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A review on global warming potential, challenges and opportunities of renewable hydrogen production technologies

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ABSTRACT

This review compares global warming potential of renewable hydrogen production technologies including wind- and solar PV-powered water electrolysis, biomass gasification and biogas reforming based on 64 hydrogen production cases compiled from the literature. Unlike many previous studies, this review discusses the cases from various countries, while selecting the production technologies that have potential of commercialisation. Among the four reviewed technologies, wind electrolysis performed the best in global warming impacts (1.29 kg CO_2 eq/kg H_2), whereas biogas reforming technology performed the worst (3.61 kg CO_2 eq/kg H_2). Key factors that contributed to most of the impacts were found to be materials used for construction of wind- and solar- electricity generation system for both wind- and solar PV-powered electrolysis, and energy consumption during gasification processes for biomass gasification, while methane leakage during biogas production had the highest contribution to the impacts of biogas reforming cases. On average, the renewable hydrogen cases demonstrated 68–92% lower global warming potential when compared to conventional coal gasification and natural gas steam methane reforming systems. Increasing demand for renewable hydrogen and possibility of hydrogen being integrated into existing natural gas networks highlight the important role of renewable hydrogen production in the future.

1. Introduction

From the introduction of Kyoto Protocol in 1997 to the recent United Nations (UN) Climate Change Conference of the Parties (COP26), efforts to mitigate greenhouse gas (GHG) emissions have been witnessed in various industrial sectors, especially in the energy sector with increasing demand for clean energy production [1,2]. Among a range of clean energy options, renewable hydrogen is gaining increasing attention as a low-carbon energy carrier [3] which does not emit GHG emissions when used for energy generation [4]. Hydrogen has potential as an energy source to replace current use of natural gas (e.g., heat supply to industry and replacement of transport fuels) [5] with numerous advantages, such as flexibility of feedstock selection (e.g., from fossil fuel sources to waste materials) [6], marginal energy loss during transmission and wide applicability to fuel cells and various industrial sectors [1,7]. Once hydrogen is compressed to a desired pressure, it can be distributed through existing natural gas pipelines with minor technological modifications [1]. Currently, hydrogen is demanded from various industrial sectors, including oil refining (33%), ammonia manufacturing (27%), methanol production (11%) and steel production (3%), [8] with anticipated demand increase by almost sixfold in 2050, mostly driven by increasing demand from the steel and ammonia industries (Fig. 1-a and 1-b) [9,10].

Hydrogen can be produced from both renewable and non-renewable sources (see Fig. 2). Nevertheless, global hydrogen production in 2020 almost entirely relied on fossil fuel sources with only 0.7% was produced from natural gas with carbon capture, utilisation and storage (CCUS) out of the total production of 90 Mt. (million tonnes) (Fig. 1-b) [11]. Despite the impressive increase in the low-emission hydrogen production in 2021 (almost 20% increase compared to 2020, including hydrogen from natural gas with CCUS and water electrolysis), it still comprised a mere fraction of total production, with only 1 Mt. of low-emission production out of 94 Mt. of global hydrogen production in 2021, while natural gas remained as the major source of hydrogen production, which resulted in

Abbreviations: AD, Anaerobic digestion; ATR, Auto thermal reforming; BG-reform, Biogas reforming; BMG, Biomass gasification; CCS, Carbon capture and storage; CCUS, carbon capture, utilisation and storage; CG, Coal gasification; GHG, Greenhouse gas; GWP, Global warming potential; LCA, Life cycle assessment; PEM, Proton exchange membrane; POX, Partial oxidation; PV, Solar photovoltaic; PV-elec, Solar PV-powered electrolysis; SCWG, Supercritical water gasification; SMR, Steam methane reforming; SOEC, Solid oxide electrolysis cells; SR, Steam reforming; W-elec, Wind-powered electrolysis.

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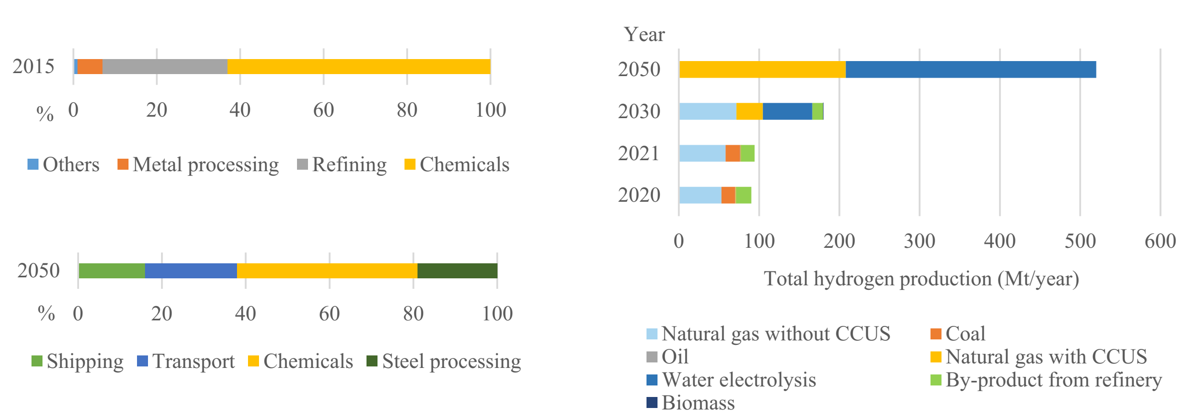
630 Mt. of direct CO_2 emissions (7% of emissions from industrial sectors) from the fossil-based hydrogen production in 2021 [12]. In order to minimise the emissions from hydrogen production, replacing natural gas with renewable sources is essential [13]. Various low-emission hydrogen production technologies are available, including forementioned water electrolysis, biomass gasification and fossil-based production with CCUS [11], which have been discussed in several countries as future energy options. For instance, Japan has announced their plans to produce hydrogen using only renewable electricity, while US intends to increase hydrogen production from biomass gasification [14]. As of 2018, around 70 ongoing projects, mostly in Germany, have been identified as renewable-sourced hydrogen production [15]. However, these low-emission technologies only share about 1% of the current global hydrogen production [12].

One possible reason that hinders expansion of the low-emission hydrogen could be high production cost. Levelised production cost of natural gas-based hydrogen ranges between US\$ 0.5/kg H_2 to \$ 1.7/ kg H_2, which could be doubled (up to 4 times) when CCUS is applied [11]. Although the cost of water electrolysis is greatly affected by the cost of electricity [16], the average production cost of renewable water electrolysis is currently about 6–16 times higher than natural gas-based hydrogen [11], with the potential cost reductions to US\$ 1.3–2.4/ kg H_2 for solar-powered electrolysis and US\$ 1.1–2.5 /kg H_2 for wind-powered electrolysis in 2030 [17]. Another challenge of low-emission hydrogen is lack of infrastructure for stable supply and transmission of the hydrogen [10]. This could be of particular problem where large-scale and long-distance hydrogen transmission is necessary. A study by [18] addressed this issue for China where renewable sources available for hydrogen production and gas supply networks are unevenly distributed. The study concluded that utilising existing natural gas pipelines for inter-province transmission of renewable hydrogen would be optimal, while the use of combined natural gas pipelines and dedicated hydrogen pipelines could only be feasible when unit transmission cost is reduced to a certain degree. Storage of hydrogen is also considered as challenging. Liquified hydrogen requires less storage volume than gaseous hydrogen but energy loss and energy consumption during the liquefying processes are disadvantageous. Storage of gaseous hydrogen, on the other hands, requires specifically-designed storage tanks that can withstand high pressure, but materials suitable for the tanks and infrastructure for transporting the hydrogen still seek for technological and economic advancement [19].

