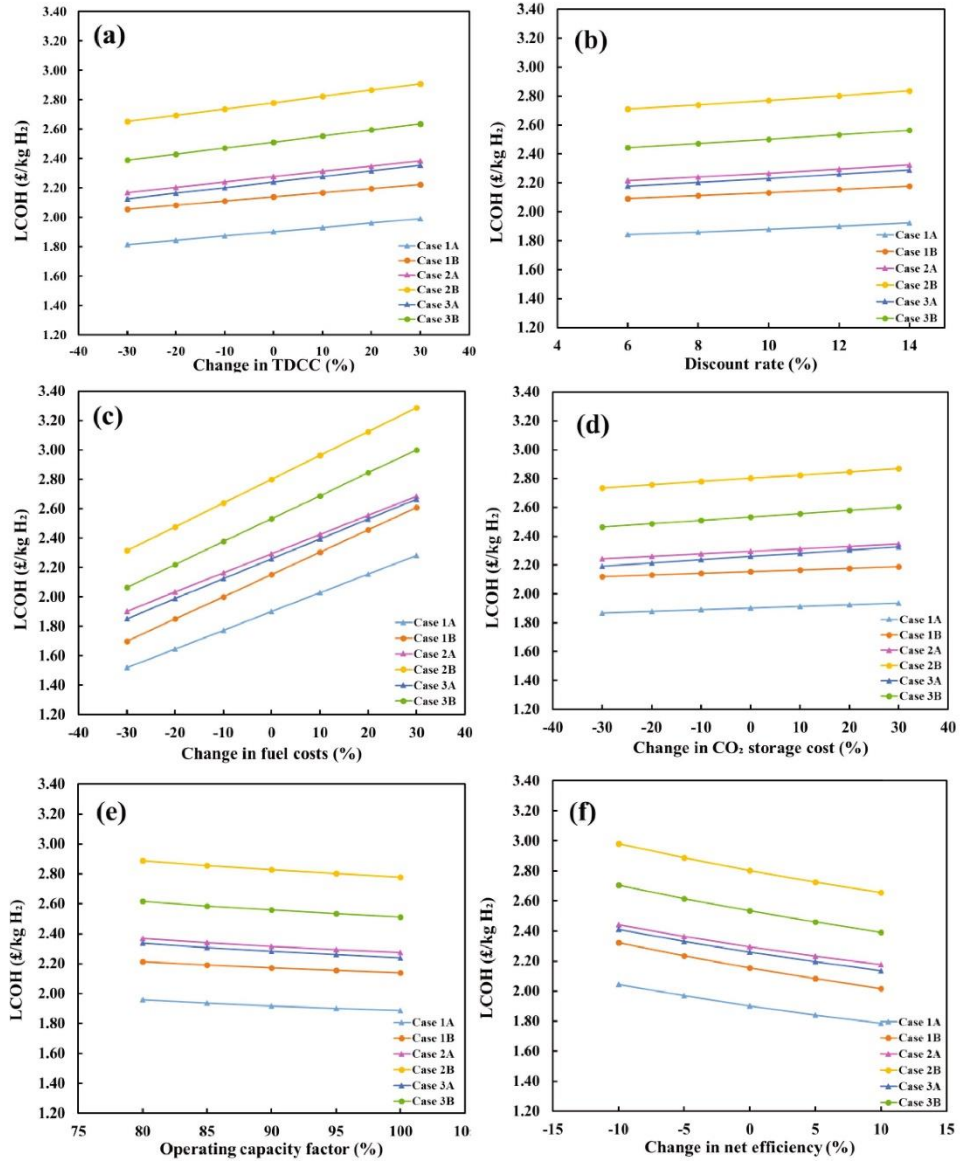


Figure 13. Sensitivity analyses (a) Total Direct Capital Cost (TDCC), (b) Discount rate, (c) Fuel costs, (d) CO₂ storage costs, (e) Operating capacity factor, (f) Net efficiency vs LCOH.

Source: Taken from Ref. [30] with permission from Elsevier.

Nguyen *et al.* [31] show that electrolytic hydrogen production with underground storage costs is comparable to SMR with CCS. Electrolytic systems with high-capacity factors, integrated with wholesale electricity markets have high feasibility potential, as depicted in Figure 14.

