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Green hydrogen: Pathways, roadmap, and role in achieving sustainable development goals

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ABSTRACT

The United Nations Sustainable Development Goals (UN-SDGs) provide a unique opportunity to achieve sustainable development and reduce climate change impact. Decarbonizing the energy system is a key approach to achieving the energy balance. Recently, green hydrogen has become the most promising energy source for decarbonizing energy systems. Therefore, determining the different production methods of green hydrogen, their economics, and their environmental impacts is essential to all stakeholders. Additionally, understanding the role of green hydrogen in achieving the different SDGs is vital for policymakers and decision-makers. Thus, this study reviewed the common hydrogen production methods. The prospect of achieving the SDGs has also been investigated, and the most relevant keywords were presented. Finally, a list of indicators (guidelines) to increase the green hydrogen contribution to the SDGs was provided. The provided indicators will assist the stakeholder in increasing the integration of green hydrogen into the SDGs and reduce the trade-off.

1. Introduction

Globally, huge amounts of fossil fuels are consumed, and this amount increases from year to year. Such use of fossil fuels is not ecological for sustainable societal development as they will diminish in the upcoming years after causing severe environmental impacts via carbon dioxide (CO_2) emissions (Wilberforce et al., 2021a). Decarbonization is the salvation that our planet seeks. In 2021, global energy consumption raised annual CO_2 emissions to more than 35 billion tons (Hannah Ritchie, 2020) (Fig. 1), further fueling global warming benefactors. Such a problem arises due to the dependency of the global economy and industry on fossil fuels as the primary energy carrier. Therefore, solving the CO_2 crisis is directly related to finding new alternatives to fossil fuels (Tanzer et al., 2020; Baroutaji et al., 2019; Ma et al., 2022; Ramadan, 2021).

Hydrogen is a perfect candidate for the future replacement of fossil

Abbreviations: UN, United nations; SDGs, Sustainable development goals; CAPEX, Capital expenditure; OPEX, Operating expense; PEC, Photoelectrochemical; STH, Solar to hydrogen; PEMWE, Proton exchange membrane water electrolysis; AWE, Alkaline water electrolysis; AEMWE, Anion exchange membrane water electrolysis; R&D, Research and development; GHG, Greenhouse gas; NHE, Normal hydrogen electrode; SHE, Standard hydrogen electrode; SOEC, Solid oxide electrolysis cell; COD, Chemical oxygen demand; LCA, Life cycle analysis; LCC, Life cycle coasting; SLCA, Social life cycle analysis; LCSA, Life cycle sustainability assessment; PV, Photovoltaics; VS, Volatile Solids; MEC, Microbial electrolysis cell; MFC, Microbial fuel cell; D, Dimensions; NADH/NAD, Reduced and oxidized forms of nocitinamide adenine dinucleotide.

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fuels. It has an energy density of 120 MJ kg− 1, which is three times larger than that of diesel and gasoline (45.5 and 45.8 MJ kg−1, respectively). In 1970s, John Bockris proposed a hydrogen economy; he envisioned a new energy production and consumption era. His idea is based on hydrogen production by water electrolysis through renewable energy, which can later be supplied through pipelines for industrial and residential applications, where it is converted into electricity through suitable energy conversion devices, such as fuel cells (Bockris, 1972; Oliveira et al., 2021).

Hydrogen is the most abundant and simplest element that comprises a proton and an electron. However, it is not usually available as a pure gas (Howarth and Jacobson, 2021b; Noussan et al., 2021). There are different hydrogen colors based on the production methods from the corresponding sources (Fig. 2).

Grey hydrogen is mass-produced to meet 96% of the global hydrogen demand. Grey hydrogen is produced from oil and coal by hydrocarbon reformation techniques, such as steam methane reforming (SMR) (Griffiths et al., 2021). To produce this type of hydrogen, syngas is first obtained. Then, the carbon monoxide is removed by a water–gas shifting reaction to obtain hydrogen and CO_2 (Ji and Wang, 2021). The downside of this process is that CO_2 is produced, which contradicts the global decarbonization task. However, the ease of obtaining such a type of hydrogen compensates for the environmental or ethical aspects that may be frowned upon (Yue et al., 2021). Grey hydrogen is produced by 6% and 2% of the global natural gas and coal production, respectively, adding up to 70 Mt of the annually produced hydrogen (Newborough and Cooley, 2020). This grey hydrogen produces ~830 Mt of CO_2 per year, a byproduct of the water–gas shifting process (Hordeski, 2020).

Hydrogen is classified as blue whenever the CO_2 generated from steam reforming or water–gas shifting is captured and stored through carbon capture and storage systems (CCSs) (Yu et al., 2021). The cost of blue hydrogen mostly depends on the cost of natural gas, reformer, and CO_2 recovery and storage facilities. For a blue hydrogen facility to be feasible, it must be implemented at an enormous scale so that the stored CO_2 can be allocated and accommodated for many different applications. Although this process adds more complexities, determining a price for waste CO_2 and the proper way for its capturing must be thoroughly researched (Abdelkareem et al., 2021b). Environmentally, green hydrogen is the most favorable type of hydrogen. It is produced by renewable energy means, such as solar, wind, and nuclear power through water electrolysis (Hassan et al., 2023; Kojima et al., 2023; Oliveira et al., 2021; Rezk et al., 2023; Sarker et al., 2023). Despite the environmental benefits of green hydrogen production, it represents 4% of hydrogen production (Nicita et al., 2020). The low percentage is directly related to the high cost of hydrogen production using renewable energy compared with other processes using fossil fuels. For instance, 1 kg of hydrogen produced by renewable energy costs upto ~$23 (varied according to the technical advances in renewable energy and hydrogen production technologies), whereas hydrogen produced by fossil fuel costs below $2 (Mohideen et al., 2023; United Nations Economic, 2022). However, the cost per kilogram of green hydrogen is expected to dip once breakthrough advancements in the renewable energy sector are effected (Mohideen et al., 2023; Taibi et al., 2020). Turquoise hydrogen is similar to blue and grey hydrogen as it uses natural gas as fuel to produce hydrogen and solid carbon through pyrolysis. This approach is considered an alternative type between green and blue hydrogen as the carbon is in solid form; thus, there is no CO_2 emission (Tran et al., 2021). If biomethane is used instead of natural gas, the process will have zero carbon emissions as the electricity driving the pyrolysis process is renewable.

Hydrogen is becoming a progressively significant enabler of transitioning from a carbon-based economy to a decarbonized economy based on renewable and sustainable energy systems. Nonetheless, there is a potential requirement to create robust scientific literature that examines the relationships between a green hydrogen economy and the "sustainable development goals" (SDGs) (Falcone et al., 2021). The United Nations (UN) 2030 Agenda for sustainable development, adopted by all UN member states in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. The 17 SDGs are at the heart of this plan as an urgent call for a global partnership. These SDGs have been further detailed into 169 specific targets to achieve them. At the heart of the SDGs is energy, and more

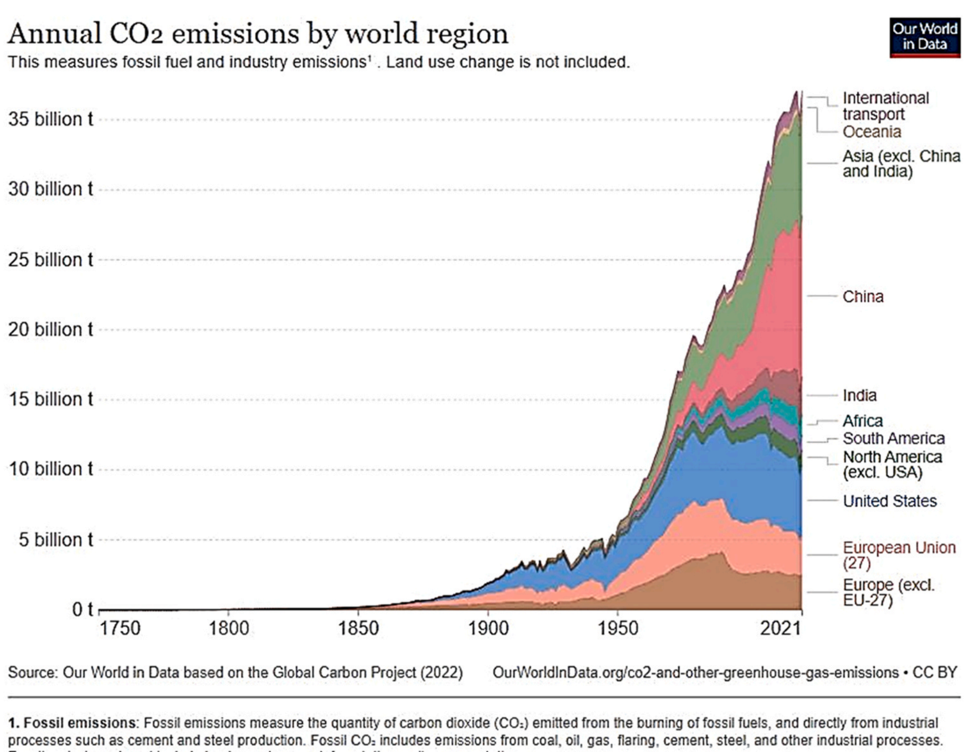


Fig. 1. Annual CO_2 emission (1750–2021), (Hannah Ritchie, 2020), open access.

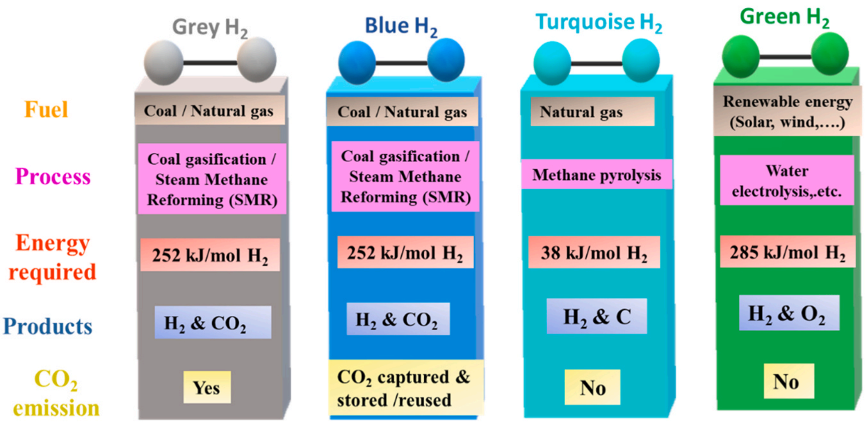


Fig. 2. Different types of hydrogen.

specifically, clean energy as the main driver of the main SDGs, specifically SDG-7 of "Affordable and Clean Energy". Meanwhile, hydrogen is one of the cleanest energy carriers that can be directly correlated to different SDGs. Falcone et al. discussed the hydrogen economy and SDGs concerning policy insights and their role in supporting SDG-7 (Falcone et al., 2021). However, we strongly believe that the widespread employment of hydrogen as an energy vector will significantly affect many SDGs. Hydrogen is an excellent energy vector, and expands itself into a hydrogen economy, and even further into hydrogen civilization, as coined by the International Association for Hydrogen Energy (IAHE) and other research (Falcone et al., 2021; Goltsov et al., 2006).

This study first summarizes the different pathways for green hydrogen production. Additionally, an assessment of the different green hydrogen production methodologies is explored. Moreover, this study investigates the role of green hydrogen in achieving the UN-SDGs. Finally, the paper provides a set of indicators (guidelines) to maximize the green hydrogen contribution to the SDGs and decrease the possible trade-offs.

2. Background of green hydrogen production methodologies

Green hydrogen is completely produced using renewable energy sources while emitting zero CO_2. Fig. 3 depicts the green hydrogen production routes. Some of those routes are in the developed technological readiness level, whereas others are still in the research and development (R&D) levels. All these routes will be addressed in this section. Some challenges are being addressed to ensure maximum sustainable hydrogen production at a reasonable cost. The economic challenge entails decreasing the green hydrogen production cost to the same level as the current major production cost.

2.1. *Water as a hydrogen resource*

Dissociating water molecules can be used to produce hydrogen through several processes. This section summarizes high and low-temperature electrolysis, photoelectrolysis, and photobiological hydrogen production methods.