The renewable electricity-operated production system is also referred to as green hydrogen, while hydrogen from natural gas with CCUS is referred as blue hydrogen with methane pyrolysis is also included in the blue hydrogen in some studies [20]. Methane pyrolysis (also known as methane decomposition or methane cracking), one of the emerging technologies according to the recent report by IEA [11] is another fossil-based production but it does not create any direct CO_2 emissions, instead it enables carbon sequestration by producing solid carbon as a by-product. Due to its unique production processes, it is also referred as turquoise hydrogen in some cases [21]. Current primary hydrogen production technologies, fossil-based production without emissions abatement, are classified as grey hydrogen [22], although this colour coding system does not fully interpret the life cycle impacts of various hydrogen production processes [3]. Green hydrogen is often considered as the cleanest [23], but when emissions during certain production stage is considered (e.g., manufacture of solar cells, for details see Section 3.2. and Table 3), it is not carbon emission free. While some studies use different colour codes interchangeably (for example, hydrogen production by coal gasification is classified as grey hydrogen [22] but in some studies, it is classified as brown hydrogen [21]), China, the world's largest hydrogen producer, established standard for defining grey, low-carbon, clean and green hydrogen by setting up emission threshold for each production pathway [24]. Based on the GHG emission from coal gasification (29.02 kg CO_2 eq/kg H_2), which is the major production pathway in China (about 63% of total production in 2020), emissions threshold of low-carbon and clean hydrogen is set at 14.51 kg CO_2 eq/kg H_2 and 4.9 kg CO_2 eq/kg H_2, respectively, while green hydrogen has the threshold below 4.9 kg CO_2 eq/kg H_2 [24].

Theoretically, all wind and solar energy could be used to produce hydrogen, but when technical constraints (e.g., land availability and collectable energy based on current technologies) are considered, the usable amount of those energy sources could be reduced. From an economic perspective, this amount could be further reduced due to the high production cost, which makes clean hydrogen less competitive in energy market [17]. Based on the anticipated cost reduction in clean hydrogen production as well as significant increase in the capacity of electrolyser, the production of green and blue hydrogen is estimated to reach 61.7 Mt. and 33 Mt. out of total production of 180 Mt. in 2030, respectively (see Fig. 1-b) [25], while global hydrogen production will almost entirely be produced from renewable sources by 2050, with more than 60% as green hydrogen and around 40% as blue hydrogen [10].

Low-emission hydrogen production technologies include electrochemical (e.g., biofuel-powered water electrolysis), thermochemical (e.g., water splitting using solar thermal energy) and biological processes (e.g. fermentation of biomass) [13,26], but many of these technologies have not yet been commercially produced due to low production efficiency, high production cost, and lack of production and distribution



(a) **(b)**

Fig. 1. Current and future hydrogen demand and production; (a) Industrial profiles of hydrogen demand in 2015 and 2050; (b) Current and projected hydrogen production technologies.
* Reproduced based on [10–12,14,16,25].

infrastructure [26–29]. Other Low-emission technologies, including biomass gasification, reforming of biomethane and renewable energy-based water electrolysis, are considered technologically mature with potentials to be produced at commercial scale today or in the near future [13,32,33]. Many of these technologies have been studied, mostly focusing on technological or economic aspects, such as investigating the influence of effective use of catalysts [34], optimising process configurations for higher hydrogen yield [35], estimating production cost and profitability [36–38] or comparing advantages and disadvantage of various technologies [39,40]. Fan et al. [41] studied the production cost of low-emission hydrogen with considering regional differences in China that would affect applicability of various types of the low-emission technologies, and concluded that coal gasification with CCUS would become cost-competitive in north-western part of China in the future, while wind- and solar-powered electrolysis could be economically viable in Gansu and Chongqing province, respectively.

In order to achieve low-carbon hydrogen economy, it is important to understand emissions and consequent impacts of clean hydrogen production technologies. Life cycle assessment (LCA) enables estimating significance of various environmental impacts of selected production processes from a life cycle perspective by evaluating energy, material and waste flows during the entire processes [29,42]. Emissions from a process differs depending on the types of technology due to different extent of material and energy requirements of the process. In case of solar photovoltaic (PV) hydrogen production, input materials and process energy required to manufacture PV modules as well as to construct solar energy systems contribute to most of the life cycle emissions of solar-based hydrogen production [29], whereas majority of emissions from conventional steam methane reforming hydrogen production is attributed to the feed fuel [43]. Thus, understanding emissions from a life cycle perspective is critical for understanding sustainability of hydrogen production technologies.

Battista et al. [44] performed both material and complete LCA for hydrogen production from biogas reforming to distinguish the impact of input materials from the impact of complete production processes. The study found that global warming impact was mostly attributed to purification process of produced hydrogen due to the metal use for constructing the purification unit, but when the complete life cycle was considered, biogas pre-processing was the most impactful process due to high energy consumption. Another review by Valente et al. [45] compared ten different renewable hydrogen production pathways with one conventional fossil-based production by applying harmonisation protocol created by the authors. Harmonisation of the reviewed studies may provide convenience in comparing the environmental impacts of various pathways by eliminating inconsistencies in methodological choices of the studies but subjectivity may be present during the harmonisation processes. Hajjaji et al. [46] also compared eight different renewable hydrogen production pathways including both fossil and renewable pathways, and concluded that biogas reforming was the least impactful pathway for hydrogen production. However, their study was only limited to the European region. Both Acar et al. [1] and Abdel-Basset et al. [47] compared sustainability of conventional and renewable hydrogen production technologies using multi criteria decision making tool which included social, economic and environmental criteria. Both studies presented their results by ranking the technologies according to the criteria without presenting the actual emission values which limits the interpretation when the impacts per unit of produced hydrogen are required. As such, previous studies have compared the environmental impacts of various hydrogen production pathways based on individual weighting or normalisation factors, while studies that present the actual impact values through life cycle impact assessment are still limited, especially for renewable hydrogen production pathways. This review aims to identify renewable hydrogen production technologies with low global warming potential by presenting and

