Review

Qusay Hassan*, Sameer Algburi, Aws Zuhair Sameen, Hayder M. Salman and Ali Khudhair Al-Jiboory

A review of green hydrogen production by renewable resources

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Abstract: This comprehensive review delves into the burgeoning field of green hydrogen production through the utilization of renewable resources. As the global demand for clean and sustainable energy escalates, green hydrogen has emerged as a promising solution, garnering significant attention due to its potential to decarbonize various sectors. The study encapsulates a thorough exploration of the key methodologies employed in harnessing renewable sources such as wind, solar, and hydroelectric power for hydrogen generation. The analysis encompasses both technological aspects and environmental implications, shedding light on efficiency, scalability, and feasibility. Moreover, the review evaluates the economic viability and policy frameworks that underpin the integration of green hydrogen into existing energy systems. By synthesizing findings from a multitude of research endeavors, this study underscores the current advancements, challenges, and future prospects in the realm of green hydrogen production. Ultimately, this review not only contributes to a deeper understanding of sustainable energy pathways but also provides insights that can guide the evolution of green hydrogen technologies toward a more environmentally conscious and energy-abundant future.

Keywords: green hydrogen; production; renewable resources; sustainable energy

1 Introduction

Efforts to curb greenhouse gas (GHG) emissions have been a global priority since the late 20th century, with the aim of limiting the global average temperature increase to 3°C above pre-industrial levels (Fasullo, Otto-Bliesner, and Stevenson 2018; Hare et al. 2015; Khan, Elahi, and Rana 2015). Hydrogen stands as a viable solution for not only reducing GHG emissions but also achieving the United Nations Sustainable Development Goals. Additionally, its large-scale integration with renewable energy sources (RES) offers an eco-friendly pathway to expedite the required transition in energy systems (Mata, Martins, and Caetano 2010).

Originally considered valuable mainly as an industrial gas and raw material in sectors like oil refining and fertilizer production (Hassan 2020; Zheng et al. 2019a), hydrogen is increasingly recognized as a versatile and clean energy carrier. It can be produced from primary energy sources and hydrogen-rich compounds, such as methane and water, or even as a byproduct from chlor-alkali processes. A variety of emerging technologies are being investigated for hydrogen production, utilizing diverse inputs ranging from traditional energy sources (Jaszczur et al. 2016) to waste materials (Hassan et al. 2022g) and biomass (Ceran et al. 2021). Hydrogen offers flexibility in energy systems by better aligning energy production with demand patterns (Hassan et al. 2022d; Ho et al. 2017). It also provides time- and location-specific storage capabilities, ranging from daily to seasonal storage, as well as facilitating both local and global distribution. Additionally, its applications extend beyond energy generation (Hassan et al. 2022i; Sato et al. 2013).

The integration of hydrogen enhances the role of renewables by addressing the existing gap between supply and demand, a challenge created by the variable nature of solar and wind energy sources (Hassan and Jaszczur 2021; Kaza et al. 2018). Additionally, it encourages cross-sector collaboration, allowing the conversion of generated energy into multiple practical forms. This integrated approach also provides for the storage and distribution of hydrogen-derived energy to a broad range of consumers. Various strategies for merging hydrogen with renewable energy sources across the energy landscape can be categorized as follows:
Energy-to-energy: Energy is converted into hydrogen, which is then retained and re-electrified as needed by a fuel cell (FC). Additionally, hydrogen could well be used to power combined cycle gas turbines (Hassan et al. 2019).

Energy-to-gas: Energy is converted to hydrogen through electrolysis. This hydrogen could be delivered, moved, and stored directly, or it could be mixed into the natural gas system or turned into manufactured methane through a process called methanol synthesis, which needs a cheap source of carbon dioxide (CO₂) (Iyamu, Anda, and Ho 2020).

Energy-to-fuel: Electrolysis converts power into hydrogen, which can be used as a transportation fuel for FC electric vehicles (EV). Hydrogen may also be turned into ammonia (NH₃) for use as a ship fuel, but this is a mobile process (Samath et al. 2020).

Energy-to-feedstock: converts power to hydrogen for use as a feedstock in the production of chemical compounds and synthetic fuels (Hetti et al. 2020; Voldsund, Jordal, and Anantharaman 2016).