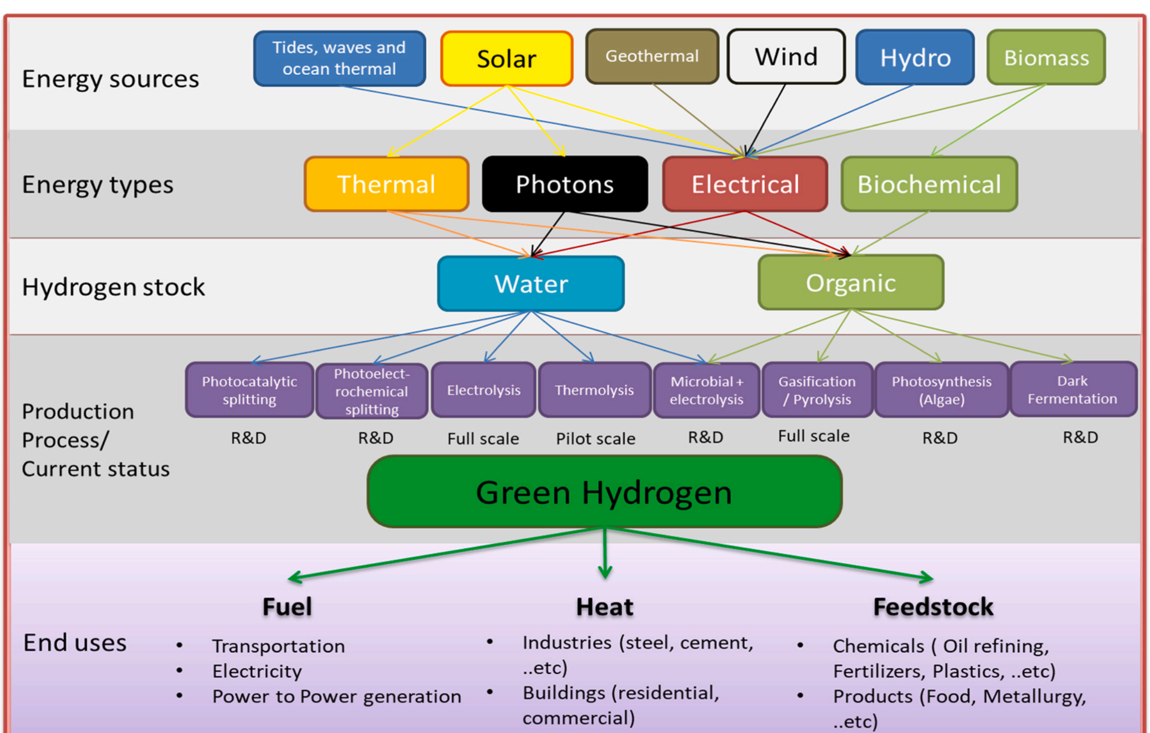


Fig. 3. Green hydrogen production routes.

2.1.1. Photon-induced water splitting

Photocatalytic (PC) water splitting has been intensively studied as a possible green route for producing hydrogen using solar energy (photon energy). The process involves using a photocatalyst to convert the energy of the photons into excited electron–hole pairs. The excited electrons facilitate the hydrogen evolution reaction, whereas the oxygen evolution reaction happens in the presence of holes in the valence band of the photocatalyst. The water oxidation potential is $E_{O_2/H_2O} = 1.23$ V vs. normal hydrogen electrode (NHE). Therefore, the photocatalyst should be able to excite electrons at an energy level below the hydrogen evolution reaction $E_{H_2/H_2O} = 0$ V vs. standard hydrogen electrode (SHE), whereas holes should be maintained at an energy level more positive than 1.23 V vs. SHE (Marepally et al., 2019). The apparent reactions that happen over the photocatalyst are:

$$2H_2O + 4h^+ \rightarrow 4H^+ + O_2 \quad E_{oxidation} = -1.23V \tag{1}$$

$$2H^+ + 2e^- \rightarrow H_2 \quad E_{reduction} = 0V \tag{2}$$

For the last five decades, intensive research has been devoted to PC water splitting (Barakat et al., 2014; Daulbayev et al., 2020) due to developing several nanostructured photocatalysts. The proposed photocatalysts can be one-, two-, and three-dimensional (1D, 2D, and 3D, respectively) structures. They can also be classified into oxide and non-oxide photocatalysts (Zhang et al., 2019). A simple search with the words photocatalytic water splitting returned 378 results from 2020 to 2021, indicating the importance of that route as a small-scale green hydrogen production route shortly. Fig. 4 shows the number of publications for selected photocatalysts in the last decade. Titanium oxide (TiO_2) nanostructures with various modifications have received significant attention as a promising photocatalyst due to their availability, durability, and adaptability for many modifications (Mahmoud et al., 2018a; Mahmoud et al., 2018b). Some factors govern the quality of the prepared photocatalyst for efficient water splitting, such as:

a. The stability of visible light absorption as it represents 55.4% of solar radiation.
b. The photocatalyst should impose a direct bandgap that triggers hydrogen and oxygen evolution reactions.
c. The capability of the photocatalyst to prolong the lifetime of the electron–hole pair before recombination. For instance, pristine TiO_2 has a typical recombination lifetime of 90 μs (Ozawa et al., 2014). Accordingly, the new photocatalyst should promote longer lifetimes.

Both hydrogen and oxygen evolution processes pass through several steps. Note that the H_2 gas evolution happens at the conduction band, whereas the O_2 production reaction proceeds in the valence band (Mahmoud et al., 2018a) as follows:

$$H_2O_{(l)} \rightarrow H_2O^*_{(ads)} \tag{3}$$

$$H_2O^*_{(ads)} \rightarrow OH^-_{(ads)} + H^*_{(ads)} \tag{4}$$

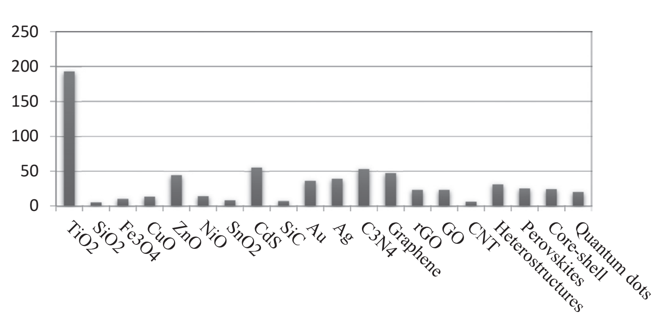


Fig. 4. Number of publications for selected photocatalysts in the last decade. The numbers show only the papers titled with the photocatalyst.

$$2(H^*)_c \rightarrow H_{2(gas)} \tag{5}$$

$$OH^-_{(ads)} + h^{\cdot} \rightarrow O^-_{(ads)} + H^+_{(ads)} \tag{6}$$

$$O^-_{(ads)} + h^{\cdot} \rightarrow O^*_{(ads)} \tag{7}$$

$$O^*_{(ads)} \rightarrow O^*_{(gas)} \quad \rightarrow \frac{1}{2} O_{2(gas)} \tag{8}$$

Water molecules are first adsorbed over the catalyst surface (Eq. 3). The electrons available in the vicinity of the conduction band facilitate the splitting of water into OH^- and H^+ (Eq. 4). In reaction (Eq. 5), the hydrogen radical is converted to hydrogen gas. Over the hole-rich areas (Eqs. 6 and 7), an $O^*_{(ads)}$ atom is produced. The final step represents the combination of oxygen radicals to produce O_2 gas.

Despite several attempts to scale-up hydrogen production through PC water splitting, solar energy conversion efficiency to hydrogen remains a major challenge. Other challenges include the stability of the photocatalyst, the cost, and the side reactions.

2.1.2. Photoelectrochemical (PEC) water splitting

In its simplest form, a PEC cell comprises a semiconductor electrode and a metal counter electrode immersed in an aqueous electrolyte. Fig. 5 shows the water-splitting principle using a semiconductor photocatalyst. When a solar beam with energy exceeding the bandgap reaches the catalyst surface, it excites the electron to the conduction band, leaving a hole in the valence band. The photo-generated electrons and holes behave as local reaction sites that induce redox reactions. The bottom level of the conduction band must be more negative than the reduction potential of H^+/H_2 (0 V vs. NHE), whereas the top level of the valence band has to be more positive than the oxidation potential of O_2/H_2O (1.23 V vs. NHE). However, the band structure potential is just the thermodynamical requirement; other factors must be considered, like charge separation, mobility, and the lifetime of photo-generated electrons and holes. The PEC water splitting has a distinctive advantage over the PC water-splitting route. The presence of a photoanode and a photocathode spatially separates the redox reactions. Therefore, PEC can achieve higher solar to hydrogen (STH) efficiency than the PC water-splitting process.

Although much research attention has been devoted to developing suitable materials for PEC water splitting, no single material can be used for photoanode and photocathode reactions. The photoanode should be made from n-type semiconductors, whereas the photocathode should be made from p-type semiconductors (Chu et al., 2017). For the n-type photoanode and p-type photocathode, the holes of the p-type photocathode recombine with the electrons of the n-type photoanode through the outer circuit, leaving the electrons and holes at the photocathode

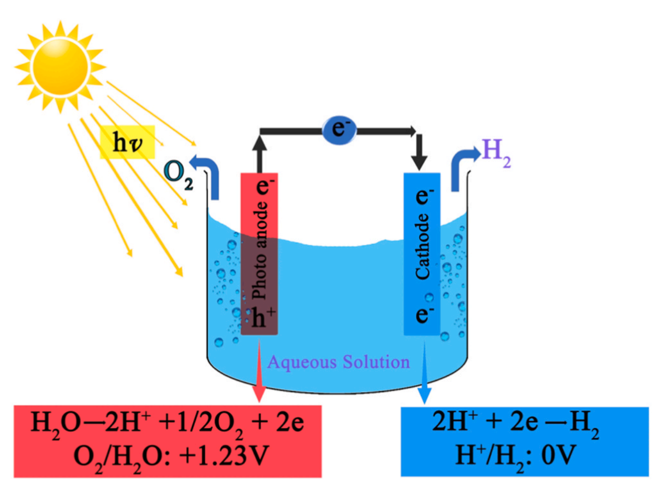


Fig. 5. Electrochemical cell viewing the principle of electrochemical hydrogen generation over water photolysis using solar energy and the related electrode reactions.

and photoanode to perform the redox reactions. This separation of the redox reactions permits smaller bandgap photocatalysts. Regarding the PEC process efficiency, several studies have been conducted to estimate the theoretical STH efficiency to exceed 25% (Fountaine et al., 2016; Seitz et al., 2014). However, some losses are also addressed, like the electrochemical overpotentials, ohmic resistance, and losses from incident light beams. Table 1 presents some experimental results for PEC water splitting.

2.1.3. Renewable energy-powered water electrolysis

Water electrolysis is an advanced technology for splitting water into oxygen and hydrogen. Here, electricity is supplied to the electrolysis cell electrodes, where the redox reactions occur over the electrodes. Green hydrogen production through water electrolysis becomes feasible, sustainable, and ecofriendly upon coupling with a renewable energy source. Thus, the intermittent renewable energy is stored as chemical energy in green hydrogen to be used on-demand. Mainly, there are three methods for water electrolysis, namely polymer electrolyte membrane water electrolysis, solid oxide electrolysis, and alkaline water electrolysis. The latter technology is the most advanced, with stable performance and relatively high-energy conversion efficiency. Alkaline water electrolysis typically includes water electrolysis in an electrolytic cell at 40–90 °C. Theoretically, the voltage required for water dissociation is 1.23 V at standard temperature and pressure conditions. Hence, at 100% current efficiency, the theoretical energy consumption per 1 m^3 of H_2 generated is 2.94 kWh m^{-3} H_2. Nevertheless, due to the overpotentials generated at the cathode and anode sites, the actual energy consumption is 4.5–5.5 kWh m^{-3} H_2. Hence, the actual efficiency is ~50% (Wang et al., 2014). The actual cell voltage (V_{actual}) is the sum of the theoretical cell voltage, the overpotentials, and another ohmic drop. It can be expressed as follows (Wang et al., 2014):

$$V_{actual} = V_{theoritical} + |\eta_A| + |\eta_C| + i \times R_{total}, \tag{9}$$

where $\eta_A and \eta_C$ are the over potentials at the anode and cathode sites, R_{total} is the total resistance of the membrane, electrolyte, and outer circuit. This technology's disadvantages include forming alkaline fogs, sluggish start-up operations, and gas permeation.