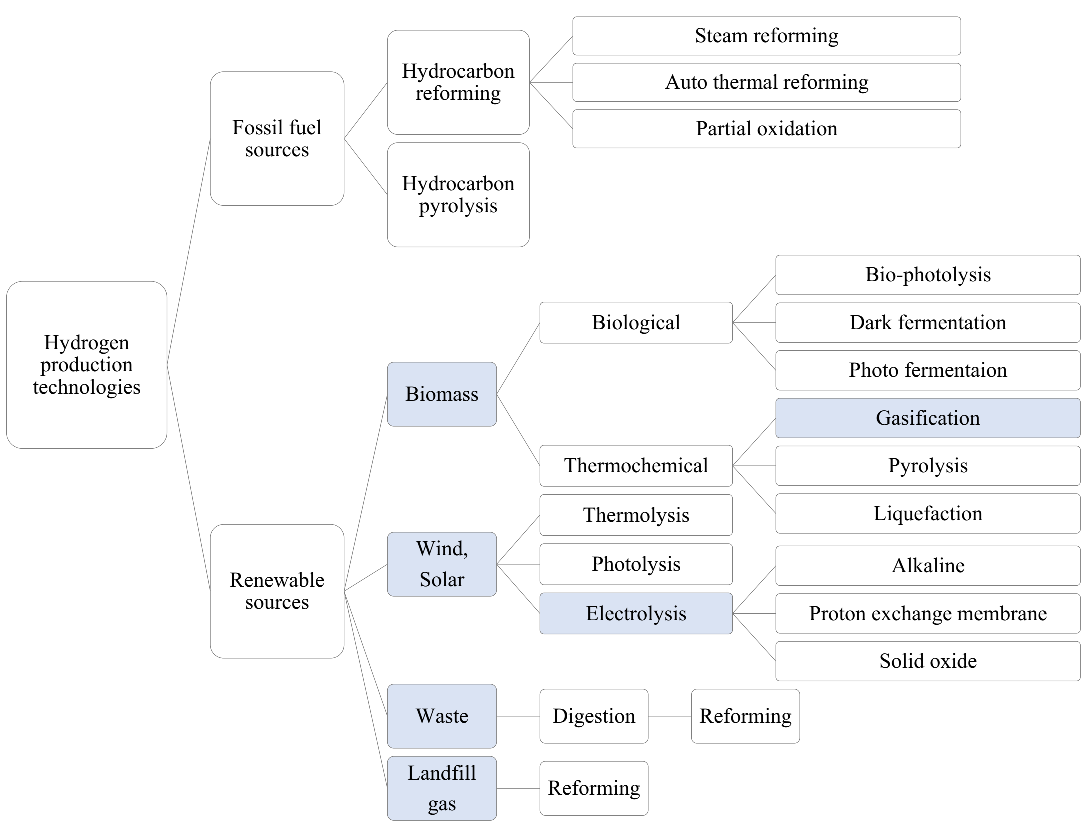


Fig. 2. Hydrogen production technologies.
* Boxes in light blue colour indicate the technologies considered in this review.
* Reproduced based on [30,31,54,55].

comparing actual emissions values reported in literature without weighting. The renewable hydrogen technologies include wind- and solar-powered water electrolysis, biomass gasification and biomethane reforming considering different methodological and technological factors. The significance of this review will include a comprehensive analysis of renewable hydrogen production cases reported from various countries in terms of the environmental impacts of each case with identifying the most impactful production processes as well as production efficiencies and the factors affecting the efficiencies. Literature was collected based on the primary hydrogen production technology and feedstock, and later classified according to system boundary, functional unit and location (Section 2). In Section 3, global warming potential (GWP) is compared according to the production technologies, while discussing the major contributors to different GWP values and comparing GWP of the renewable hydrogen systems with conventional ones. Challenges and opportunities in hydrogen industry are further discussed in Section 4.

2. Selection criteria

2.1. Selection of renewable hydrogen production technologies

Renewable hydrogen production technologies at commercial or near commercial readiness today are selected as the focus of this review. Brief description of the selected technologies, wind- and solar-powered water electrolysis, biomass gasification and biogas reforming technologies, and their current development status with other remarks are discussed in this section. Despite large-scale production of biogas, it has not been commercially used for hydrogen production, which makes the technology remains as pilot- or lab-scale production. Hydrogen production from renewable-powered electrolysis and biomass gasification are also in small- to medium- scale production with a few countries having commercial scale electrolysis projects (e.g., Germany and Denmark) [13,29].

2.1.1. Water electrolysis

While water electrolysis has almost no direct process emissions [29], the process is energy-intensive [43,48], thus the source of the process energy is directly linked to the overall GHG emissions of the system [49–51]. The process of water electrolysis involves splitting of water molecules into H and O by a supply of electrical energy [32,55], of which water is pre-treated (deionised) to prevent mineral deposition which can lead to undesired chemical reactions [43,52]. The process energy of current large-scale electrolysers is supplied mostly from fossil fuel-dominated grid electricity which has considerable GHG emissions [50], and in some cases, emissions from the electrolysis could be higher than natural gas steam reforming hydrogen production [4]. When fossil fuels in the grid electricity are replaced with renewable sources (82% hydro and 18% geothermal), up to 90% of potential emissions can be reduced [52]. Despite the great potential, less than 0.1% of the global hydrogen is produced by water electrolysis [8].

Electrolysers can be integrated with wind or solar electricity system [43], and the integration does not only reduce emissions [4] but also enables effective valorisation of renewable sources [48]. Wind and solar energy systems are already well-established and available for commercial-scale hydrogen production [13,53,56]. Recently, several countries have demonstrated commercial scale water electrolysis with the potential integration with solar and wind energy [8], and some examples include successful demonstration of the world's first 1000 t scale hydrogen production via solar PV electrolysis with improved efficiency using alkaline electrolyser in China in 2020 [48] and large-scale wind electrolysis projects in both Germany and Denmark, although the projects are connected to grid [29]. Grid-assisted electrolysis system is already in its technological maturity with high production efficiency and lower establishment cost comparing to the 100% renewable source-assisted system, thus this system is likely to be used in the short term in order to meet the demand for energy [1] and to overcome the intermittency issues in energy supply for wind and solar electrolysis. Expanding the production of 100% renewable-sourced hydrogen could be achieved by increasing capacity and corresponding cost reductions in renewable electricity production [29,48,57].

2.1.2. Biomass gasification

Biomass gasification is another promising option for utilising waste biomass [43,58] by converting into valuable energy product with higher energy density [4,59] through a high-temperature process (between 500 and 1400 °C) [43]. The temperature of gasification process affects product gas quality as well as total energy requirement of the gasifier, with the low process temperature resulting in lower gas quality [60]. Applying catalyst (e.g., sulphur) to the gasifier has been reported to lower the gasification temperature while maintaining the gas quality, thus increasing process efficiency [60]. The conversion of biomass produces syngas mainly consisting of CH_4, H_2, CO, CO_2 and N_2 with some minor species which are later removed during syngas cleaning [61]. Before the cleaning process, tar removal is also performed to enhance the syngas production and quality [62]. Thermochemical conversion of biomass to hydrogen can be performed through various pathways, including pyrolysis, gasification and liquefaction, and among these, gasification is reported to have higher hydrogen yield per unit of biomass with higher production efficiency, which makes gasification more attractive [58,63]. However, in order to achieve favourable production efficiency of conventional gasification, moisture content of biomass should be reduced before gasification, and during which process, additional energy is required. To overcome this shortfall, supercritical water gasification (SCWG) has been suggested. SCWG is not only more efficient but also accommodates a wide range of biomass with higher moisture content [64,65], although higher production cost, safety issues during its operation due to high temperature and pressure and corrosion of reactor cause by solid deposition from using salt- or lignin-containing biomass remain as obstacles for upscaling of SCWG [64]. A recent study by Takeda et al. [66] presented better environmental performances and efficient use of feedstock than conventional biomass gasification by integrating solar energy system into indirect gasification of biomass. Their novel design enables solar thermal energy to fully supply required heat for the gasifier, allowing the whole fraction of biomass feedstock being used for hydrogen production without being partially combusted for the heat supply. The full utilisation of the biomass for gasification achieved 61% reduction in global warming impact than conventional gasification (from 2.67 kg CO_2 eq/kg H_2 to 1.04 kg CO_2 eq/kg H_2). A range of biomass, including agricultural (e.g., corn stover) and industrial (e.g. wood and paper) waste, as well as municipal solid waste can be used as a gasification feedstock [32,63]. The gasification technology has already reached its maturity with potential of being integrated into various industrial processes [26,67]. Biomass gasification has drawn attraction in several countries including initiatives from the US, Germany, Scandinavia, France and UK indicating increasing hydrogen production from biomass gasification [14].