According to the International Renewable Energy Agency (IRENA) (Day and Day 2017), stationary energy applications are projected to be responsible for 77% of the world greenhouse gas emissions from electricity generation by 2020 (Birol 2019). The level of emissions is influenced by the types and amounts of fossil fuels each country uses for electricity generation. For instance, Scandinavia leads in clean energy within the European Union due to its heavy reliance on wind and hydro power, while Poland has the highest emissions due to its dependence on coal-fired electricity (Birol 2019). As a result, it is crucial to augment the share of renewable energy in electricity generation. IRENA forecasts that initiatives to deploy renewable energy sources (RES) and enhance energy efficiency could lead to a 94% reduction in pollution (Day and Day 2017). While there has been considerable growth in the renewable sector, reaching a total installed capacity of over 2500 GW by 2020 (Carrasco et al. 2017), it remains insufficient to achieve the necessary reductions in greenhouse gas emissions, especially as global energy consumption continues to rise. Currently, renewable energy accounts for just 12% of total global final energy consumption. To align with the Paris Agreement objectives, this percentage needs to increase by three to six times by 2050, indicating that further action is required (Aydin et al. 2021).

As a result, various countries are focusing their research endeavors on the adoption of hydrogen as the driving force for a cleaner energy system. These efforts often involve comprehensive plans and roadmaps, created in collaboration with manufacturers and hydrogen-focused organizations, aimed at reducing carbon emissions in stationary energy applications (Mahinpey and Gomez 2016; Salaudeen, Arku, and Dutta 2019). This paper categorizes the uses of hydrogen into four primary stationary applications, as identified by current scientific studies: large-scale power generation; industrial settings; residential buildings; and other infrastructure. Table 1 provides an overview of how renewable energy sources and sustainable hydrogen technologies are currently being used, as well as future plans for industrial applications, in countries that are most interested in employing hydrogen technologies.

### 2 Hydrogen production by renewable sources

In recent years, the cost of renewable energy has plummeted significantly, especially in comparison to the fluctuating prices of oil and natural gas (Bamisile et al. 2020). While hydrogen can be sourced from various energy types, including fossil and renewable sources, the majority is currently produced via fossil fuel combustion. The environmental drawbacks of these fossil-based methods, along with the rapid depletion of these resources, make them unsustainable options for hydrogen production (Acar and Dincer 2019). Consequently, recent research has focused on generating hydrogen from renewable sources, which currently make only a small contribution to overall hydrogen production (Andrews 2020). Advancements in renewable energies like biofuels, solar, and wind have facilitated the development of more efficient systems for fuel production (Soltani et al. 2021). This section reviews key methods for renewable-based hydrogen production, including techniques involving biomass, hydro, solar, wind, and electrolysis, as well as emerging methods such as nuclear power for hydrogen production. Figure 1 illustrates the various hydrogen production techniques using renewable resources.

#### 2.1 Solar-to-hydrogen

Solar energy is widely considered the most promising renewable source for addressing future global energy demands (Hassan et al. 2022h). Its potential for providing low-cost electricity bodes well for the development of solar-hydrogen as a clean alternative fuel (Abdulateef et al. 2021; Hassan et al. 2022b). While the intermittent nature of solar energy has been a challenge, advancements in renewable
energy storage techniques offer some solutions. Nevertheless, converting solar energy into hydrogen presents a more reliable and cost-effective approach (Zhang et al. 2019). Utilizing solar energy to produce hydrogen without emitting greenhouse gases offers a viable pathway towards solar-hydrogen transition. This process typically involves the thermal decomposition of methane in a reactor, which is heated by high-temperature solar thermal energy.