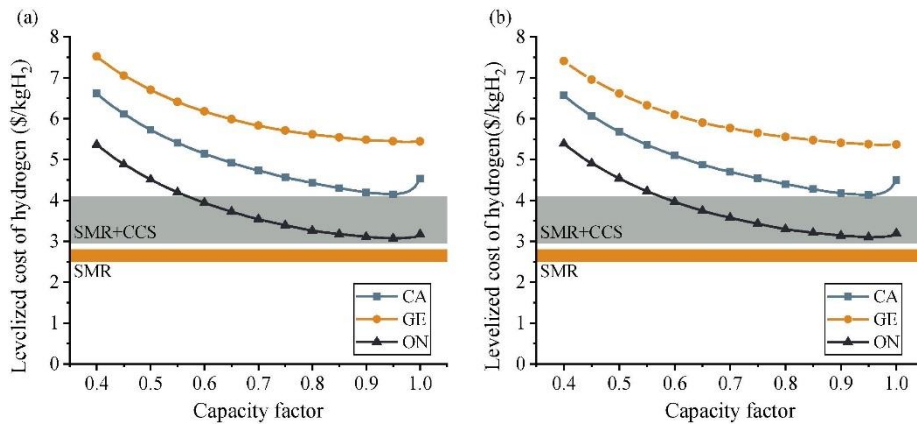


Figure 14. LCOH in three wholesale electricity markets as a function of capacity factor: (a) Alkaline electrolysis underground storage, (b) Proton exchange membrane electrolysis underground storage (CA=California; GE=Germany; ON=Ontario).

Source: Taken from Ref. [31] with permission from Elsevier.

LCC analysis is conducted on PEM electrolysis by Zhao *et al.* [32]. The results show that hydrogen costs for energy applications are higher than fossil fuels. The scale and geography may affect the costs of the system since research is conducted on the Orkney Islands. Other reasons include high electricity consumption and lesser renewable energy sources for the power grid (Figure 15).

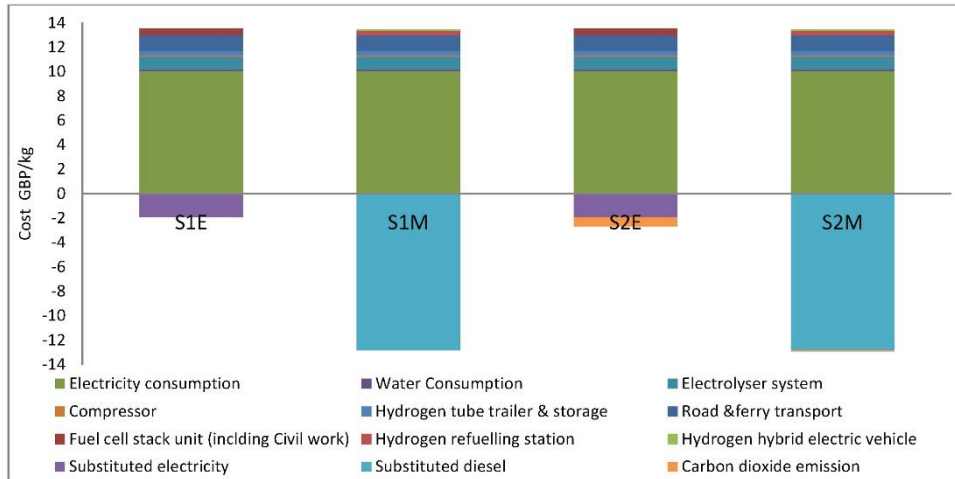


Figure 15. LCC analysis of hydrogen in four scenarios.

Source: Taken from Ref. [32] with permission from Elsevier.

Pozo *et al.* [18] found that co-gasification of coal and biomass is potentially a viable alternative to natural gas or electrolysis. Approximately 30% cost reduction can also be generated by recovering waste heat from hot water production. The study by Valente *et al.* [33] incorporates an overall evaluation of environmental, cost, and social indicators. The levelised cost of hydrogen (LCOH) from biomass gasification is approximately 1.7 times higher than SMR (Figure 16). Improvements to system efficiency, feedstock and labour reduction can improve the economic performance of biomass gasification.