Proton electrolyte membrane water electrolysis (PEMWE) comprises a cathode, an anode, and a membrane. The solid polymer membrane is responsible for the proton movement from the anode to the cathode. Also, this membrane acts as a gas separator and an electrical insulator. The PEMWE can operate at high current densities, thereby reducing the operating cost. It could be coupled with green energy sources, such as wind-generated or photovoltaics (PV)-generated electricity. The energy consumption of the PEMWE cells is ~4.0–4.2 kWh $(Nm^3)^{-1}$ H_2 (Grigoriev et al., 2009). The current challenges with this technology include (i) the improvement of the oxygen evolution reaction rate at the anode, (ii) gas cross-over during the PEMWE operation, and (iii) operating the PEMWE cell at a relatively higher pressure to store the produced hydrogen in pressurized vessels directly. The ohmic loss due to the motion of protons across the membrane can be reduced by decreasing the membrane size while maintaining high operating pressure. Several development attempts have been reported concerning the electrodes and membranes of the PEMWE electrolyzer to meet the requirements of hydrogen production at a competitive price (Abdol Rahim et al., 2016). However, the hydrogen production cost and the operating conditions of this process are still under consideration. Nonetheless, the cell operates at low temperatures (50–90 °C) at the commercial level (Brauns and Turek, 2020; Xu et al., 2022).

Similarly, alkaline water electrolysis (AWE) is an established low-temperature (65–100 °C) device (Raja Sulaiman et al., 2022). As the name indicates, the cell operates under alkaline conditions. As a result, AWE does not require the usage of precious metals in its catalysis, cutting down the costs of the cell. Non–noble catalysts such as Ni and Co oxides are used to reduce water into H_2 and OH^- at the cathode (Brauns and Turek, 2020; Yang et al., 2021a). Thereafter, OH^- migrates to the cathode through a diaphragm such as ceramics or polypropylene to be oxidized into O_2 and water. The electrodes are separated at a distance where oxygen and hydrogen gases would form. Alkalinity is provided to the electrolyte by various classes of chemicals such as NaOH, KOH, etc. Electrolyte operational conditions are optimized at the highest specific conductivity and lowest gas solubility at the target operating temperature. The gas solubility determines the electrolyte intoxication potential with carbonation from the surroundings (Brauns and Turek, 2020). CO_2 consumes OH^- to dissolve into CO_3^{2-}, therefore, harming ion transport process via slower mobility. Occasionally, the dissolved CO_3^{2-} precipitates into K_2CO_3, which is notorious for clogging the diaphragm (Mandal, 2021; Naughton et al., 2011).

Anion exchange membrane water electrolysis (AEMWE) uses an ion exchange membrane that permits the transfer of hydroxide anions as the diaphragm in a compact design working at 40–80 °C (Xu et al., 2022). Therefore, AEMWE is also known as advanced AWE. However, unlike conventional AWE, the cell employs a zero-gap assembly where the anode, membrane, and cathode are placed next to each at no distance to minimize cell resistance and allow stacks assembly. The cell can operate on distilled water or unconcentrated alkaline solutions to produce hydrogen momentarily (Brauns and Turek, 2020; Yang et al., 2021a). As a result, hydrogen is produced at a rate of 118.25 kg H_2 h^{-1} from electricity consumption of 53.9 kWh (kg H_2)$^{-1}$ (Kuckshinrichs et al., 2017). Despite the monetary potential sought after from AEMWE, the cell is still under development level due to its lower efficiency compared to PEMWE. Its main components, AEM and catalysts, exhibit low durability and activity. Hence, AEMWE is still under development (Raja Sulaiman et al., 2022).

Hydrogen production by the solid oxide electrolysis of steam is another process that can involve less energy consumption due to the improved thermodynamics and kinetics of the redox reaction at higher temperatures (Udagawa et al., 2007). According to Udagawa et al. (Udagawa et al., 2007), the estimated energy consumption of solid oxide electrolysis cells (SOECs) is ~3 kWh $(Nm^3)^{-1}$ H_2, which is lower than that of the PEMWE electrolysis. The SOECs can be subdivided into H^+-based SOECs, O^{2-}-based SOECs, and co-electrolysis cells (Chi and Yu, 2018). However, the process suffers from some challenges, such as electrode stability and high-temperature control, because of the dynamic operation of SOECs (Bi et al., 2014).

2.1.4. Thermochemical water splitting (thermolysis)

Thermodynamically, water decomposition commences at 3000 °C, where more than 10% of water decomposes to hydrogen and oxygen. To

Table 1
Experimental results for PEC water-splitting process.

Catalysts	PEC current density (mA cm^{-2})	STH efficiency (%)	Stability (h)	Ref.
InGaP/GaAs double junction	11.7	9	150	(Varadhan et al., 2019)
InGaP/GaAs double junction (epitaxial integration)	13–14.8	> 16	-	(Young et al., 2017)
Two PEM electrolysers in series with one InGaP/GaAs/GaInNAsSb triple-junction solar cell	565.9	30	48	(Jia et al., 2016)
n + p-Si/Ti/Pt photocathode	39.7	17.6	72	(Karuturi et al., 2020)
Pt/CdS/$CuGa_3Se_5$/(Ag,Cu)$GaSe_2$ photocathode, and NiOOH/FeOOH/Mo:$BiVO_4$ photoanode	-	0.76	2	(Kim et al., 2016)

alleviate the high-temperature dissociation of water, other processes have been studied for thermochemical water splitting, such as:

a. **Thermochemical energy cycles**: Here, several chemical reactions coupled with heat energy are responsible for the overall hydrogen production from water. The chemicals are then recycled for the next hydrogen production cycle. The needed heat is supplied from the waste heat recovery from nuclear plants and by the concentration of the solar beams through heliostats, parabolic dishes, or a set of Fresnel lenses. Numerous thermochemical water-splitting cycles have been proposed so far. Some of those cycles are presented in Table 2. Such processes can achieve above 50% hydrogen production efficiency, thus decreasing the hydrogen production cost. However, the challenges of this process are mainly related to the material development that can withstand high-temperature operations.

a. Plasma chemical decomposition of water

Plasma-driven water electrolysis is considered an alternative method for hydrogen production. Simply, it comprises plasma generated by a high-voltage power supply that produces an electrical spark, making plasma inside the electrolyte solution (Saksono et al., 2016). Several water additives can significantly enhance hydrogen production, such as KOH, glycerol, and ethanol (Saksono et al., 2016; Saksono et al., 2018). Several factors affect the plasma electrolysis process, such as the electrolyte type, applied voltage, ion conductivity, and pH (Jinzhang et al., 2008). However, until now, this process has been under development due to several challenges, such as gas separation, energy consumption, and radical elimination.

2.2. Biological hydrogen production

Biomass can be considered an alternative sustainable source of hydrogen (Ndayisenga et al., 2022; Taipabu et al., 2022). It includes all agricultural residues. Some crops, such as switchgrass, jatropha, and willow trees, can also act as feedstock. Other sources include animal and municipal solid waste. Some of the routes that use organic feedstock will be discussed in the following points.

2.2.1. Microbial electrolysis cell

Microbial electrolysis cells (MEC) use electrochemically active bacteria to oxidize the organic matter and generate electrons, protons, and CO_2 gas (Jadhav et al., 2022; Olabi et al., 2020b; Wilberforce et al., 2021b). It is a promising approach for hydrogen production as it couples two merits of utilizing organic waste to produce energy carriers. Basically, exoelectrogenic bacteria transfer the electrons extracellularly at the anode, whereas the protons move into the solution. Then, electrons combine with the protons at the cathode, which is kept at a potential of at least 0.414 V. A schematic of the MEC is shown in Fig. 6.

An example of the reactions that occur at the anode and cathode at standard biological conditions (pH = 7, T = 25 °C, and P = 1 atm.) are (Kadier et al., 2014):

$$\text{Anode}: CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^- \tag{10}$$

$$\text{Cathode}: 8H^+ + 8e^- \rightarrow 4H_2 \tag{11}$$

Intensive research activities have been devoted to enriching the performance of such cells, including (Kadier et al., 2020; Kadier et al., 2016):

a. Cheap electrodes and membranes or membraneless.
b. Different organic feedstock.
c. Enhanced transfer of protons.
d. Electricity source.
e. Hybrid coupling of MEC with other hydrogen production technologies.

Nevertheless, MEC technology has some challenges under investigation, such as low H_2 production rate, cell resistance (slow migration of protons), microorganism rate of digestion, expensive electrodes and membranes, and complicated installation and operation.

2.2.2. Algae hydrogen production (photosynthesis)

Microalgae can produce hydrogen through oxygen-evolving photosynthesis (oxygenic photosynthesis) (Oey et al., 2016; Lam et al., 2019). Water is split into protons, electrons, and oxygen through this process. Then, the protons recombine with electrons with the help of enzymes (hydrogenase or nitrogenase) to generate hydrogen. Solar beams

Table 2
Summary of some thermochemical energy cycles.

No	Cycle reactions	Operating temperature	efficiency	Ref.
1	Cu–Cl thermochemical–electrolysis cycle $2Cu + 2HCl(g) \rightarrow 2CuCl(l) + H_2(g)$ (430–475 °C) 2CuCl2 + H2O(g) → Cu2OCl2 + 2HCl(g) (400 °C) $2Cu_2OCl_2 \rightarrow 4CuCl + O_2(g)$ (500 °C) $2CuCl \rightarrow CuCl_2(aq) + Cu$ (ambient-tempertaure electrolysis)	< 600 °C	45%	(Dokiya and Kotera, 1976; Orhan et al., 2009)
2	Sulfur–iodine thermochemical cycle1.$I_2 + SO_2 + 2H_2O \xrightarrow{Heat} 2HI + H_2SO_4(120°C)$2.$2H_2SO_4 \xrightarrow{Heat} 2SO_2 + 2H_2O + O_2(830°C)$3.$2HI \xrightarrow{Heat} I_2 + H_2(450°C)$	850 °C	78%	(García et al., 2013)
3	Sulfuric acid–iodine thermochemical–electrolysis cycle 1. $SO_2 + I_2 + 2\,H_2O \rightarrow 2HI + H_2SO_4$ (electrolysis) 2. $H_2SO_4 \rightarrow H_2O + SO_2 + \frac{1}{2}O_2$ (900 °C) 3. $2HI \rightarrow H_2 + I_2$	900 °C	52%	(Wang, 2012)
4	Iron–Iron oxide thermochemical cycle $Fe_3O_4 \xrightarrow{Heat} 3FeO + \frac{1}{2}O_2$ $3FeO + H_2O \xrightarrow{Heat} Fe_3O_4 + H_2$	1300 °C	54%	(Charvin et al., 2007)
5	Zn–ZnO thermochemical cycle $ZnO \rightarrow Zn + \frac{1}{2}O_2$ $Zn + H_2O \rightarrow ZnO + H_2$	1900 °C	40%	(Haltiwanger et al., 2010)
6	$ZnO–ZnSO_4$ thermochemical cycle $ZnSO_4 \rightarrow ZnO + SO_2 + \frac{3}{2}O_2$ $ZnO + SO_2 + H_2O \rightarrow ZnSO_4 + H_2$	1000 °C	48.9%	(Bhosale et al., 2017)