2.1.3. Biogas reforming

Rapid development and urbanisation have led to increasing amount of solid waste and about 5% of global GHG emissions are attributed to the solid waste [61]. Waste materials created by natural or anthropogenic activities are considered as potential renewable energy sources in waste-to-energy conversion processes [61]. The conversion of waste materials does not only produce heat but also generates other types of energy, including hydrogen, which can assist to reduce the dependence on fossil fuel energy sources while creating additional economic values [67]. Biogas (also referred to as biomethane), mostly consists of CH_4 and CO_2 [44,68,69]. It can be produced from a wide range of waste materials, such as organic solid wastes, agricultural waste, landfill gas, waste sludge and animal manure by an anaerobic digestion (AD) process [32,44,46,61,68,69]. However, low overall process efficiency of AD due to additional processes required for removing impurities in the biogas and low efficiency of methane recovery could be a hurdle for AD system to be used for hydrogen production [70].

Once biogas is produced, it is further reformed to produce hydrogen by steam reforming (SR), auto thermal reforming (ATR) or partial oxidation (POX) process [27], with SR being the most widely used process, during which, high-temperature steam and catalyst can be added to effectively convert the biogas to gas mixtures of H_2, CO_2, CO and CH_4 although the gas composition is also affected by digested material, reforming pressure and steam-to-carbon ratio [32,46]. CO_2 emissions during the conversion of biogas to hydrogen is considered as biogenic, thus biogas reforming is a promising renewable hydrogen production option [68]. Potential of biogas as a hydrogen production feedstock has already been demonstrated with a favourable yield of biogas, while reducing emissions from direct use of biogas (e.g., examples are found in Bangladeshi and Nigeria) [23,71]. Also, a recent study found that industrial-scale biogas reforming for hydrogen production could achieve desirable hydrogen yield [72].

2.2. Selection of literature

Peer-reviewed literature on renewable hydrogen production technologies were first gathered regardless of technology, type of feedstock and production scale, in order to determine which technologies will be included in this review. Later, the literature selection was performed based on the near-term commercial viability of technologies with an effort to select recently-published articles. A total of 32 publications published between 2008 and 2021 were selected with 64 renewable hydrogen production cases, including wind- and solar PV (photovoltaic)-powered electrolysis, biomass gasification and biomethane reforming technologies (seeTable 1, Fig. 2 and Supplementary Table S1 for full details). 15 out of 32 publications were based on EU countries, 7 from North America, two from Asia and one from each Middle East and Oceania. The remaining 6 publications did not specify the study locations. The older publications were only used to describe technological background of hydrogen production. Among various environmental impacts, global warming potential (GWP) was discussed in all reviewed literature where GWP was estimated based on 100-year time horizon. GWP can be used to understand overall emissions of a system because it converts greenhouse gas emissions into CO_2 equivalent [32], and it is widely accepted proxy for understanding the environmental impacts of a system [42], thus this review focuses on GWP as the LCA parameter of concern.

Table 1
Selection of literature and system boundary.

Reference	H_2 production technology				System boundary		Country
	W-elec	PV-elec	BMG	BG-reform	First stage	Last stage	
Valente et al. (2020) [73]	√				Wind turbine manufacture	H_2 compression [a]	Spain
Koj et al. (2015) [74]	√				Wind turbine manufacture	H_2 production [b]	Spain
Ghandehariun and Kumar (2016) [75]	√				Wind turbine manufacture	H_2 compression	Canada
Valente et al. (2021) [76]	√		√		Biomass supply	H_2 compression	Spain
Patyk et al. (2013) [77]	√				Wind turbine manufacture	H_2 compression	Europe
Suleman et al. (2016) [56]	√	√			Not specified	Not specified	N.A.
Cetinkaya et al. (2012) [78]	√	√			Wind turbine and PV manufacture	Plant disposal [c]	Canada
Reiter and Lindorfer (2015) [79]	√	√			Process energy supply [d]	H_2 production	Europe
Al-Qahtani et al. (2021) [20]	√	√	√		Feed production [e]	H_2 production	US
Parkinson et al. (2019) [58]	√	√	√		Feed production	H_2 production	N.A.
Pereira and Coelho (2013) [80]	√	√	√		Feed production	H_2 compression	Portugal
Miller et al. (2020) [81]	√	√			Process energy supply	H_2 production	N.A.
Simons and Bauer (2011) [67]	√	√	√		Feed production	H_2 compression	Europe, Spain [f]
Mehmeti et al. (2018) [43]	√		√		Feed production	Material recycling [g]	N.A.
Sadeghi et al. (2020) [28]		√			PV module manufacture	Plant disposal [h]	Iran
Palmer et al. (2021) [29]		√			PV module manufacture	H_2 compression	Australia
Marshall et al. (2017) [33]		√	√	√	Feed production [i]	H_2 production	North America
Wulf and Kaltschmitt (2013) [51]			√	√	Feed production	H_2 production	Germany
Susmozas et al. (2013) [82]			√		Biomass production	H_2 production	N.A.
Iribarren et al. (2014) [62]			√		Biomass production	H_2 production	N.A.
Salkuyeh et al. (2018) [83]			√		Biomass pre-treatment	H_2 production	Canada
Li et al. (2020) [84]			√		Biomass production	H_2 production	China
Siddiqui and Dincer (2019) [4]			√		Biomass collection	H_2 compression	US
Martín-Gamboa et al. (2016) [85]			√		Biomass production	H_2 production	Spain
Koroneos et al. (2008) [86]			√		Biomass collection	H_2 production	Greece
Zhou et al. (2021) [32]			√	√	Feed production [j]	H_2 production	Europe
Antonini et al. (2020) [87]				√	Biogas supply	H_2 compression	Europe
Hajjaji et al. (2013) [46]				√	Biogas production	H_2 production	France
Hajjaji et al. (2016) [68]				√	Biogas production	Plant disposal [c]	US
Yoo et al. (2018) [88]				√	Landfill gas collection	H_2 production	Korea
Battista et al. (2017) [44]				√	Biogas supply	H_2 production	Germany
Di Marcoberardino et al. (2019) [89]				√	Biogas supply	H_2 production	Europe

For references, see the numbers in square bracket.
Abbreviations: W-elec (wind-powered electrolysis), PV-elec (solar PV-powered electrolysis), BMG (biomass gasification), BG-reform (biogas reforming).
[a] Hydrogen compression indicates the system boundary includes hydrogen compression process.
[b] Excluding hydrogen compression.
[c] Plant disposal includes hydrogen plant decommissioning.
[d] Process energy supply indicates supply of energy from wind and solar power station to hydrogen plant.
[e] Feed production indicates biomass production for BMG cases, while electricity generation for W-elec and PV-elec.
[f] Assessment for W-elec was performed based on Europe, while PV-elec was based on Spain.
[g] Final production stage includes recycling of hydrogen plant construction materials.
[h] Excluding hydrogen compression.
[i] Feed production indicates electricity generation for PV-elec, biomass production for BMG and biogas production for BG-reform.
[j] Feed production indicates biomass production for BMG and biogas production for BG-reform.