<table>
<thead>
<tr>
<th>Region/Country</th>
<th>Green hydrogen production and applications</th>
<th>Renewable energy sources</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>– 20% hydrogen supplied through blending with natural gas. – 100% green hydrogen for steelmaking, refineries.</td>
<td>– 77% of renewable energy cover electricity demands by 2050.</td>
<td>Miller et al. (2020); Momirlan and Veziroglu (2002)</td>
</tr>
<tr>
<td>China</td>
<td>– Green hydrogen will decrease energy losses caused by long distances between production and consuming regions. – Multiple MW of electricity generating and district heating pilot projects.</td>
<td>– 30% of renewable energy cover country demand by 2030.</td>
<td>Bamisile et al. (2022); Meng et al. (2021)</td>
</tr>
<tr>
<td>Canada</td>
<td>– 30% of final energy delivered by hydrogen FC systems and combined cycle turbines by 2050. – 86% of hydrogen supplied through blending and dedicated network by 2050. – Exports the green hydrogen to Japan, USA, South Korea, EU, and China.</td>
<td>– 67% of renewable energy cover country demand by 2035.</td>
<td>Karaca and Dincer (2021)</td>
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<tr>
<td>Japan</td>
<td>– 5.4 million hydrogen units for the commercial and residential sector by 2050. – Exports the green hydrogen to USA, Australia, Brunei, and Chile.</td>
<td>– 17% of renewable energy cover electricity demands by 2030.</td>
<td>Iida and Sakata (2019); Arias (2019)</td>
</tr>
<tr>
<td>Germany</td>
<td>– 5 GW electrolyzer capacity to produce 100 TWh of electrical energy by 2030. – 100 TWh of green hydrogen energy to feed refineries, steelmaking, and ammonia production by 2050.</td>
<td>– 20 TWh renewable energy for hydrogen production by 2030. – 5 GW renewable energy electricity demands by 2040.</td>
<td>Federal Ministry for Economic Affairs and Energy (2020)</td>
</tr>
<tr>
<td>Australia</td>
<td>– Green hydrogen production based on off-grid scenarios by 2030. – Green hydrogen production for domestic used and exports by 2030.</td>
<td>– Several GW projects for renewable electricity production by 2030.</td>
<td>Commonwealth of Australia (2018); Kar et al. (2022)</td>
</tr>
<tr>
<td>UK</td>
<td>– 10,000 green hydrogen production units for electricity by 2025. – More than 100 MW of fuel cell systems by 2025.</td>
<td>– 20% of green hydrogen blending in natural gas for grid electricity by 2040.</td>
<td>Scott and Powells (2019); Hart et al. (2016)</td>
</tr>
<tr>
<td>France</td>
<td>– 12% of green hydrogen for energy supply to the residential buildings by 2050. – 10% of green hydrogen contribution for energy supply to the industry by 2050.</td>
<td>– 40% renewable energy production by 2030.</td>
<td>Damette et al. (2022)</td>
</tr>
<tr>
<td>South Korea</td>
<td>– More than 250 MW capacity of fuel cell project. – 62 TWh capacity for electrical energy generation by fuel cell systems by 2050.</td>
<td>– 40 TWh capacity of renewable energy for with industrial by 2050.</td>
<td>Hart et al. (2015); Cader, Konecza, and Olczak (2021); Verheul (2019)</td>
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<tr>
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<td></td>
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<td>IEA (2021)</td>
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<td></td>
<td></td>
<td>IEA (2021)</td>
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</table>
2.1.1 PV-to-hydrogen

In the realm of energy production, Photovoltaic (PV) technology produces electricity through the piezoelectric effect and the direct transformation of solar energy into electrical power. On the other hand, photothermal energy involves the collection of solar energy using an array of reflectors to generate heat, which can then be utilized to power steam turbines (Zhang et al. 2022a). Figure 2 illustrates the process of using solar PV-electrolyzers for green hydrogen production. For generating hydrogen via solar power, existing technologies include alkaline water electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis cells. Among these, alkaline water and proton exchange membrane electrolysis stand out as the most promising methods currently available on the market, with the latter having the additional advantage of being renewable energy compatible (Carmo et al. 2019; Kim et al. 2018). The basic principle behind proton exchange membranes involves setting up an electrolytic cell with pure water, dividing it into two chambers, namely the cathode and anode, and inserting electrodes into each compartment (Carmo et al. 2013).