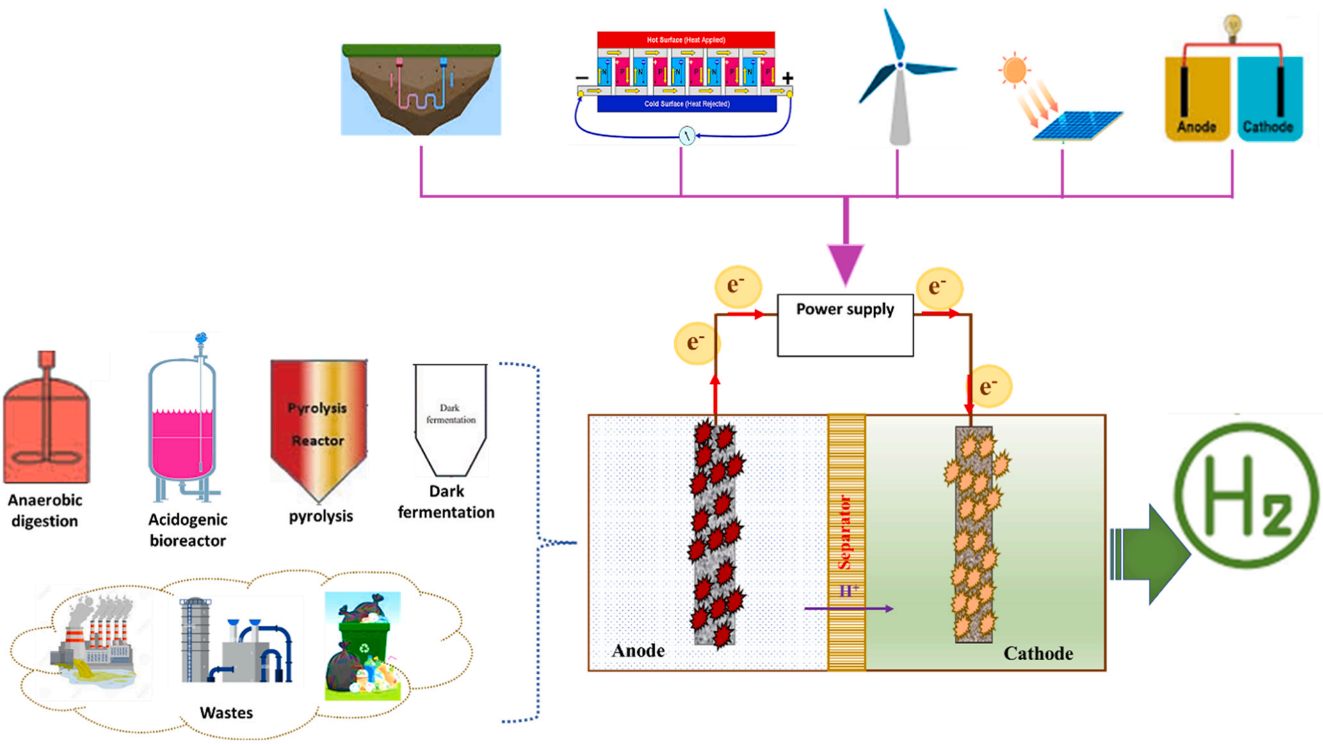


Fig. 6. Microbial electrolysis cell (MEC) substrates, sources of electricity, and downstream products.

provide the necessary energy for the microalgae reactions to oxidize H_2O, transfer electrons, and produce hydrogen (Eroglu and Melis, 2016). This process can be subdivided into direct and indirect pathways. In the direct process, a direct transfer of electrons from the water-splitting sites to the hydrogen-producing hydrogenase enzyme occurs. However, in the indirect process, microalgae store solar energy in the form of carbohydrates, which are then used to produce hydrogen with the aid of hydrogenase enzymes. Several microalgae strains have been proposed, as presented in Table 3. Some of them can produce hydrogen at a substantial rate, whereas others experience some challenges. Although this process has several advantages, such as hydrogen production at atmospheric temperature without the need for precious photocatalysts, several challenges have must be addressed before full-scale production, such as (i) gas separation, (ii) solar beam capture efficiency, (iii) limited electron flow to the enzyme, (iv) sustainable hydrogen production under microalgae normal growth conditions, and (v) scale-up engineering.

2.2.3. Hydrogen production by dark fermentation

Dark fermentation bioprocess involves breaking down biomass feedstock, producing hydrogen, volatile fatty acids, and alcohols (Ebrahimi et al., 2022; Rizwan et al., 2019; Yağlı et al., 2021). Unlike the photofermentation process, this process is performed under anaerobic, light-free conditions. Table 4 compares the dark and photo fermentation processes (Bolatkhan et al., 2019). In the anaerobic digestion step, long-chain biomasses, such as proteins and carbohydrates, are hydrolyzed through two routes in the presence of specific coenzymes (Koutra et al., 2020; Singh and Das, 2020). (1) Acetyl coenzyme A can generate acetate with or without reducing nicotinamide adenine dinucleotide (NADH). This route has a theoretical yield of 4 mol of H_2 per mol of glucose. (2) Glucose conversion to pyruvate augmented with the conversion of NADH to NAD^+ via anaerobic glycolysis, with a theoretical yield of 2 mol of H_2 per mol of glucose. Despite the relatively low hydrogen yield of the dark fermentation process (4 moles of H_2 per mole of glucose) and the accumulation of the chemical oxygen demand (COD), it is still attractive due to its high production rates, simple design, operation, and dual goal of wastewater treatment and hydrogen production.

2.3. Pyrolysis/gasification

The biomass gasification process uses controlled thermal energy, steam, and/or oxygen to convert the biomass into hydrogen and other products. Pyrolysis is also a thermal route that uses thermal energy in the absence of oxygen to decompose biomass into gases (CH_4, CO, CO_2, and H_2), oils (bio-oil), and char (Pietraccini et al., 2023; Suriapparao and Tejasvi, 2022; Trada et al., 2022; Xu et al., 2023). The pyrolysis process requires a high-temperature range of 500–900 °C to maximize the gas and liquid yields and minimize the char yield. Table 5 shows the different conditions for pyrolysis and gasification processes (Bridgwater, 2012).

Several biomass feedstocks can be used in such processes, including nonedible crops and agricultural residues. Those processes are in the commercial stage, and hydrogen production by this route is attainable. Also, since the feedstock is biomass that already utilizes CO_2 from the atmosphere, the net carbon footprint of such processes is relatively low, especially if the CO_2 product of the process is captured and stored or used for further production steps.

Recent research trends focus on maximizing the hydrogen production rate by:

i. Improving the design of gasification (Ishaq and Dincer, 2021; Nurdiawati et al., 2019) and pyrolysis (Cui et al., 2020) reactors.
ii. Utilization of an effective catalyst for both pyrolysis and gasification reactions. For gasification, several catalysts have been tested, such as nickel (Balat, 2008), KOH/K_2CO_3 (Zhang et al., 2014), and Al_2O_3/Ni (Farooq et al., 2020). For pyrolysis, several catalysts have been studied, such as $NiZnAlO_x$ (Dong et al., 2017), $NiAl_2O_3$ (Akubo et al., 2019), Ni/Mg/Al/Ca (Kumagai et al., 2015), and Ni–Al nanosheets (Yang et al., 2021c).
iii. Using different substrate feed stocks, such as recycled high-density polyethylene (Kumagai et al., 2015), wood + plastic

Table 3
Some microalgae strains used for hydrogen production.

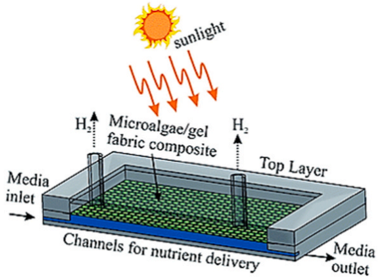
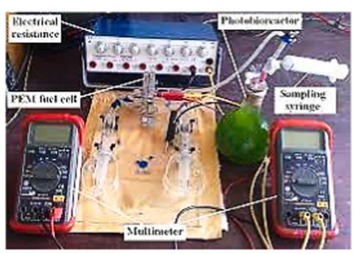
No.	Microalgae strain	Reactor/process	Hydrogen production	Ref.
1	C. *reinhardtii cy6Nac2.49*	Photoheterotrophic conditions in regular tris-acetate-phosphate (TAP) medium with a 10-h:14-h light–dark regime.	0.21 mL H_2 h^{-1} g^{-1}	(Batyrova and Hallenbeck, 2017)
2	Immobilized C. reinhardtii CC-124	 The microalgae is immobilized in a fabric and a micro bioreactor was used	0.7937 mL h^{-1} g^{-1}	(Das et al., 2015)
3	C. *reinhardtii* CC-124	* Roux type flat glass-packed bed reactor * Magnetic stirring, T = 200 °C, and pH = 0.9	7 mL H_2 L^{-1} h^{-1}	(Zhang and Melis, 2002)
4	Chlorella *vulgaris*	 Hydrogen production in both direct and indirect pathways without using nutrient starvation.	12 mL H_2 L^{-1} h^{-1}	(Touloupakis et al., 2021)
5	Chlorella *sorokiniana*	 Photobioreactor of 500-mL coupled to a small proton exchange membrane fuel cell (PEMFC)	0.87 mL H_2 L^{-1} h^{-1}	(Chader et al., 2011)
6	Scenedesmus *obliquus*	Three photobioreactor cells, and hydrogen production is measured by gas chromatography	4.7–12.3 mL H_2 L^{-1} h^{-1}	(Papazi et al., 2012)
7	Platymonas *subcordiformis*	A flat-plate photobioreactor system combined with an alkaline fuel cell	1.1 mL H_2 L^{-1} h^{-1}	(Yang et al., 2008)

Table 4
Comparison between light-induced and light-free fermentation processes (Bolatkhan et al., 2019).

Parameter	Photofermentation	Dark Fermentation
Light requirement	Yes	No
O_2 requirement	Absent	Absent
Reaction	$CH_3COOH + 2\ H_2O$ + light → $4\ H_2 + 2CO_2$	$C_6H_{12}O_6 + 6\ H_2O \rightarrow 12\ H_2 + 6CO_2$
Enzymes involved	PSII, [Fe]-hydrogenase	CoA, acetyl-CoA
Microorganisms involved	Photosynthetic bacteria and Algal species (e.g., *Rhodobacter sphaeroides and Anabaena variabilis*).	Anaerobic bacteria (e.g. *lostridium, Escherichia coli*, and *Sporolactobacillus*).
Advantages	Large range of feedstock and a large spectrum of light.	Cost-effective, and a wide range of feedstock.
Weaknesses	High-priced photobioreactors, light dependency, and low conversion efficiency of solar energy.	Require effluent treatment and additional gaseous byproducts (H_2S, CO_2, CO, and CH_4).

(Alvarez et al., 2014), rice husk, sugar cane bagasse (Waheed and Williams, 2013), cellulose/hemicellulose/lignin (Wu et al., 2013).

iv. Integrating the pyrolysis/gasification processes with a second step for improved hydrogen production (Arregi et al., 2016; Duman and Yanik, 2017)

However, challenges still pertain to both the pyrolysis and gasification routes, including reducing the CAPEX associated with the equipment and feedstock costs.

2.4. Hybrid coupling of processes

Several attempts have been reported to couple some routes of hydrogen production to intensify green hydrogen production and alleviate some challenges associated with the production process. Here, some of the integrated processes currently being investigated are highlighted.

2.4.1. Anaerobic digestion coupled with dark fermentation

Integrating dark fermentation with the anaerobic digestion process

Table 5
Conditions for pyrolysis and gasification processes (Bridgwater, 2012).

Mode	Temperature (°C)	Residence Time		Product Yields (wt)		
		Vapor	Solid	Liquid	Solid	Gas
Fast	500	1–2 s		75	12	13
Intermediate	500	5–30 s		50	25	25
Slow (carbonization)	400	Hours-days	Hours	30	35	35
Gasification	750–900	1–5 s		3	1	95
Torrefaction	280		10–60 min	0	80	20

can alleviate the challenges currently hindering the scale-up of the dark fermentation process (Bundhoo, 2019). Eroğlu et al. (Eroğlu et al., 2006) reported 100% efficiency of biomass conversion into hydrogen with 29 L of H_2 per L of feed. Kim et al. (Kim et al., 2006) reported 88% efficiency by converting starch and glutamate into hydrogen in a two-stage process with 8.2 mol of H_2 per mol of hexose. Also, Phanduang et al. (Phanduang et al., 2019) investigated hydrogen production using pretreated *Chlorella* sp. biomass by coupling the anaerobic digestion, dark fermentation and photofermentation processes. The results showed an energy yield of 5.98 kJ per g *VS* (172.2 mL hydrogen per g *VS*) compared with 1.86 kJ per g *VS* for the dark fermentation coupled with the photofermentation process. This two-stage process provides an economically viable option for large-scale implementation, but it needs more efforts to be scaled up.

2.4.2. Dark fermentation coupled with bioelectrochemical systems

Dark fermentation is linked with electrochemically induced hydrogen production to enhance substrate degradation and hydrogen generation. Wang et al. (Wang et al., 2011) reported the application of such a route using cellulose as a substrate. They used a microbial fuel cell (MFC) as the power source for the MEC connected to the dark fermentation reactor. Without any external electricity source, they reported a hydrogen production rate of 0.24 m^3 m^{-3} d^{-1} and an energy recovery efficiency of 23%. Marone et al. (Marone et al., 2017) used real wastewater as a feedstock for the dark fermentation reactor coupled with a MEC unit. The overall process achieved a hydrogen production of 1609 mL H_2 per g $COD_{removed}$ and a maximum of 79% COD removal. Other research focused on improving the COD removal efficiency and energy conversion efficiency (Table 6).