3. Comparison of LCA studies

3.1. GWP of different renewable hydrogen options

The reviewed publications exhibited great variations in reported GWP values (Fig. 3) with the wind-powered electrolysis (W-elec) having the lowest average GWP followed by biomass gasification (BMG) with the average GWP values of 1.29 kg CO_2 eq/kg H_2 and 1.67 kg CO_2 eq/kg H_2, respectively (Table 2). Biogas reforming (BG-reform) showed the greatest deviation with the lowest GWP found in cases where large carbon credits were given to the digestate, a by-product of biogas processing, when used as a fertiliser and its carbon sequestration potential by avoided use of mineral fertiliser, as well as carbon uptake during biomass cultivation [87]. Although carbon credits were applied to the digestate use in two different production cases (Hajjaji et al. [68] and Antonini et al. [87]), greater assumptions on the credit values in the study by Antonini et al. [87] led to lower overall GWP. Other studies also reported very low or even negative GWP values by taking into account the avoided fossil fuel use for hydrogen production processes by applying the produced biomethane as a process energy and as a feedstock for hydrogen production [32]. Generally, negative GWP values are found among various renewable hydrogen production cases where credits are applied to any by-product or surplus energy produced during the whole system operation [45]. However, only two out of the reviewed 18 BG-reform cases had negative GWP values which resulted in the highest average GWP of BG-reform among the four reviewed hydrogen production technologies. Among the three types of biogas reforming processes (see Section 2.1.3), steam reforming tends to have lower GWP (2.9 kg CO_2 eq/kg H_2) because of its higher process efficiency and lower feedstock requirement with a proportion of the moisture and CO_2 in the waste materials improving the process efficiency by acting as steam [68]. Considering methane emissions have higher impact than CO_2 (28 times higher than CO_2), greater assumptions on methane leakage during the biogas production can affect the overall emissions for BG-reform systems [28,46]. It should be noted that the reviewed studies employ various types of LCA methods with different impact factors applied to the emissions of CO_2, CH_4 and N_2O, the pollutants that are commonly used to estimate GWP [88]. The impact factor of CH_4 by GREET v1.6. is 21 whereas by ReCiPe2016 method, it becomes 34 [90,91]. Given the CH_4 emissions from hydrogen production by wind-powered electrolysis is 0.3 g/kg H_2 [78], when this emission is converted to CO_2 equivalent emission, it becomes 6.3 g CO_2 eq/kg H_2 by GREET, while 10.2 CO_2 eq/kg H_2 by ReCiPe2016 method (for details about the LCA method for each reviewed study, see Supplementary Table S1). Since detailed emissions are not explicitly discussed in the studies, normalisation of GWP based on the applied LCA methods are unfeasible, thus cautions should be made when directly compare the GWP of various studies.

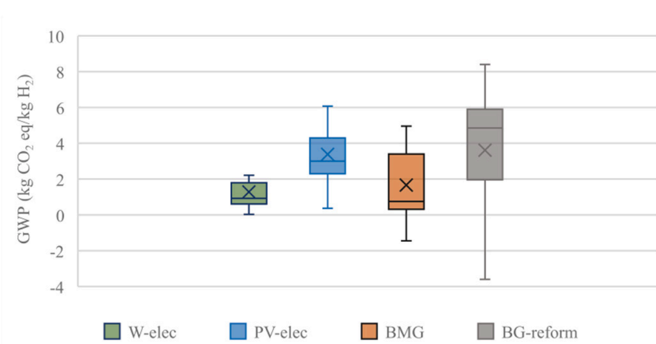


Fig. 3. Distribution and average GWP values of 64 renewable hydrogen production cases.
*Abbreviations: W-elec (wind-powered electrolysis), PV-elec (solar PV-powered electrolysis), BMG (biomass gasification), BG-reform (biogas reforming).
*Point X in each box indicates the average GWP value.
*This figure is drawn based on the GWP values in Table 2. For detailed references, see Table 1.

Table 2
Average, minimum and maximum GWP values.

	Renewable hydrogen production technology			
	W-elec [a]	PV-elec	BMG	BG-reform
Average GWP [b] (kg CO_2 eq/kg H_2)	1.29 (± 1.15)	3.38 (± 1.86)	1.67 (± 1.79)	3.61 (± 3.38)
Min	0.03	0.37	−1.45	−4.8
Max	5.10	7.50	4.96	8.4

[a] Abbreviations: W-elec (wind-powered electrolysis), PV-elec (solar PV-powered electrolysis), BMG (biomass gasification), BG-reform (biogas reforming), GWP (global warming potential), Min (minimum value found in the reviewed studies), Max (maximum value found in the reviewed studies).
[b] Average GWP values are; the average of each 16 W-elec cases, 11 PV-elec cases, 19 BMG cases and 18 BG-reform cases. For the reference of each case, see Table 1.

In terms of hydrogen yield, additional steam (steam to methane ratio of 3) and increasing reforming temperature (around 800 °C) appear to increase hydrogen yield [68], but additional water and energy consumption for supplying the steam could increase system inputs, thus negatively affect overall sustainability of the system. Biogas from AD of agri-food waste presents a great potential with lower feedstock requirement than other waste materials for producing a unit of hydrogen, although the yield is also affected by chemical composition of the biogas [44]. The feedstock and water requirements based on the type of feedstock and production technologies are further discussed in Section 3.3.

Negative GWP values were also found in three of the 19 BMG cases where emission compensations during biomass cultivation were taken into account, and additional carbon credits were assumed for avoided fossil energy use by applying surplus energy throughout the BMG process [62,83]. In contrast, the highest GWP (4.96 kg CO_2 eq/kg H_2) was found in the case where contribution of biomass production and transport to total GWP was assumed to be much greater than the other studies (39.4% contribution to total GWP) [84], while the second highest GWP was found where no credits were applied to any of the processes or co-products [33]. Among different types of gasifiers (fluidised bed gasifier, entrained gasifier and indirect gasifier), indirect gasifiers tended to have lower GWP values possibly due to heat supply by char combustion in a separate reactor [82]. Since the heat supply for indirect gasification takes place in a separate reactor, there is a lower chance for the produced syngas to be contaminated by other combustion co-products (e.g. nitrogen), while preventing its combustion in the gasifier [59,83]. In addition, only steam is injected to the indirect gasifier together with biomass, whereas both steam and air are used in direct gasifier, thus, nitrogen is present in the produced syngas by direct gasification which results in lower hydrogen concentration than from the indirect gasifier [59,69,92]. Similar to the biogas reforming, adding steam to the gasification process (increasing steam to biomass ratio) improves the hydrogen yield with low tar formation by increased carbon conversion efficiency [59,62,92], although maintaining high gasification temperature (~ 800 °C) is essential [93]. According to Dincer [30] increasing the steam-to-biomass ratio to 4.7 with gasification temperature of 800 °C yielded more hydrogen, but when the temperature decreased to 750 °C, steam-to-biomass ratio of 0.51 appeared to be the optimal condition. Type of biomass and required pre-treatment processes for the biomass also influenced the GWP with inclusion of impact of diesel and agrochemical use during biomass production, and additional pre-treatment processes (e.g., drying or chipping) resulting in higher emissions during the biomass production and supply processes [51].

Since water electrolysis system requires electricity and water as major inputs, upstream processes, including manufacture of solar PV modules and wind turbine, as well as process energy requirements, have the greatest influence on the overall GWP [50,51]. The highest GWP in W-elec cases was found where considerable amount of natural gas consumption was assumed as part of the energy. This system had relatively lower energy requirement per unit of hydrogen than the other cases (36.1 kWh/kg H_2 and 51–58 kWh/kg H_2 for this case and other cases, respectively) [28,43,73,74], indicating assumptions on fossil energy use in the production process result in high GWP. Among the three types of electrolysers, alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC), alkaline electrolyser is the most common system in commercial production [26,55] with recent expansion of PEM electrolysers [26,94]. SOEC has been reported to be the most electrically efficient among the three types although it is less developed [26]. However, no clear relationship between the efficiency of electrolyser and GWP was found in this review. Overall, PV-elec cases had higher GWP than W-elec with solar PV modules and associated structures having more significant impact on total GWP than electrolysis process components [20,29].