The intensity of solar irradiation and other environmental parameters such as humidity, wind speed, temperature, and so on are used to calculate photovoltaic power production. The PV output power can be computed with Eq. (1), whereas the PV cell temperature can be determined with Eq. (2) (Carmo et al. 2013).

\[
P_{\text{pv}} = C_{\text{pv}}D_{\text{pv}}[1 + \alpha p(T_c - T_a)]\left(\frac{H_T}{H_S}\right)
\]

\[
T_c = T_a + H_T\left(1 - \frac{\eta_c}{\tau}\right)\left(\frac{T_{\text{c,NOCT}} - T_{\text{a,NOCT}}}{H_{T,\text{NOCT}}}\right)
\]

The rate of hydrogen generation by electrolyzer can be calculated as Eq. (4). In addition, the quantity of electricity input needed by the electrolyzer can be calculated as Eq. (5) (Carmo et al. 2013).

\[
Q_{\text{H}_2} = \eta f\left(\frac{N_c I_e}{2F}\right)
\]

\[
I_E = A_e \cdot m_{\text{H}_2} + B_e \cdot m_{\text{H}_2}^\prime
\]

The energy needed to compress the hydrogen contained in the hydrogen tank is shown in Eq. (6). In addition, the anticipated pressure within the hydrogen tank in Eq. (7) (Carmo et al. 2013).

\[
P_{\text{com}} = Q_{\text{H}_2} \cdot R \left(\frac{P_{\text{H}_2}}{P_{\text{H}_2}}\right)^{\frac{z - 1}{z}} \left(\frac{T_{\text{hce}}}{\eta_{\text{hce}}}\right)\left(\frac{y}{y - 1}\right)
\]

\[
P_{\text{tan}} \cdot K = \left(\frac{RT_{\text{hce}}}{V_{\text{h}}}\right)\eta_{\text{h}} \cdot \tau \cdot K
\]

The renewable components such solar panels provide DC electricity, but the demand is typically AC. Therefore, the
A converter is required to convert DC power to AC power. In addition, the converter is used in the electrical system to regulate the power flow. The converter efficiency can be calculated using Eq. (8) (Carmo et al. 2013).

\[ \eta_{\text{con}} = \frac{P_{\text{out}}}{P_{\text{in}}} \]  

(8)

Multiple articles have explored diverse techniques for hydrogen production based on assessments of solar PV energy. Liu et al. (2019) provided a review article that delves into solar hydrogen production. Kudo (2007) explored hydrogen generation through solar energy, using a specialized photocatalytic activity system that demonstrates global water splitting under visible light irradiation. Additionally, Kudo developed efficient sulfide catalysts for PV-hydrogen production by integrating ZnS with narrow bandgap semiconductors. Joshi, Dincer, and Reddy (2010) studied the efficiency of a solar hydrogen production system based on PV technology, finding efficiency rates between 3.68 and 4.84 %. They concluded that this method is not yet cost-effective due to the high expense of PV technology and suggested that further research is needed in this domain (Joshi, Dincer, and Reddy 2009).

Utilizing solar PV energy for hydrogen production not only addresses the high cost of water electrolysis by optimizing the use of solar resources, but it also offers an economical, carbon-minimizing, and eco-friendly approach to hydrogen generation. Moreover, the relatively low cost of water electrolysis, which is the cleanest method for hydrogen production, has somewhat hindered its advancement.

### 2.1.2 Solar thermal-to-hydrogen

Solar thermal water electrolysis for hydrogen production involves harnessing concentrated solar energy to maintain elevated temperatures within a chemical reactor. This facilitates the water-splitting process, thereby generating hydrogen fuel that can be stored and transported (refer to Figure 3). Over the past few decades, a range of solar collectors and receivers have been designed and deployed worldwide to support solar thermal installations, as documented in (Avila-Marin 2011; Behar, Khellaf, and Mohammedi 2013; Ho and Iverson 2014; Kalogirou 2004; Reddy et al. 2013; Tian and Zhao 2013).

The efficiency of solar thermal hydrogen is the proportion of solar irradiation collected as hydrogen, as shown by the Eq. (9) (Reddy et al. 2013).

\[ S_{\text{th}} = \frac{LHV_{\text{H}_2}}{\sum_{i} Q_{\text{solar},i}} \times 100 \]  

(9)

\[ Q_{\text{solar},i} = \frac{Q_{\text{in},i} \Omega_{\text{opt}}}{1 - \sigma \Omega_{\text{opt}}} \]  

(10)

In the context of their technical and financial viability, as well as their potential role in future hydrogen supply chains, numerous studies have scrutinized hydrogen production methods grounded in solar thermal energy assessments. Pregger et al. (2009) offer an in-depth evaluation of the prospects for solar thermal hydrogen production.