2.4.3. Dark fermentation coupled with photofermentation

Combining dark fermentation with photofermentation processes provides a promising biohydrogen production route. This approach has successfully reached the maximum overall hydrogen yield from a single substrate (Ren et al., 2011). Zhang et al. (Zhang et al., 2020) studied the hydrogen production from corn using dark fermentation followed by photofermentation. They achieved a hydrogen yield of 141.42 mL (g $TS)^{-1}$ and an energy conversion efficiency of 6.45%. Also, Quanguo Zhang et al. (Zhang et al., 2018) conducted a study at the pilot-scale level. They constructed a 3-m^3 dark fermenter and an 8-m^3 photo fermenter for corn stove substrates. They reported a maximum production rate of 87.8 m^3 day^{-1} of biogas containing 68% hydrogen. Also, they reported the challenges of pilot-scale operation, including the effects of poor mixing, washout, and other inhomogeneities.

3. Hydrogen contribution to sustainable development

Many researchers across the globe see hydrogen as an excellent substitute for conventional energy resources such as coal, petroleum, and natural gas (Rosen and Koohi-Fayegh, 2016). Unlike fossil fuels, when hydrogen is burned, it does not produce hazardous gases, including GHGs, such as CO_2, carbon monoxide, and methane, making it an excellent energy carrier with little to no environmental effects. Hydrogen can be converted into electricity with high-energy conversion efficiency using fuel cells to meet the world's prevailing energy demands (Felseghi et al., 2019). Similarly, when hydrogen is blended with natural gas, it reduces carbon emissions, making it an excellent alternative method to use alongside the current energy resources. Just 20% of hydrogen blended with natural gas and coal will reduce global CO_2 emissions by 6 million tons (Felseghi et al., 2019), corresponding to the CO_2 emissions from 2.5 million cars and meeting the Paris agreement on reducing climate change (Jovan and Dolanc, 2020).

Hydrogen has been categorized as a clean and green energy carrier with a popular renewable energy system that can be used in the worldwide long-term sustainable development of industries and societies. The carbon-less future using green hydrogen can be attained by considering its uses in the following ways:

1. Green hydrogen production expansion will lead to a degradation in the production of fossil fuels generated hydrogen, reducing the production of CO_2 and GHG emissions (Howarth and Jacobson, 2021a).

2. Green hydrogen can be added to natural gas (just a few percent of hydrogen). This approach will decrease the use of natural gas to generate electricity, which will eventually reduce GHG generation and help in meeting the Paris agreement and decarbonization goal (Verhelst,

Table 6
Hydrogen production by integrated processes.

No	Substrate	Integration processes	Hydrogen production	COD removal	Energy efficiency	Ref.
1	Rotted wood crumbs enriched with other nutrients	Dark fermentation + MEC + MFC	0.24 m^3 m^{-3} d^{-1}	64%	23%	(Wang et al., 2011)
2	Wastewater	Dark fermentation + MEC	1609 mL H_2 per g $COD_{removed}$	79%	-	(Marone et al., 2017)
3	Sugar beet juice	Dark fermentation + MEC	6 mol H_2 per mol hexose	25%	57%	(Dhar et al., 2015)
4	Macroalgae	Dark fermentation + MEC	438.7 mL H_2 per g TS	75.6%	34.1%	(Nguyen et al., 2020)
5	Palm oil mill	Dark fermentation + MEC	236 mL H_2 per g $COD_{removed}$	86%	-	(Khongkliang et al., 2019)
6	Simple sugars + volatile fatty acids + water hyacinth	Dark fermentation + MEC	67.69 L H_2 per kg $COD_{consumed}$	70.3%	46%	(Varanasi and Das, 2020)
7	Wastewater	Dark fermentation + MEC+ MFC	0.66 L H_2 per g $COD_{removed}$	-	44%	(Estrada-Arriaga et al., 2021)
8	Corn stalk	Dark fermentation + MEC	387.1 mL H_2 per g corn stalk	46%	166%	(Li et al., 2014)

2014).

3. Clean and green hydrogen provides better health and well-being with less air pollution and is considered an excellent source to overcome climate change.

4. Green hydrogen production expansion will create more jobs, investment opportunities, and sustainable development. Moreover, energy security can be achieved by reducing exposure to oil price instability and interruptions (Jovan and Dolanc, 2020).

Green hydrogen can be used to meet the SDGs as a clean and green energy resource. Being a renewable energy resource, the important role of green hydrogen in meeting the energy transition and SDGs (Beniugă et al., 2021) is as follows:

- Green hydrogen relies on renewable energy resources, which helps in decarbonization and meets the Paris agreement to limit global warming and climate change by reducing the production of harmful and hazardous gases.
- Green hydrogen is considered a better, more reliable, and more efficient way to meet and reduce the current worldwide energy crisis.
- Green hydrogen is an efficient way of creating systems to improve the transportation and industrial sectors by providing energy with zero GHG emissions. The fuel is more efficient than conventionally used fuel, which will also help maintain vehicle engines (Chaube et al., 2020). Hydrogen use in fuel cell cars will eliminate a significant part of the emitted pollution by the transportation sector (Olabi et al., 2021).
- Green hydrogen can effectively secure the power and heat requirements in buildings and other domestic applications using fuel cells that have low or no environmental impacts (Olabi et al., 2020a; Birol, 2019).
- While developing countries can benefit from already present technology, a green hydrogen economy will provide more market opportunities for investors and buyers, resulting in an improved overall economy and investment for countries across the world.

The green hydrogen technology scale-up can be achieved through research, development, and advancement in hydrogen production and conversion. Research and development will provide better methods for producing more hydrogen while considering the environmental impact. Enhancing the present system's design of green hydrogen generation and renewable electricity production is a prerequirement that can be actualized by creating large-scale hydrogen production and conversion systems with excellent and closed storage facilities. However, to effectively support and encourage large-scale implementation of green hydrogen, a strong policy framework and better government involvement are required (Scita et al., 2020). Furthermore, with the perseverance and ongoing collaboration of research, industry, and government to provide a policy framework and incentives, advancement in this field can be achieved.

4. Role of green hydrogen in SDGs

The UN 2030 Agenda for sustainable development, adopted by all UN member states in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. Fig. 7 shows the 17 SDGs, further divided into 169 specific targets to realize the different SDGs. Clean energy is one of the main drivers of the SDGs. Hydrogen as an energy vector, which is considered one of the cleanest energy carriers, can be directly correlated to the different SDGs. The relation of hydrogen energy to the various SDGs is introduced in this section, following the relation strength order.

The realization of SDG-7 would help achieve SDG-13, SDG-6, and SDG-12. The realization of SDG-7 can also help realize SDG-4 by making electrical power available to the poor and remote communities, thereby increasing the civilization level in these areas, which is to drive obtaining a quality education. The realization of SDG-13 helps realize SDG-3 due to reduced emissions-related pollution, which in turn enables SDG-14 and SDG-15. Similarly, realizing SDG-9 through investment in R&D and new processes will drive the realization of SDG-1 due to the increased rate of employment and SDG-8 due to large investments in the hydrogen economy, accordingly enabling SDG-5 and SDG-10 (Espegren et al., 2021; Saeedmanesh et al., 2018). Table 7 summarizes the possible contribution of green hydrogen to the SDGs. Here, this role will be further explained.

4.1. Green hydrogen (indicators) guideline

Green hydrogen could play an important role in achieving the SDGs, as discussed in the following sections. However, 84 indicators (Table 8) have been proposed to ensure this achievement. The proposed indicators will provide guideline for stakeholders to ensure that green hydrogen fully adheres to the basics of the SDGs. Moreover, the indicators will

Fig. 7. The 17 UN-SDGs "United Nations Sustainable Development Goals", www.un.org/development/desa/disabilities/envision2030.html, accessed January 2023.

Table 7
Direct contribution of green hydrogen to the most related SDGs.

SDGs	Contribution
SDG 1: "No Poverty"	1. Provide new jobs (Pollet, 2021). 2. Reduce poverty (Mac Dowell et al., 2021). 3. Increase access to basic services and economic resources (Ayodele and Munda, 2019; Xiang et al., 2021).
SDG 2: "Zero Hunger"	4. Increase agriculture productivity by increasing sustainable production and decrease fertilizer prices (Thapa et al., 2021). 5. Support smallholders (Smith and Torrente-Murciano, 2021).
SDG 3: "Good Health and Well-being"	6. Reduce deaths and illnesses from pollution (Hemming, 2021; Trattner et al., 2022).
SDG 6: "Clean Water and Sanitation"	7. Increase the drinking water production (Beswick et al., 2021; Newborough and Cooley, 2021). 8. Improve water quality and wastewater treatment process (Beswick et al., 2021; Germscheidt et al., 2021; Newborough and Cooley, 2021; Sarkar et al., 2022).
SDG 7: "Affordable and Clean Energy"	9. Increase access to energy (Dembi, 2022; Gondal et al., 2018). 10. Improve energy efficiency (Gao et al., 2021; Oliveira et al., 2021).
SDG 8: "Decent Work and Economic Growth"	11. Sustain inclusive economic growth and improve economic productivity (AbouSeada and Hatem, 2022; Babayomi et al., 2022; Liu et al., 2022; Seada and Hatem, 2022). 12. Create decent work (Compact, 2020; Heinemann et al., 2021; Taibi et al., 2020). 13. Improve resource efficiency (Allwood et al., 2020; Durusut et al., 2020; Elavarasan et al., 2022).
SDG 9: "Industry, Innovation, and Infrastructure"	14. Develop high resilient infrastructure and improve industrialization sustainability (Barceló Álvarez, 2021; Shahid, 2021). 15. Add a value to the waste and decrease the carbon footprint (Allwood et al., 2020; Biggins et al., 2022; Durusut et al., 2020; Elavarasan et al., 2022; Lai et al., 2021). 16. Enhance R&D within the industrial sector (Karaca and Dincer, 2021; Li et al., 2021).
SDG 11: "Sustainable Cities and Communities"	17. Improve transportation sustainability (Kazi et al., 2021; Li and Taghizadeh-Hesary, 2022; Oliveira et al., 2021) 18. Improve air quality (Becerra-Ruiz et al., 2019; Okedu et al., 2022). 19. Decrease urbanization impacts (Akhtar and Liu, 2021; Cheshmehzangi and Chen, 2021; Chien et al., 2022). 20. Increase access to basic services (Ayodele and Munda, 2019; Xiang et al., 2021).
SDG 12: "Responsible Consumption and Production"	21. Improve resource usage sustainability (D'Errico et al., 2013; Naveenan and Teoh, 2021; Vidinopoulos et al., 2020). 22. Increase product lifespan (Boretti, 2021; d'd'd'Amore-Domenech et al., 2020). 23. Reduce waste and improve waste recycling (Camacho et al., 2017; Hovorukha et al., 2021; Shaban et al., 2021). 24. Support circular economy (Collera and Agaton, 2021; Fan et al., 2021; Kakoulaki et al., 2021).
SDG 13: "Climate Action"	25. Reduce the overall GHG emission (Abad and Dodds, 2020; van Renssen, 2020).
SDG 14: "Life Below Water"	26. Reduce land source pollution (Abad and Dodds, 2020; Pangsy-Kania and Flouros, 2021). 27. Improve maritime transport and sustainability (Atilhan et al., 2021; Safara Nosar, 2021).
SDG 15: "Life on Land"	28. Decrease land-use change and deforestation (BHAGWAT and Olczak, 2020; d'd'd'Amor-e-Domenech et al., 2020; Nurdiawati and Urban, 2022). 29. Reduce the overall GHG emission (Abad and Dodds, 2020; van Renssen, 2020). 30. Improve the sustainable usage of terrestrial resources (Amulya and Mohan, 2022; Mac Dowell et al., 2021; Nadaleti et al., 2021).

minimize the trade-off impacts of the green hydrogen and increase the synergy. The indicators were extracted from the literature (Falcone et al., 2021; Gondal et al., 2018; Reporting, 2019).

4.2. Role of green hydrogen in achieving the SDGs

Here, the role of green hydrogen in achieving the SDGs is covered.