3.2. Stage contribution

Contribution of each production process to the total GWP differs according to the applied hydrogen production technology with required energy and materials as system inputs. As summarised in Table 3, GWPs of the W-elec and PV-elec cases were mostly attributed to the electricity generation system with ranges between 78 and 97% for W-elec and 88–99% for PV-elec which included material use and embedded energy for manufacturing of wind turbines and solar PV modules as well as constructing power plants with only minor impacts of the electrolysis process (4–11.5% contribution rate for electrolysis process) [52,75,77,78]. Metals and other materials used for production of different components in wind and solar electricity generation systems, such as wind turbine, wind stacks and solar cells with the cell frames accounted for most of the upstream process impacts (a and b in Table 3) with up to 90% of emissions being attributed to the use of metals [50,52,74].

Although off-gas produced during biomass gasification was used as part of process energy in some cases, overall energy requirements to promote effective gasification processes had the highest contribution to total GWP of BMG (59–66%), while the additional production processes, including syngas cleaning and tar removal processes, contributed to 22–38% of total GWP. Energy consumption for collection and pretreatment of biomass (e.g., drying biomass for reducing moisture content and hiring heavy duty vehicles for collecting large-volume biomass) resulted in 18% of the total GWP [62]. Although carbon absorption during biomass production largely compensated the overall emissions from BMG, much higher emissions in the following production processes, contributing to 81–97% of the total GWP (sum of c and d in Table 3) led BMG to have positive GWP in 16 out of 19 cases. Fertiliser and diesel use during biomass production and transport of biomass exhibited risks in increasing some environmental impacts other than GWP (e.g., acidification, eutrophication and photochemical oxidant formation) [62,82]. In case of BG-reform system, biogas production was the single most impactful process mainly due to the assumptions of 1–5% of methane leakage from the AD plants (e in Table 3).

Table 3
Major contributor to total GWP.

H_2 production technology	Production process	Contribution (%)
W-elec	Manufacture of wind turbine and wind electricity plant operation [a]	78–97
PV-elec	Manufacture of solar PV module and solar electricity plant operation [b]	88–99
BMG	Process energy demand [c]	59–66
	Gasification, tar removal and syngas cleaning [d]	22–38
BG-reform	Biogas production [e]	89–99

Abbreviations: W-elec (wind-powered electrolysis), PV-elec (solar PV-powered electrolysis), BMG (biomass gasification), BG-reform (biogas reforming).
Reproduced based on [20,29,44,46,51,52,62,68,73–75,77,78,82,85,95,96].
[a] Metal and other material use for constructing wind turbine and wind stack account most of the contribution.
[b] Metal and other material use for constructing solar cells with the cell frames and cell stacks account most of the contribution.
[c-e] Major contributors to GWP of each hydrogen production technology.

Due to inconsistent system boundaries among LCA studies, inclusion or exclusion of particular production processes can lead to discrepancy in GWP values. Majority of the reviewed studies began with feedstock production (e.g., biomass cultivation) as the first stage of the production life cycle, while other studies considered feedstock supply at the hydrogen plant gate as the first stage. For instance, transport of solar PV modules to hydrogen plant contributed to about 8% of total GWP by assuming 310 km of transport distance [28], while another study concluded insignificant contribution of transport distance to total GWP [46]. About 65.5% of the reviewed studies considered hydrogen purification as the last production stage (see Supplementary Table S1), but the rest of the studies considered hydrogen compression, one of the most energy consuming processes as the last production stage. Energy consumption during the compression process was assumed to be between 1.2 and 3.8 kWh/kg H_2 [73,76] which contributed to about 17.5–22% of the total GWP [52,75,78]. In the case where hydrogen was already compressed to high-pressure during the production prior to the compression stage, energy consumption by the compression process only contributed to 1% of GWP [29].

3.3. Energy and feedstock requirement

Successful establishment of renewable hydrogen production system may depend on process energy and feedstock requirements of the system because these are key aspects of determining the overall process efficiency and hydrogen yield [62]. In many case studies, energy requirements have been used as a parameter to estimate the overall process efficiency and to identify the most energy consuming processes [68]. In case of electrolysis, energy requirement and source of the energy with corresponding energy conversion system are considered as the major factors that affect the production cost and environmental impacts of the system [43]. As presented in Table 4, electrolysis system exhibits the highest energy requirements although the process efficiency is the highest among the three hydrogen production technologies. Assumptions on high energy requirements of electrolysis appeared to have higher GWP among the reviewed cases, with 62% decrease in GWP (from 3.08 to 1.17 kg CO_2 eq/kg H_2) when the energy consumption decreased from 57.5 to 50.9 kWh/kg H_2. A study by [79] also pointed out on the influence of energy requirement on GWP of electrolysis system with 86.8% and 97.4% increase in GWP in wind- and solar-powered electrolysis systems when the energy requirement was doubled. The energy requirements are also associated with system efficiency. Although there was no strong relationship found in majority of the reviewed cases, electrolysis with lower energy requirements tended to have slightly higher process efficiency.

BMG had the lowest energy requirement per unit of hydrogen among the three technologies with average 8.3 kWh/kg H_2 (Table 4). BMG system can be designed to be self-sufficient in energy use by utilising off-gas and surplus energy produced during the gasification processes, while reducing external energy supply [62]. In some cases, total energy requirement of BMG was lower than that of conventional natural gas steam reforming process [82]. Together with the energy requirement, biomass or waste requirement also has a great impact on GWP because higher feed requirements coincide with higher energy consumption during the feed pre-treatment and supply processes, leading to lower overall process efficiency [82]. Feedstock requirement appeared to be higher in wood biomass (e.g., poplar) than agricultural residues (e.g., corn straw) possibly due to higher moisture content in woody biomass

Table 4
Process energy, feed and water requirements with overall efficiency and production cost.

	Process energy requirement (kWh/kg H_2)	Feedstock requirement (kg/kg H_2)	Water requirement (L/kg H_2)	Capital cost[b] (USD/kg H_2)	Overall process efficiency (%)
Electrolysis	57.3	N.A.	15.6	26,429–166,665	74.3
BMG	8.3	25.3	38.9	35,715–107,146	50.7
BG-reform	42.2	5 (biogas)/50 (waste)[a]	11.9	N.A.	72.5

Abbreviations: BMG (biomass gasification), BG-reform (biogas reforming).
Values are average from [8,20,28,29,33,39,44,46,49,51,52,58,62,68,69,73–78,82–85,89,92,96–103].
[a] On average, 50 kg of waste materials are required to produce 1 kg of biogas, while 5 kg of biogas required to produce 1 kg of hydrogen.
[b] Capital cost include initial investment and instalment cost. Costs were converted from Euro to USD using the exchange rate of 1 Euro = 1.07 USD.

that hampers conversion process from raw biomass to syngas [61].