![Figure 3: Schematic of solar-thermal hydrogen production.](image)
highlighting the uncertainty surrounding hydrogen role as a major energy source by 2050. Graf et al. (2008) performed a financial analysis comparing thermo-chemical cycles and electroplating using concentrated solar thermal energy for multi-stage hydrogen production. They found that electrolysis costs for producing 1 kg of hydrogen varied between €2.1 and €6.8. Hoffmann (2019) explores various strategies for employing solar thermal technology in South Africa to produce carbon-free hydrogen, noting that the nation’s vast solar resources could position it as a leader in the hydrogen sector. Baykara (2004) examines the thermochemical effectiveness of several production methods, including water electrolysis and high-temperature hydrogen extraction, finding that they offer comparatively lower production costs. Joshi, Dincer, and Reddy (2016) assess a solar-thermal hydrogen production system from a thermodynamic standpoint. Their study shows that factors like increased solar irradiation and concentration affect the system efficiency positively. Zamfirescu et al. (2012) introduced small-scale concentrated solar-driven heat turbines and conducted exhaustive exergy, ecological, and economic assessments. Yilanci, Dincer, and Ozturk (2009) performed a comprehensive review of various hydrogen production technologies and found that the overall energy performance of a solar-hydrogen/fuel cell hybrid system in Turkey ranged from 0.88 to 9.7% efficiency. Abanades and Flamant (2008) focus on solar thermal decomposition for hydrogen generation, using a medium-scale solar reactor. Their experiments showed that methane conversion and hydrogen production could achieve up to 96% and 92%, respectively. Liu et al. (2009) propose an innovative method for solar hydrogen synthesis that blends methanol steam reforming with moderate-temperature

<table>
<thead>
<tr>
<th>Type of cycle</th>
<th>Hydrogen production rate</th>
<th>Energy efficiency (%)</th>
<th>Hydrogen cost</th>
<th>Electricity production</th>
<th>Other productions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rankine cycle</td>
<td>360 kg/day</td>
<td>–</td>
<td>–</td>
<td>50.49 MW – –</td>
<td>– –</td>
<td>Sadeghi, Ghandehariun, and Naterer (2020)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>1530 kg/day</td>
<td>–</td>
<td>–</td>
<td>47.6 GW Heat: 452.8 GWh/year Freshwater: 160,392.1 metric ton/year</td>
<td>– –</td>
<td>Sadeghi and Ghandehariun (2022)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>33.9 kg/day</td>
<td>–</td>
<td>–</td>
<td>– –</td>
<td>– –</td>
<td>Temiz and Dincer (2021a)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>26,000 tons/year</td>
<td>37.3</td>
<td>–</td>
<td>– Methanol</td>
<td>– –</td>
<td>Giaconia et al. (2007)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>100 tons/day</td>
<td>21</td>
<td>–</td>
<td>– –</td>
<td>– –</td>
<td>Liberatore et al. (2012)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>–</td>
<td>38.0</td>
<td>–</td>
<td>– Heat</td>
<td>– –</td>
<td>Cumpston et al. (2020)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>1530.4 kg/h</td>
<td>29.18</td>
<td>$7.58/kg</td>
<td>– Heat</td>
<td>– –</td>
<td>Dincer and Ratlamwala (2013)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>0.19 kg/s</td>
<td>23</td>
<td>–</td>
<td>41.9 MW Steam: 12.6 kg/s Oxygen: 0.76 kg/s Freshwater: 531.75 ton/year Thermal energy: 85.1 GWh</td>
<td>– –</td>
<td>Sadeghi, Ghandehariun, and Rezaie (2021)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>2144.45 tons/year</td>
<td>22.7</td>
<td>2.73/kg</td>
<td>1235 MW Freshwater: 11,983.68 tons/year Thermal energy: 136.51 GWh</td>
<td>– –</td>
<td>Temiz and Dincer (2021b)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>1034.18 tons/year</td>
<td>52.6</td>
<td>–</td>
<td>420.05 GW Freshwater: 11,983.68 tons/year Thermal energy: 136.51 GWh</td>
<td>– –</td>
<td>Temiz and Dincer (2021c)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>491.26 kg/h</td>
<td>45.07</td>
<td>–</td>
<td>41.68 MW Steam: 11.39 kg/s</td>
<td>– –</td>
<td>Sadeghi and Ghandehariun (2020)</td>
</tr>
<tr>
<td>Rankine cycle</td>
<td>59.45 mol/s</td>
<td>29.9</td>
<td>–</td>
<td>8.3 MW –</td>
<td>– –</td>
<td>Ishaq and Dincer (2019)</td>
</tr>
</tbody>
</table>
solar energy, attaining over 91% chemical transformation of methanol. Table 2 summarizes studies that have investigated solar thermal hydrogen production.