4.2.1. SDG 1 "No Poverty"

Direct contribution

A. **Provide new jobs** (Pollet, 2021).
B. **Reduce poverty** (Mac Dowell et al., 2021).
C. **Increase access to essential services and economic resources** (Ayodele and Munda, 2019;Xiang et al., 2021).

Indicators:
1. Total products and services procured from local market.
2. Lower utility fees.
3. Taxes contribution.
4. Direct economic value shared: employee wages and benefits, and payments to providers of capital and community investments.

Poverty is considered an important SDG to eradicate in all of its forms. With hydrogen as an energy generation means, a more uninterrupted supply of electricity will be generated, resulting in better transportation in areas with food shortages and health issues. Also, the job market will increase with more jobs due to green hydrogen generation. It is estimated that in Europe, green hydrogen will provide ~5.4 million jobs (Pollet, 2021). Moreover, transportation will be improved using green hydrogen, which will help in reducing poverty across the globe and providing better food transportation (Benevenuto and Caulfield, 2019).

4.2.2. SDG 2 "Zero Hunger"

Direct contribution:

A. **Increase agriculture productivity by increasing sustainable production and decrease fertilizer prices** (Thapa et al., 2021).
B. **Support smallholders** (Smith and Torrente-Murciano, 2021).

Indicators:
5. Occupied land type (arable/nonarable).
6. Conduct a risk assessment.
7. Help smallholders by lower the utility price.

Ill-nourished people across the globe who do not have better food and nutrient facility are increasing drastically. An increase in jobs across the world due to green hydrogen will reduce poverty, there by reducing hunger and nutrient deficiency across the globe due to access to better food facilities (Gielen et al., 2019). Moreover, green hydrogen could be produced in the desert and remote areas from properly managed

Table 8
Green hydrogen Sustainable Development Goals (SDGs) indicators and guidelines.

SDG	Indicators
	1. Total products and services procured from local market. 2. Lower utility fees. 3. Taxes contribution. 4. Direct economic value shared: employee wages and benefits, and payments to providers of capital and community investments.
	5. Occupied land type (arable/nonarable). 6. Conduct a risk assessment. 7. Help smallholders by lower the utility price.
	8. Accounts all hazard materials. 9. Implement an occupational health and safety policy. 10. Control measures the dust. 11. Ensure the that the number of accidents lower to the minimum. 12. Lower the noise to the minimum. 13. Measure the healthcare benefits given to employees. 14. Use the life cycle assessment (LCA) to evaluate human toxicity and particulate matter.
	15. Provide a training for every employee. 16. Ensure zero child labor policy is available. 17. Improve employees' skills by offering training program. 18. Provide support for retired or terminated employees and any preretirement plan for intended retirees.
	19. Proportion of recruited and employed women. 20. Ensure fair equality in all positions. 21. Ensure fair women's involvement and engagement in all project decisions. 22. Measure the sex percentage within the company. 23. Measure the employees by age group percentage. 24. Ensure the fair salaries paid.
	25. Water usage before and after project. 26. Measure the water quality. 27. Lower water footprint. 28. Employee the LCA to measure eutrophication potential and freshwater aquatic ecotoxicity potential.

(*continued on next page*)

Table 8 (*continued*)

SDG	Indicators
7 AFFORDABLE AND CLEAN ENERGY	29. Sum of energy produced. 30. Level of accessibility 31. Total finance support provided for clean energy for R&D. 32. Lower energy cost after implementing the project. 33. Energy utilization efficiency 34. Security of primary energy supply. 35. Contribution to energy sufficiency. 36. Total investment for support energy efforts.
8 DECENT WORK AND ECONOMIC GROWTH	37. Total products and services procured from local market [similar to indicators 1]. 38. Proportion of accommodation provided to temporary employees. 39. Occupational index. 40. Inherent safety index. 41. Direct economic value shared. 42. Economic value retained. 43. The total of materials utilized. 44. Economic value retained.
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	45. Conduct environmental, social and economic impact assessments throughout the whole lifecycle of the project. 46. Total convening power employed. 47. Total value-added. 48. Implementing circular business models.
10 REDUCED INEQUALITIES	49. Provide a training for marginalized populations. 50. Ensure an equal d distribution of the salary between different working groups. 51. Percentage of employees in minority groups. 52. Measure the inclusion and diversity level.
11 SUSTAINABLE CITIES AND COMMUNITIES	53. Ensure resources sustainability policies is accessible. 54. Increase the engagement in microgrids implementation. 55. Lower the generated waste.
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	56. Increase energy efficiency. 57. Put an effort to lower the most significant environmental impacts of the project this includes materials used, water, emissions, effluents, noise, waste, and energy usage. 58. Quantified energy requirements of products and services achieved during the reporting period. 59. Measure all types of pollution. 60. Total materials used. 61. Total direct materials and nonrenewable materials used. 62. Energy consumption by nonrenewable and renewable primary sources.
13 CLIMATE ACTION	63. Type of occupied land. 64. Measure all types of pollution [similar to indicator 60] 65. Total research conducted to tackle climate change. 66. Level of engagement in industrial climate discussions.

(*continued on next page*)

Table 8 (*continued*)

SDG	Indicators
14 LIFE BELOW WATER	67. Measure water-related pollution. 68. Measure marine ecotoxicity.
15 LIFE ON LAND	69. Conduct an environmental impact assessment. 70. Total contribution to research initiatives and landscape planning. 71. Evaluate the impact on biodiversity and ecosystem. 72. Total land required to develop the project. 73. Quantify the eutrophication potential, NO_x, SO_x, particulate matter, persistent organic pollutants, equivalent volatile organic compounds, organic pollutants, hazardous air pollutants, stack, freshwater aquatic ecotoxicity, and fugitive emissions. 74. Effect on mitigation of harmful gases. 75. Total land required. 76. Initiatives to reduce GHG emissions. 77. Impact of significant spills. 78. Total resources required.
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	79. Degree of stakeholders' involvement. 80. Degree of conformity with regulations and disclosing information. 81. Antibribery management systems availability.
17 PARTNERSHIPS FOR THE GOALS	82. Ensure a high level of participation with industry groups. 83. Integrate the SDGs' principles within the company policies. 84. Ensure a high level of collaboration with local authorities and government.

wastewater of the respective community via MEC and other biological means. In coastal areas, such hydrogen can power desalination plants for irrigation purposes, thus securing food for such places. Additionally, the increase in the production of green ammonia will increase the sustainable production of fertilizer, which is one of the essential elements in improving agricultural production and food security (Imasiku et al., 2021).

4.2.3. SDG 3 "Good health and Well-being"

3 GOOD HEALTH AND WELL-BEING	**Direct contribution:** A. **Reduce deaths and illnesses from pollution** (Hemming, 2021;Trattner et al., 2022) Indicators: 8. Accounts all hazard materials. 9. Implement an occupational health and safety policy. 10. Control measures the dust. 11. Ensure the that the number of accidents lower to the minimum. 12. Lower the noise to the minimum. 13. Measure the healthcare benefits given to employees. 14. Use the LCA to evaluate human toxicity, particulate matter, and photochemical ozone.

SDG-3 focuses on ensuring a healthy life and promote well-being for humans. The emissions associated with fossil energy resources causing air pollution have resulted in degraded health conditions and many respiratory system diseases (Orach et al., 2021; Tainio et al., 2021). Several studies have evaluated the benefits of reduced fossil fuel consumption with increased prices, relating it to improved air quality and fewer health problems (Shaw et al., 2018; Yang et al., 2021b). Accordingly, the expansion in utilizing hydrogen as fuel will significantly reduce health problems associated with air pollution and even be further reduced upon using green hydrogen specifically.

With minimal to zero gas emissions, green hydrogen is considered an environmentally friendly energy carrier and a step forward toward low levels of air and water pollution. Air pollution caused by conventional fuel includes GHG emissions, including CO_2, methane, and carbon monoxide. When mixed with air, these gases increase the overall temperature, humidity, and dust in the air, thereby increasing the risk of chronic health diseases. Low air pollution reduces the risk of acute and chronic respiratory and health diseases, thus helping in achieving good health (Laumbach et al., 2015). With low air pollution, it would be easy for individuals to go out and travel, which helps better their health and well-being.

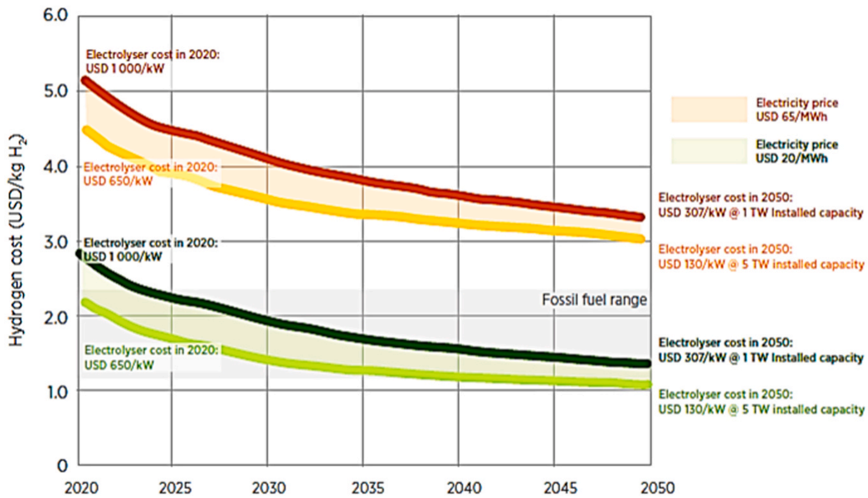


Fig. 8. Horizon of green hydrogen cost (IRENA, 2020).

4.2.4. SDG 4 "Quality Education"

15. **Provide a training for every employee.**
16. **Ensure zero child labor policy is available.**
17. **Improve employees' skills by offering training program.**
18. **Provide support for retired or terminated employees and any preretirement plan for intended retirees.**

With green hydrogen providing an uninterrupted energy source, it would become easy to provide quality education across the globe through online education and schools (Gielen et al., 2019). Moreover, the improved income with green hydrogen would encourage people to care for their children's education.

4.2.5. SDG 5 "Gender Equality"

19. **Proportion of recruited and employed women.**
20. **Ensure fair equality in all positions.**
21. **Ensure fair women's involvement and engagement in all project decisions.**
22. **Measure the sex percentage within the company.**
23. **Measure the employees by age group percentage.**
24. **Ensure fair salaries are paid.**

With an improved job market and an increase in the quality of education using green hydrogen, women across the globe can also play their part in gaining education and performing different jobs. Similarly, providing a better means of transport helps improve women's health-related issues.

4.2.6. SDG 6 "Clean water and sanitation"

Direct contribution:

A. **Increase the drinking water production (**Beswick et al., 2021;Newborough and Cooley, 2021**).**
B. **Improve water quality and wastewater treatment process (**Beswick et al., 2021**;** Germscheidt et al., 2021;Newborough and Cooley, 2021;Sarkar et al., 2022**).**

Indicators:

25. Water usage before and after project.
26. Measure the water quality.
27. Lower water footprint.
28. Employee the LCA to measure eutrophication potential and freshwater aquatic ecotoxicity potential.

Industries use fossil fuels as a source to meet the energy requirements of combustion chambers. These industries and sources emit many gases, including methane, CO_2, carbon monoxide, and residuals, that partially dissolve into clean water resources, including lakes, clean water resources, oceans, and rivers (Allen et al., 2012). Switching these conventional energy resources to green hydrogen energy can help achieve zero emissions of gases and residuals, which will help in keeping the freshwater resources clean for drinking and sanitation purposes. Similarly, sanitation will increase based on clean water, thereby reducing diseases created by poor sanitation.

SDG-6 focuses on ensuring the availability and sustainable management of water resources. Thus, transitioning from the fossil energy era to hydrogen civilization will considerably help achieve this goal (Peer and Sanders, 2018). The green hydrogen contribution to SDG-6 can be discussed in different aspects. First, energy, with hydrogen as an energy carrier, is essential to drive water and wastewater treatment processes to produce water for domestic and industrial applications. The water-energy nexus has been widely discussed to describe water and energy interdependence (Healy et al., 2015; Siddiqi and Anadon, 2011). This interdependence is becoming clearer in the energy needed to drive water desalination in areas with no to poor freshwater resources due to the high-energy demand of desalination (Al-Karaghouli and Kazmerski, 2013; Ghalavand et al., 2015). Second, hydrogen combustion produces water, which can be considered an added-value product rather than waste, hence increasing local water resources (Ando and Tanaka, 2004; El-Bassuoni et al., 1982). Third, replacing fossil energy resources with hydrogen helps to reduce water use and pollution due to the extraction and utilization of such fossil resources (Nouri et al., 2019; Pan et al., 2018).