Energy requirement of BG-reform cases was mostly ascribed to electricity consumption during the reforming process which led to average energy requirement of 42.2 kWh/kg H_2. Overall efficiency, estimated by input energy and output hydrogen production, was affected by composition of biogas which was determined by the type of waste material. Assumptions on high CH_4 composition in biogas was deemed to have better performance with lower GWP and higher efficiency (low feed requirement to produce a unit of hydrogen) when the reforming temperature and pressure remained the same. For example, assuming 60% of CH_4 composition in biogas led to lower GWP of 1.85 kg CO_2 eq/kg H_2 than 2.15 kg CO_2 eq/kg H_2 when CH_4 composition of 44.2% was assumed under the same reforming temperature of 800 °C. On average, 5 kg of biogas was required to produce 1 kg of hydrogen when the biogas was produced from 50 kg of waste material (food and agricultural waste, see Table 4) although the biogas yield was highly dependent on type of the waste and digestion technology [51].

3.4. Comparison of GWP with conventional hydrogen production

In order to better understand the sustainability of renewable hydrogen, GWP of the reviewed renewable hydrogen cases was benchmarked against the conventional hydrogen production cases. Coal gasification (CG) and natural gas steam methane reforming (SMR) were selected as benchmark processes because they are the most widely used technologies for commercial hydrogen production [11]. CG processes are similar to those of biomass gasification, but consume mostly coal as a hydrogen feedstock with about 1% of electricity, while biomass gasification utilises about 95% of biomass with the rest supported by electricity [32]. SMR processes are also similar to biogas reforming without biogas production processes [82]. As summarised in Table 5, average GWP values of the CG and SMR were considerably higher, and even when the highest GWP of renewable hydrogen production was considered, average GWP of SMR was still higher by 33% than the highest GWP of BG-reform. Despite the higher impacts of fossil-based hydrogen systems, current hydrogen supply market is dominated by the two systems. In order to alleviate the concerns about the high impacts, emission reduction measures such as deployment of carbon capture and storage (CCS) to conventional hydrogen production plant has been introduced in several countries, including Hydrogen Energy Supply Chain project in Australia which plans to produce hydrogen via brown coal gasification with CCS [11].

Table 5
Comparison of global warming potential of renewable and conventional hydrogen production.

	Renewable hydrogen[a]				Conventional hydrogen	
	W-elec	PV-elec	BMG	BG-reform	CG	SMR
Average GWP (kg CO_2 eq/kg H_2)	1.29 (± 1.15)	3.38 (± 1.86)	1.67 (± 1.79)	3.61 (± 3.38)	16[b] (± 4.08)	11.18[c] (± 0.47)
Min	0.03	0.37	−1.45	−4.8	11	10.6
Max	5.10	7.50	4.96	8.4	23.7	12

Abbreviations: W-elec (wind-powered electrolysis), PV-elec (solar PV-powered electrolysis), BMG (biomass gasification), BG-reform (biogas reforming), CG (coal gasification) and SMR (natural gas steam methane reforming).
[a] Average, minimum and maximum GWP values from this review.
[b] Average GWP value of 9 CG cases [source: 4,11,43,49,52,78,104,105].
[c] Average GWP value of 10 SMR cases [source: 46,68,76,78,82,106,107].

4. Challenges and perspectives

4.1. Challenges in hydrogen industry

4.1.1. Source of process energy and efficiency

Despite the renewable hydrogen technologies have reached their maturity, there still are barriers that hinder upscaling of renewable hydrogen production. Water electrolysis is one of the sought-after technologies because it is readily applicable in existing energy systems, such as wind or solar electricity generation system, but its low production efficiency, mainly due to low wind- or solar-to-electricity conversion efficiency [99,108], is considered to be a challenge [48]. In order to meet the increasing demand for energy, grid-assisted water electrolysis is likely to be the dominant hydrogen system in the short term, thus the share of renewable electricity in the grid mix will have a considerable influence on GWP of electrolysis systems [49,69]. Austria with 58% of hydro power and only 26% of the grid electricity produced from fossil fuels (9% from black coal and 17% from natural gas) resulted in GWP of 6.5 kg CO_2 eq/kg H_2 in grid-assisted hydrogen production which was slightly higher than the maximum GWP value of the reviewed W-elec case, and even lower than the maximum GWP value of PV-elec case. In contrast, higher share of fossil fuel electricity in the German grid (17% from black coal, 21% from brown coal and 18% from natural gas, which comprise 56% of the grid) with the rest from renewable sources, led to considerably higher GWP of 26 kg CO_2 eq/kg H_2 of the electrolysis system which was much higher than the average GWP of conventional coal gasification or natural gas steam reforming [4,50].

Low biomass to syngas conversion efficiency is one of the barriers of BMG hydrogen production system along with energy consumption during the syngas purification processes, which together led to low overall efficiency and higher production cost of the BMG systems [48,83]. Purification of BMG-produced hydrogen up to the industrial standard (e.g., hydrogen purity of 99.9%) is essential for hydrogen to be used as an energy source, or a feedstock of chemical production [5,83]. Process energy for the purification and follow-up compression processes is currently supplied by fossil fuel sources through external production, but this can be internally supplied by a full combustion of biomass, or by replacing the external energy generation with renewable sources [14].

4.1.2. Integration into existing infrastructure

One of the advantages of renewable hydrogen production is decentralised installation for supplying energy to remote areas [44,52] because hydrogen production facilities can be integrated with small-scale and decentralised wind- and solar-electricity systems and biogas plants [52]. The integration with existing energy infrastructure is not only possible for hydrogen production stage, but also available for post-production stages, such as distribution of hydrogen. Hydrogen can be distributed through natural gas networks although there is a threshold on hydrogen concentrations to reduce embrittlement risks and gas leaks, as well as to achieve optimal energy performance with minor modification of existing systems [69]. Projects are under way in several countries aiming to reduce the risk of embrittlement and potential gas leaks caused by using existing iron based natural gas pipelines. For example, UK has already commenced their 30-year program (IMRP; Iron Mains Replacement Program) for replacing iron pipes with polyethylene pipes which is expected to be completed by 2030s to successfully distribute hydrogen blended gas throughout the UK [5]. Integration of hydrogen production into the existing natural gas networks also enables circumventing establishment of new infrastructure for hydrogen distribution which ultimately reduces the production costs [69]. Several countries have already commenced projects for integrating hydrogen into natural gas networks without impacting the gas quality, including HyDeploy Project in the UK which suggests that 20% of hydrogen blended with natural gas is feasible [109]. In Australia, up to 5% of renewable hydrogen was blended with and supplied through natural gas networks in 2021 (Hydrogen Park South Australia) [10]. A study by Gondal [110] concluded that only 2% of hydrogen can be blended with natural gas for maintaining quality of the blended gas, while others suggest hydrogen concentration between 5 and 15% can be feasible without having risks of harmful impacts on final application of hydrogen [69].

Due to its low conversion efficiency and high process temperature of renewable hydrogen production technologies [59,99], some authors argue that hydrogen production cannot be integrated with intermittent energy generation systems, such as wind and solar energy in order to secure stable supply of energy [52,111], while others suggest use of intermittent or wasted energy from industries to reduce the environmental impacts of hydrogen production [112]. Although individual technology for renewable electricity generation (e.g., solar electricity) and hydrogen production (e.g., electrolysis) are already technologically advanced, full integration of hydrogen production with renewable energy generation systems, and integration of relevant upstream and downstream processes (e.g., integration of biomass gasification with follow-up gas cleaning process) still have areas of improvement [14,29]. These include optimisation of the operating conditions of the renewable hydrogen production systems and cost reductions.

High capital costs for renewable hydrogen production has been identified as one of the main barriers for upscaling of renewable hydrogen production (see Table 4) [1,28]. The higher capital costs than conventional hydrogen production technologies are mainly due to material use, such as noble metals, required for electrodes and catalysts as well as solar PV modules and wind turbines [28,49,55,56], while cost of electricity generation contributes to a large part of production cost of biomass gasification [13,44].