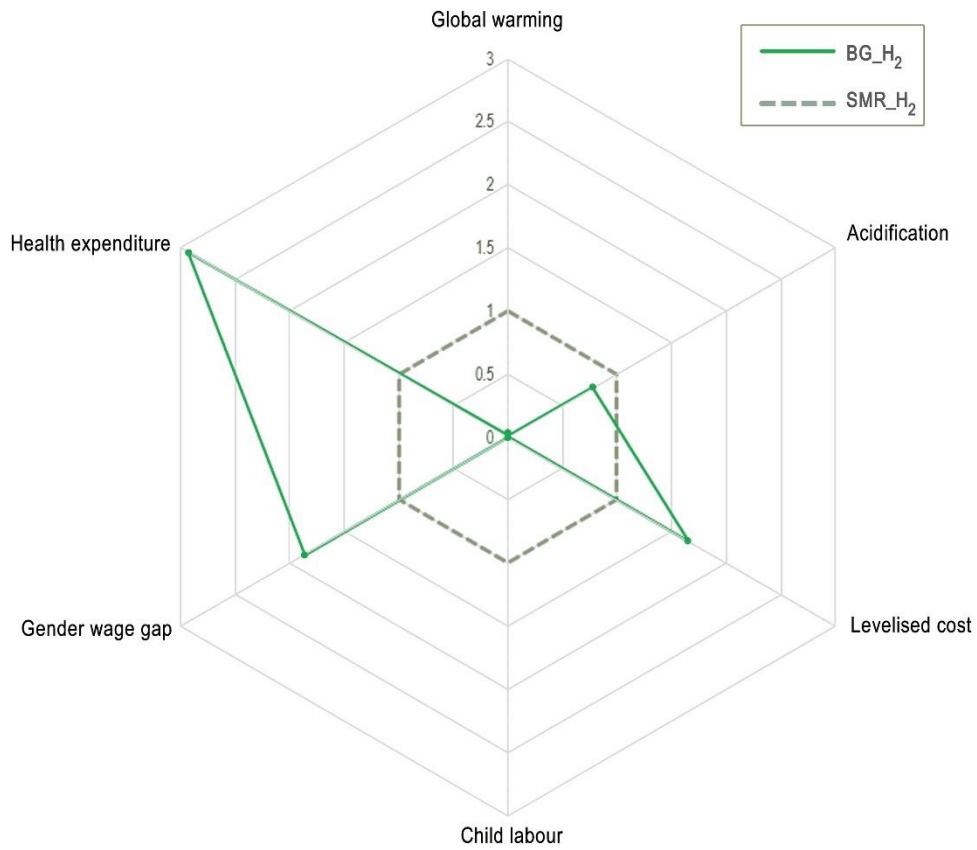


Figure 16. Comparison of environmental, economic, and social performance of hydrogen from Biomass Gasification (BG) and Steam-Methane Reforming (SMR).

Source: Taken from Ref. [33] with permission from Elsevier.

5. Conclusion

Hydrogen is rapidly gaining momentum. Decarbonisation efforts in advanced methods for hydrogen production are ongoing in countries like Singapore, Japan, China, and the United Kingdom. Challenges relating to technical and non-technical barriers relating to its production and sustainability are still present. The current mainstream technologies (SMR and CG) are to obtain hydrogen from natural gas and coal. However, hydrogen produced from fossil fuels resulted in high carbon dioxide emissions. SMR and CG can be coupled with CCS for lower carbon dioxide emissions. With the use of renewable energy sources, other environmental impacts can potentially be reduced.

Electrolysis and BG are potential emerging hydrogen production options. Although they have lower environmental impacts with renewable energy usage, the hydrogen production cost is higher than SMR and CG. Factors influencing the production cost include investment costs, location, system efficiency, electricity consumption, labour and operational requirements.

Other than the above-mentioned pathways, there are other promising pathways such as white and aquamarine hydrogen. White hydrogen is made by solar catalytic thermochemical water splitting with concentrated solar energy, and aquamarine hydrogen, is made by methane solar thermal pyrolysis in the presence of a carbon catalyst [34].

This review shows the importance of investigating the entire life cycle of hydrogen production options for a well-rounded sustainability assessment in terms of environment and cost. All in all, more research and development of emerging hydrogen production options are required at a larger scale to establish their potential for better economic and environmental costs.

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