4.2.7. SDG 7 "Affordable Clean Energy"

7 AFFORDABLE AND CLEAN ENERGY

Direct contribution:

A. **Increase universal access to energy** (Allwood et al., 2020; Durusut et al., 2020; Elavarasan et al., 2022).
B. **Improve energy efficiency** (Shahid, 2021) (Hannah Ritchie, 2020; Shahid, 2021).

Indicators:
29. Sum of energy produced.
30. Level of accessibility
31. Total finance support provided for clean energy for R&D.
32. Lower energy cost after implementing the project.
33. Energy utilization efficiency
34. Security of primary energy supply.
35. Contribution to energy sufficiency.
36. Total investment for support energy efforts.

This goal aims to ensure access to affordable, reliable, sustainable, and modern energy for all. SDG-7 relies on two pillars: affordability and cleanness of worldwide energy supply. Achieving SDG-7 can be realized by rising the renewable energy share within the energy supply, improving the energy efficiency, facilitating access to clean energy research and technology, and expanding infrastructure and upgrading technology to supply sustainable energy services (Obaideen et al., 2023; Ren and Toniolo, 2020; Saeedmanesh et al., 2018). Compared to conventional energy resources, green hydrogen is considered a clean and sustainable energy resource. It uses other renewable energy resources, including solar and wind, to produce hydrogen that can be stored and transformed to electricity. In fact, green hydrogen fuel is more efficient than conventional energy resources because more energy can be extracted. Thus, green hydrogen is an efficient and affordable source of energy generation in automobiles and other various industries. Affordable energy from green hydrogen will help mitigate fuel poverty and energy requirement in industries in various parts of the world. Expanding infrastructure, improving production methods, and upgrading technology to provide clean and green hydrogen with more efficient energy in all countries will encourage growth, create more jobs, increase investments and help the environment and economy.

The affordability pillar of hydrogen energy is mainly related to its cost, accessibility, and availability. There are many hydrogen production methods, and depending on the energy resources and feedstock utilized for hydrogen production, produced hydrogen color indicators can be assigned (Bacquart et al., 2019). Starting with white hydrogen for naturally occurring hydrogen, as present in the Sun, to black hydrogen, produced from fossil fuels/hydrocarbons (becoming grey when using natural gas) using conventional thermal methods. Among the different hydrogen products, blue and green hydrogen products have attracted more attention as the cleaner hydrogen. Blue hydrogen is a black/grey hydrogen modification in which carbon emissions are avoided by carbon capture and storage/sequestration/utilization (Martínez-Rodríguez and Abánades, 2020; Olabi et al., 2022). Green hydrogen is currently considered the cleanest hydrogen product, as it is produced from non-fossil resources using renewable energy resources, exemplified by seawater electrolysis using solar and wind energy (Hosseini and Wahid, 2016; IRENA, 2020). Green hydrogen used to be more expensive than black/grey hydrogen due to the higher renewable energy cost. However, recent developments in renewable energy production have significantly decreased such costs (Obaideen et al., 2021; Olabi et al., 2023). The cost of green hydrogen ranges from \$3–6.5 per kg to \$2.4 and \$1.8 per kg for blue and grey hydrogen products, respectively (Commission, 2020). However, reductions in electrolyzer and power costs are believed to significantly decrease the cost of green hydrogen to the grey hydrogen range by 2025 and further below by 2040 (Fig. 8) (IRENA, 2020).

Hydrogen is the fuel with the highest gravimetric energy density and the cleanest fuel, with water as the only product, considering the energy production phase (Ozbilen et al., 2013). Furthermore, water produced from hydrogen combustion can be considered an added-value product, especially for areas with water resource shortages (El-Bassuoni et al., 1982). The current challenge to achieving the full cleanness of hydrogen energy is due to material extraction and manufacturing phase-related emissions, such as those related to the materials used as electrolyzers and renewable energy production, such as semiconductors for photovoltaic cells (Cetinkaya et al., 2012; Zhao et al., 2020; Alami et al., 2022). Several LCAs of different hydrogen production methods have been conducted to compare conventional and renewable-driven production routes (Bhandari et al., 2014; Sadeghi et al., 2020). Green hydrogen has shown better environmental performance in most LCA categories than conventional ones. A recent study on comparative LCSA has shown that the harmonized global warming potential (GWP), as the most significant environmental indicator, for wind-powered electrolysis, is ~1.16 kg CO_2-eq. kg^{-1} H_2, as compared to 11.4 kg CO_2-eq. kg^{-1} H_2 for the conventional SMR is slightly less for biomass gasification, with only 0.18 CO_2-eq. kg^{-1} H_2 due to the negative emission of biomass utilization (Bhandari et al., 2014).

4.2.8. SDG 8 "Decent Work and Economic Growth"

8 DECENT WORK AND ECONOMIC GROWTH

Direct contribution:

A. **Sustain inclusive economic growth and improve economic productivity** (AbouSeada and Hatem, 2022; Babayomi et al., 2022; Liu et al., 2022; Seada and Hatem, 2022).
B. **Create decent work** (Compact, 2020; Heinemann et al., 2021; Taibi et al., 2020).
C. **Improve resource efficiency** (Allwood et al., 2020; Durusut et al., 2020; Elavarasan et al., 2022).

Indicators:
37. Total products and services procured from the local market [similar to indicators 1].
38. Proportion of accommodation provided to temporary employees.
39. Occupational index.
40. Inherent safety index.
41. Direct economic value is shared.
42. Economic value retained.
43. The total of materials utilized.
44. Economic value retained.

As the global economy recovers from COVID-19, an overview shows slower growth, widening inequalities, and insufficient jobs to keep up with a growing labor force. Better environmental safety for using green hydrogen as an energy resource will lift the economic growth of countries with green hydrogen infrastructure. Hydrogen infrastructural development will result in job opportunities, thereby fostering economic growth. This growth and development will encourage entrepreneurship, which will help reduce forced labor, slavery, and human trafficking. Besides, it will also provide socio-economic benefits, which foster economic growth. It is predicted that by switching toward clean and green hydrogen energy, million jobs will be created by the end of 2050, thus reducing poverty and hunger with decent work and economic growth enhancement (Yuksel, 2012).

Green hydrogen is characterized as an innovative and sustainable energy carrier that can provide low to zero gas emissions in industries. As hydrogen is flammable, similar to conventional energy resources, similar infrastructure is required to store hydrogen fuel (with modification), thereby reducing the infrastructural cost of the storage system and thus proving green hydrogen as an excellent energy carrier (Eljack and Kazi, 2020). On the other hand, large-scale production and conversion of hydrogen require large infrastructures, resulting in more jobs in the development sector (Jovan and Dolanc, 2020).

4.2.9. SDG 9 "Industry, Innovation, and Infrastructure"

Direct contribution:

A. **Develop resilient infrastructure and improve industrialization sustainability** (Barceló Álvarez, 2021;Shahid, 2021).
B. **Add a value to the waste and decrease the carbon footprint** (Allwood et al., 2020; Biggins et al., 2022;Durusut et al., 2020; Elavarasan et al., 2022;Lai et al., 2021).
C. **Enhance R&D within the industrial sector** (Karaca and Dincer, 2021;Li et al., 2021).

Indicators:
45. Conduct environmental, social and economic impact assessments throughout the whole lifecycle of the project.
46. Total convening power employed.
47. Total value-added.
48. Implementing circular business models.

SDG-9 aims to promote sustainable industrialization and foster innovation. The goal is to increase the sustainability and energy efficiency of different industrial processes, emphasizing the adoption of clean and environmentally friendly technologies. The transition toward hydrogen energy as a clean and environmentally friendly energy resource has led to significant developments and innovations in many industrial processes for hydrogen production. This transition, of course, has been co-driven by pollution prevention and environmental protection forces, with hydrogen being seen as a strong enabler of such objectives. For example, the demand to produce hydrogen from nonfossil feedstock has led to significant development in the water electrolysis process. Furthermore, more focus is given to utilizing seawater as a globally available and free feedstock for hydrogen production to eliminate competition with limited freshwater resources (Abdel-Aal et al., 2010; d'd'd'Amore-Domenech et al., 2020; Germscheidt et al., 2021).

4.2.10. SDG 10 "Reduced Inequality"

49. **Provide a training for marginalized populations.**
50. **Ensure an equal d distribution of the salary between different working groups.**
51. **Percentage of employees in minority groups.**
52. **Measure the inclusion and diversity level.**

With more energy output from green energy than conventional energy resources, more electricity can be produced, and more jobs can be created. This development will equally distribute opportunities worldwide, thus mitigating the worldwide energy crisis and inequality (Awumbila, 2017).

Moreover, one of pillars of this SDG is social licence and resource justice whereby they are crucial aspects to consider in the development of green hydrogen projects. The willingness of local communities to accept and support these projects is essential, as concerns about potential impacts such as net income of persons, losing some of jobs relies on traditional energies, opening new jobs opportunities relies on renewable energy and green hydrogen, possible displacement may arise. Developers must engage with communities early and frequently to address these concerns and establish social licence. Resource justice, on the other hand, pertains to the fair distribution of benefits and burdens associated with natural resource development. In the case of green hydrogen projects, there is a risk that benefits may disproportionately favor a small number of individuals, while the burdens fall on a larger group. Developers must ensure equitable sharing of project benefits among all stakeholders. Steps to address social licence and resource justice issues include early and frequent community engagement, the formulation of a community benefits plan, transparency about the projects, and the establishment of relationships with local stakeholders. By following these steps, developers can secure the necessary support to successfully develop green hydrogen projects, thereby advancing this clean energy source (Gugerell et al., 2018; Hitch and Barakos, 2021; Hitch et al., 2014; Hitch et al., 2020; Kügerl et al., 2023; Lesser et al., 2021; Paat et al., 2021a; Paat et al., 2021b; Puthiya Veetil et al., 2021; Veetil and Hitch, 2020).

Table 9
Major LCA indicators of different hydrogen production routes.

Production route	GWP	AP	Year, Ref.
Nuclear-based thermochemical Cu–Cl cycle	0.56–0.68	2.84–3.44	2013 (Ozbilen et al., 2013)
Nuclear-based high-temperature electrolysis	2.00	4.84	2013 (Ozbilen et al., 2013)
Natural gas steam reforming	11.9	14.5	2013 (Ozbilen et al., 2013)
	8.6–12.8	-	2014 (Bhandari et al., 2014)
	10.28	-	2020 (Sadeghi et al., 2020)
	11.43	18.6	2021 (Valente et al., 2021)
Coal gasification	11.3	-	2012 (Cetinkaya et al., 2012)
	11.1–12.3	-	2014 (Bhandari et al., 2014)
	11.59	-	2020 (Sadeghi et al., 2020)
Biomass gasification	0.18	14.5	2021 (Valente et al., 2021)
Biomass-based electrolysis	2.40	29.0	2013 (Ozbilen et al., 2013)
Wind-based electrolysis	0.97	2.58	2013 (Ozbilen et al., 2013)
	1.16	11.3	2021 (Tran et al., 2021)
Solar-based electrolysis	2.50	8.06	2013 (Ozbilen et al., 2013)
Solar–PV electrolysis	1.62–7.02	-	2014 (Bhandari et al., 2014)
	3.08	-	2020 (Sadeghi et al., 2020)
Solar–thermal electrolysis	1.89	-	2014 (Bhandari et al., 2014)
	2.06	-	2020 (Sadeghi et al., 2020)

*GWP: Global Warming Potential, kg CO_2-eq. kg^{-1} H_2; AP: Acidification Potential, g SO_2-eq kg^{-1} H_2.

4.2.11. SDG 11 "Sustainable Cities and Communities"

Direct contribution:

A. **Improve transportation sustainability** (Kazi et al., 2021;Li and Taghizadeh-Hesary, 2022; Oliveira et al., 2021).
B. **Improve air quality** (Becerra-Ruiz et al., 2019;Okedu et al., 2022).
C. **Decrease urbanization impacts** (Akhtar and Liu, 2021;Cheshmehzangi and Chen, 2021; Chien et al., 2022).
D. **Increase access to basic services** (Ayodele and Munda, 2019;Xiang et al., 2021).