Water consumption is another important system input that is particularly important in the areas with water deficiency. Among the reviewed cases, BMG had the highest water consumption of 38.9 L/kg H_2, while BG-reform had the lowest (11.9 L/kg H_2, Table 4), because considerable amount of water is required for syngas cooling and cleaning processes as well as supplying steam to gasifier in BMG. It should be noted that water required for the BMG can be recycled by circulating between the gas cooling and cleaning units which can later be recycled as boiler feed water to supply steam to the gasifier [113,114]. A recent study found sustainable and more efficient integrated biological and chemical wastewater treatment process that could almost completely remove toxic materials from the wastewater, thus can be recycled in BMG processes [115]. On the other hand, water required for electrolysis undergoes pre-treatment processes, such as deionisation, or is mixed with potassium hydroxide to guarantee conductivity of the water, thus additional energy is required during the pre-treatment processes [51,52]. Generally, water consumption was attributed to process energy generation at various extents depending on the hydrogen production feedstock, conversion efficiency and pre-treatment of the hydrogen feedstock [43]. Land use change was another factor that had significant impact on endpoint damage to ecosystems in biomass-based hydrogen production case [43]. Therefore, investigating various aspects of the technologies from a multi-dimensional perspective will be useful to successfully upscale the renewable hydrogen production, while abating negative impacts.

4.2. Challenges in LCA studies

LCA is an efficient tool for quantifying outputs of a system based on the system inputs, thus quality of the input data plays an important role in LCA processes [62]. Due to the infancy of commercialisation of renewable hydrogen production systems, many of the process data are confidential [116] which leads to many LCA studies relying on secondary data sources including commercial databases and data from other literature with modifications and assumptions for particular processes (see Supplementary Table S1 for data sources). During data adjustment, subjectivity may lead to LCA results not adequately reflecting real operating circumstances. Hydrogen production efficiency and hydrogen yield are also estimated according to available input and output data [99] which could be a key factor for establishing commercial scale renewable hydrogen system, but when the data sources are not reliable, it may cause difficulties in decision making for stakeholders.

As discussed in Section 3.2. and 4.2., inconsistencies or unclear definition of system boundaries among LCA studies jeopardise the direct comparison of the impact, of which importance is highlighted in several LCA studies [68,76]. Even studies with the same system boundary (e.g., hydrogen compression as the final stage of the production) do not clearly specify the final pressure of hydrogen, leading to difficult estimation of process contribution to total impacts. Considering 38.2% reduction in energy consumption during hydrogen compression process when pressure of produced hydrogen decreases from 700 bar to 200 bar [76], detailed information about the production processes should be clearly stated to better estimate the impacts of each production process with possibility of sound comparison of the impacts with other studies. One of the reviewed studies included decommissioning and disposal of hydrogen plant as a final production process [28], but did not break down the impacts according to each production process, instead reported it as a total. Another study by Hajjaji et al. [68] included recycling of plant construction materials together with the decommissioning and disposal which resulted in 2% decrease in abiotic depletion potential of BG-reform case by applying credits to by-product (bio-fertiliser) and recycling of the materials. However, the credits were not large enough to compensate GWP, because the GWP was mainly derived by CH_4 emissions during biogas processing. In case of solar-powered electrolysis system, plant decommissioning and disposal of plant construction materials contributed about 2.56% of total CO_2 equivalent emissions [78], while a study by [28] claimed as negligible.

4.3. Opportunities in renewable hydrogen production systems

Increasing share of renewables in the grid mix in many countries shed light on the potential of renewable source-based electrolysis as a predominant hydrogen production technology in the short term with reduced environmental impact [69]. As discussed in Section 4.1.1., GWP is dominated by the share of renewable electricity in the grid mix which also implies potential of achieving low emission hydrogen by increasing the share of renewables in the grid not only for electrolysis but also for supplying heat for gasifiers [59]. Solar, wind and bio-feedstock (e.g., agricultural residues and industrial waste) are abundant and readily available for hydrogen production [61] which can also accelerate the renewable hydrogen production. Biomass gasification and biogas reforming technologies are particularly meaningful for transforming waste materials into valuable energy products while alleviating emissions control issues from waste management processes and mitigating emissions from hydrogen production [5]. It is expected that the production capacity of biomass gasification for hydrogen production will observe significant increase by 2050 in the US and some European countries [14]. It is also forecasted that the demand for hydrogen will increase in various industrial sectors including hydrogen as a feedstock for ammonia and methanol production, as a fuel for medium and large vehicles, and as a high-grade thermal energy source for various industries [117].

5. Conclusions

Many previous works have investigated production and supply of renewable hydrogen as one of the solutions for achieving emission reduction target. Among various renewable hydrogen options, this review compared hydrogen production from wind- and solar-powered water electrolysis, biomass gasification and biomethane reforming in terms of global warming potential (GWP) of each technology based on the 64 hydrogen production cases found in literature. Wind-powered water electrolysis exhibited the lowset average GWP with 1.29 kg CO_2 eq/kg H_2, followed by biomass gasification (1.67 kg CO_2 eq/kg H_2), while biogas reforming cases showed the greatest variations in GWP due to the inclusion of carbon credits to the assessment processes, with the lowest GWP found where large carbon credits were applied to the replacement of mineral fertilisers with digestate, a by-product from the biogas production process. Similarly, lower, or negative in some cases, GWP values were reported where carbon credits during biomass cultivation were considered in biomass gasification cases. Despite the similar hydrogen production processes of wind- and solar PV-electrolysis, GWP of solar electrolysis (3.38 kg CO_2 eq/kg H_2) was more than twice higher than that of wind electrolysis due to differences in the upstream processes. There are difficulties in direct comparison of impact values from the reviewed cases due to inconsistencies in system boundaries in each case, especially for inclusion of downstream processes, such as hydrogen compression, which was estimated to contribute to 17.5–22% of the total GWP.

Contribution of each production process to total GWP varied depending on the production technology with wind and solar electricity generation system having the greatest contribution to the total GWP of water electrolysis, mainly due to material use for constructing the system, with the contribution rate ranging between 78 and 97% and 88–99% for wind and solar PV electrolysis cases, respectively. In biomass gasification system, energy requirement for operating the gasifier was the key factor affecting most of GWP with contribution rate between 59 and 66%, while 22–38% of the GWP were attributed to syngas cleaning process. Biogas production was found to be the most impactful process in biogas reforming cases with contribution rate between 89 and 99% due to methane leakage during the biogas production.

When GWP of the reviewed renewable hydrogen production cases was compared with conventional systems, about 77–92% lower GWP were observed when compared to coal gasification hydrogen production and 68–88% lower GWP than natural gas steam reforming system. Although barriers exist in commercialisation of renewable hydrogen production, such as low production efficiencies, threshold in hydrogen concentration when blended with natural gas, water consumption and high capital costs, there are opportunities for future hydrogen production which include increasing low-emission hydrogen production supported by larger share of renewable electricity in the future grid mix, integration into existing natural gas networks, and decrease in the production cost of renewable hydrogen.

CRediT authorship contribution statement

Hannah Hyunah Cho: Conceptualization, Data curation, Methodology, Writing – original draft. **Vladimir Strezov:** Conceptualization, Methodology, Writing – review & editing, Supervision, Validation. **Tim J. Evans:** Writing – review & editing, Validation.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.susmat.2023.e00567.

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