Indicators:

53. Ensure resources sustainability policies are accessible.
54. Increase engagement in microgrids implementation.
55. Lower the generated waste.

Recently, many population shifts have been seen in urban areas due to increased population and migration (Saner et al., 2021), resulting in more transportation and energy use, which causes pollution and gas emissions issues in big cities. Making cities sustainable means creating career and business opportunities, safe and affordable housing, and building a resilient society and economy (Basit et al., 2020; Saner et al., 2021). This includes investing in public transport, creating lush public spaces, and improving city planning and governance in a participatory and comprehensive manner. With low emissions and an uninterrupted energy source, green hydrogen is considered a sustainable fuel for cities and communities. Unlike solar and wind energy, which depend on sunlight and wind conditions, hydrogen can easily be stored and used afterwards to stabilize the energy demand during energy shortfall and breakdown (Shatnawi et al., 2018). Moreover, green hydrogen in public transportation will improve transportation and air quality (Kazi et al., 2021; Li and Taghizadeh-Hesary, 2022; Okedu et al., 2022; Oliveira et al., 2021).

4.2.12. SDG 12 "Responsible consumption and Production"

Direct contribution:

A. **Improve resource usage sustainability** (D'Errico et al., 2013;Naveenan and Teoh, 2021;Vidinopoulos et al., 2020).
B. **Increase product lifespan** (Boretti, 2021; d'd'd'Amore-Domenech et al., 2020).
C. **Reduce waste and improve waste recycling** (Camacho et al., 2017;Hovorukha et al., 2021; Shaban et al., 2021).
D. **Support circular economy** (Collera and Agaton, 2021;Fan et al., 2021;Kakoulaki et al., 2021).

Indicators:

56. Increase energy efficiency.
57. Put an effort to lower the most significant environmental impacts of the project this includes materials used, water, emissions, effluents, noise, waste, and energy usage.
58. Quantified energy requirements of products and services achieved during the reporting period.
59. Measure all types of pollution.
60. Total materials used.
61. Total direct materials and nonrenewable materials used.
62. Energy consumption by nonrenewable and renewable primary sources.

Achieving economic growth and sustainable development must address the production and consumption of goods, which requires a reduction of the carbon footprint-generating sources and reducing the carbon output to better the environment. The production of green hydrogen is a completely clean source of energy generation. It is easier to produce by electrolysis than burning fossil fuels, as it can be easily stored and converted to fuel and electricity using fuel cells. Moreover, green hydrogen produces no pollution when converted to electricity (using fuel cells) than conventional energy resources (Abdelkareem et al., 2021a). SDG-12 has the specific target of implementing programs for sustainable consumption and production. The SDG aims to achieve an environmentally focused management of chemicals throughout their lifetime, reducing their leakage to air, water, and soil. The expansion of hydrogen usage as an energy vector can contribute significantly toward achieving SDG-12 as it will reduce the consumption of fossil energy resources, which has been associated with many environmental and health problems. Additionally, green hydrogen promotes further responsible consumption and production patterns by utilizing water as feedstock through electrolysis using renewable energy resources (Camacho et al., 2017; Hovorukha et al., 2021; Shaban et al., 2021). Seawater electrolysis further saves priceless freshwater resources (d'd'd'Amore-Domenech et al., 2020; Khan et al., 2021; Mohammed-Ibrahim and Moussab, 2020). These approaches will enhance the movement toward a circular economy (Collera and Agaton, 2021; Fan et al., 2021; Kakoulaki et al., 2021).

4.2.13. SDG 13 "Climate Change"

Direct contribution:

A. **Reduce the overall GHG emission** (Abad and Dodds, 2020;van Renssen, 2020).

Indicators:

63. Type of occupied land.
64. Measure all types of pollution [similar to indicator 60]
65. Total research conducted to tackle climate change.
66. Level of engagement in industrial climate discussions.

SDG-13 for climate action urges the adoption of effective measures and actions to combat the climate changes that the Earth has experienced since the beginning of the industrial revolution. The heart of these actions entails keeping the Earth's temperature rise within the 1.5 °C or 2 °C by 2050 scenarios compared to the preindustrial era (Pachauri et al., 2014). The overexploitation of fossil energy resources with its various gaseous emissions of CO_x, NO_x, SO_x, and many others are the major constituents of GHGs, which have been firmly associated with the rise in atmospheric temperature (Yuksel, 2012). Accordingly, hydrogen energy utilization helps avoid much of the fossil-associated GHG emissions, thereby combating climate change. Different LCA studies have shown a considerable reduction in emissions as represented by the GWP expressed as CO_2-equivalent emissions. Table 9 below shows the major LCA indicators for different hydrogen production routes. Evidently, the GWP and the acidification potential (AP) are the major indicators for the emissions associated with hydrogen production. The GWP is clearly shown to be far less for green hydrogen than black/grey hydrogen, which considerably helps combat climate change due to fossil-related emissions. Emissions associated with hydrogen production can also be expressed in terms of carbon footprint. Valente et al. have estimated a carbon footprint of − 0.43 to − 0.11, 0.43–0.43, and 11.3–9.5 kg

CO_2-eq. kg^{-1} H_2 for biomass gasification, wind-based electrolysis, and SMR, respectively, for the 2050 scenario compared to the reference scenario (Valente et al., 2020). Their results indicate the uniqueness of biomass-based hydrogen production with biomass growth as a tool to enable negative emissions targets. GWP can vary significantly depending on the electrolyzer technology as well. Zhao et al. have estimated GWP values of 0.4 and 0.55 kg CO_2-eq. kg^{-1} H_2 for SOEC, proton exchange, and alkaline electrolysis cells (Zhao et al., 2020).

No country is spared from the extreme consequences of climate change. GHG emissions have grown by more than 50% compared to 1990 (Ayompe et al., 2021). Global warming causes continuing changes to our climate system, thereby threatening irreversible consequences if steps are not taken to mitigate it. With low to zero carbon emissions during production and utilization, green hydrogen is an ideal fuel and energy carrier to help mitigate climate change. It can be an excellent energy carrier to meet the zero carbon emission goals under the Paris agreement and decarbonization goals. Among various climate-related goals for 2050, decarbonizing the planet is one of the most prominent goals to be achieved by various countries by 2050 with zero carbon footprints (Saner et al., 2021). Reduction in air and water pollution makes green hydrogen an excellent energy carrier to meet the Paris agreement and climate action plan.

4.2.14. SDG 14 "Life Below water"

Direct contribution:

A. **Reduce land source pollution (**Abad and Dodds, 2020;Pangsy-Kania and Flouros, 2021**).**
B. **Improve maritime transport and sustainability (**Atilhan et al., 2021;Safara Nosar, 2021**).**

Indicators:
67. Measure water-related pollution.
68. Measure marine ecotoxicity.

In industries, when fossil fuels are burned to obtain the energy to initiate the power plants, large amounts of gases and residuals are produced, which are emitted into water. These emissions endanger the lives of species below water. However, using hydrogen to initiate a power plant produces no gas or residual (Gielen et al., 2019). With no emission of dangerous gases, including CO_2, carbon monoxide, and methane, into the water, the lives of species below water can be improved using clean and green hydrogen energy resources.

4.2.15. SDG 15 "Life on Land"

Direct contribution:

A. **Decrease land-use change and deforestation (**BHAGWAT and Olczak, 2020;d'd'd'Amore-Domenech et al., 2020;Nurdiawati and Urban, 2022**).**
B. **Reduce the overall GHG emission (**Abad and Dodds, 2020;van Renssen, 2020**).**
C. **Improve the sustainable usage of terrestrial resources (**Amulya and Mohan, 2022;Mac Dowell et al., 2021;Nadaleti et al., 2021**).**

Indicators:
69. Conduct an environmental impact assessment.
70. Total contribution to research initiatives and landscape planning.
71. Evaluate the impact on biodiversity and ecosystem.
72. Total land required to develop the project.

(*continued on next column*)

(*continued*)

73. Quantify the eutrophication potential, NO_x, SO_x, particulate matter, persistent organic pollutants, equivalent volatile organic compounds, organic pollutants, hazardous air pollutants, stack, freshwater aquatic ecotoxicity, and fugitive emissions.
74. Effect on mitigation of harmful gases.
75. Total land required.
76. Initiatives to reduce GHG emissions.
77. Impact of significant spills.
78. Total resources required

Human and animal lives are endangered due to ozone layer degradation, resulting in several carbon emissions and health-related issues (Laumbach et al., 2015). With low carbon emissions and pollution, the lives of humans and animals can be improved on land using green hydrogen energy as a substitute for conventional energy resources (Gielen et al., 2019). Green energy use can help reduce the bad health effects created by hazardous gas emissions in the environment that destroys lives on land and underwater.

4.2.16. SDG 16 "Peace, Justice, and Strong Institutions"

79. **Degree of stakeholders' involvement.**
80. **Level of stakeholders' engagement in project planning.**
81. **Degree of conformity with regulations and disclosing information.**
82. **Antibribery management systems availability.**

With better health, electricity, climate, and hunger levels achieved by green hydrogen adoption, poverty levels can be reduced, thereby creating peace, providing justice, and creating a strong government by improving the economy, which will benefit humans worldwide.

4.2.17. SDG 17 "Partnerships to achieve the Goal"

83. **Ensure a high level of participation with industry groups.**
84. **Integrate the SDGs' principles within the company policies.**
85. **Ensure a high level of collaboration with local authorities and government.**

The above discussions reveal that green hydrogen is essential in achieving the different SDGs directly or indirectly. The world is more connected than it has ever been. It is critical to improving access to technology, communication, and knowledge to share ideas and create creativity and uniqueness. For long-term growth and development, it is essential to coordinate policies to assist countries in managing their debt and to promote investment for the least developed. Green hydrogen has the potential to form fundamental partnerships between goals by combining goals such as affordable and clean energy, industry, innovative infrastructure, sustainable cities and communities, responsible production and consumption, and climate action to create a sustainable environment around the world (Eljack and Kazi, 2020).

5. Recommendations

It is difficult to judge the most suitable hydrogen production route for each country because of the complications in the green hydrogen production chain. A thoughtful assessment of the presented information leads to the following recommendations:

More efforts should be made toward alleviating the green hydrogen utilization barriers, i.e., (1) production cost reduction to meet the targeted cost per kg H_2, (2) cheap, compact, light, and safe hydrogen storage, (3) settlement of hydrogen distribution infrastructure, (4) studies about value chain analysis for industries that could rely on green hydrogen, (5) sustainability of supply, (6) hydrogen utilization safety rules and measures, and (7) study of the integrated system should be investigated.

- Although some promising routes exist for green hydrogen production that can compete with the current production methods, they require a detailed economic, environmental, and social analysis of the 3D sustainability concepts using LCA. The effect of green hydrogen production origin should also be considered a selection criterion.
- Some studies have elaborated on the relationship between green hydrogen production and the 17 SDGs. However, more efforts are needed to link all the aspects of green hydrogen production with the 17 SDGs and their sub-targets. Also, more studies on the linkage between green hydrogen production and the interrelated SDGs are needed.

6. Conclusions

This paper discusses the different methods of green hydrogen production. More specifically, this paper discusses the following hydrogen pathway (production) methods: photon-induced water splitting, photoelectrochemical water splitting (PEC), renewable energy-powered water electrolysis, thermochemical water splitting (thermolysis), plasma chemical decomposition of water, biomass–microorganism-based, MEC, algae (photosynthesis), dark fermentation and pyrolysis/ gasification, anaerobic digestion coupled with dark fermentation, and dark fermentation coupled with bioelectrochemical systems (MEC and MFC). Also, the analysis herein shows that the main contribution came from its ability to provide a clean source of energy (SDG 7: “Affordable and Clean Energy”), improve resource efficiency (SDG 8: “Decent Work and Economic Growth”), add value to the waste (SDG 9: “Industry, Innovation, and Infrastructure”), increase the product lifespan (SDG 12: “Responsible Consumption and Production”), and reduce the overall GHG emission (SDG 13: “Climate Action”). Also, to increase the green hydrogen contribution to the SDGs and lower the possible trade-offs, 84 indicators (guidelines) were provided.

Declaration of Competing Interest

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

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