Utilizing solar thermal energy for hydrogen production can not only mitigate the high costs associated with water electrolysis but also offers an eco-friendly, cost-effective, and carbon-reducing method for hydrogen generation. Moreover, the advancement of the cleanest hydrogen production methods has been impeded by the relatively low costs of water electrolysis.

2.2 Wind-to-hydrogen

In light of declining costs and growing public demand for renewable energy, the global installed capacity for such sustainable resources is expected to rise. Governments around the world are actively promoting the adoption of renewable energy sources. Recently, there has been an increased focus on wind energy as a viable option for sustainably generating electricity. This form of energy is especially considered suitable for hybrid power systems that rely on various sources for clean and reliable power (Almutairi et al. 2021a). To maximize the utility of wind-generated electricity and avoid wastage, it is commonly recommended to employ storage systems alongside wind power operations (Xiao et al. 2020). Despite its potential, wind energy often presents challenges for utility providers, making it a complex choice for investments in some cases (Hassan et al. 2019). Figure 4 illustrates the process of using wind turbines (WT) and electrolyzers for the production of green hydrogen.

When the wind speed surpasses the cut-in threshold, the wind turbine begins to generate electricity. Furthermore, the turbine produces stable power when the wind speed is within its operational range. If the wind speed crosses the cut-out limit, the turbine generator shuts down to prevent any damage. The mathematical representation of wind energy production is given in Eq. (11) (Ceran et al. 2017).

\[ P_{\text{wt}}(t) = \begin{cases} 0 & \text{if } v(t) \leq v_{\text{cut,in}} \quad \text{or} \quad v(t) \leq v_{\text{cut,out}} \\ P_r & v_{\text{cut,in}} < v(t) < v_r \\ P_r & v_r < v(t) < v_{\text{cut,out}} \end{cases} \] (11)

The total power produced by many wind turbines may be computed by Eq. (12) (Jaszczur et al. 2020).

\[ P_{\text{wt}}(t) = P_{\text{wt}}(t) \times N_{\text{wind}} \] (12)

At the level where the turbine blades are turning, the wind speed varies with height and may be determined using Eq. (12) (Jaszczur et al. 2019).

\[ \frac{v_2(t)}{v_1(t)} = \left( \frac{h_2}{h_1} \right)^{c_f} \] (13)

There are several methods to store the extra electricity generated by wind energy, using lithium–ion batteries, conversion power to gas, mechanical flywheel etc., but the conversion energy to hydrogen considered the most popular options (Guandalini et al. 2017; He et al. 2015). Fuel cell cars and industrial demands are only a few of the uses for hydrogen energy, which is also known as a greener fuel source (Hassan et al. 2022f). The electrolysis of water, which has a production rate of more than 75%, is also recognized as the most established and mature method for producing hydrogen gas from fossil fuels (An et al. 2014). In an electrolyzer, the breakdown of water molecules into hydrogen and oxygen is accomplished using renewable energy sources such as wind energy. In earlier investigations, a hybrid renewable energy power generation system used to produce hydrogen was also examined. When compared to solar energy, the results showed that wind energy made the most hydrogen (Al-Sharafi et al. 2017). Researchers agree that the world will once again develop a hydrogen economy and also that hydrogen will serve as the world energy carrier of the future. As a result, research into hydrogen energy has grown steadily over the last 20 years. Nowadays, the significant production of hydrogen from fossil fuels is dropping year-over-year due to the increased use of hydrogen production by renewable resources.

In review research, Genç, Çelik, and Karasu (2012a) evaluated publications on the examination of production of hydrogen from wind energy and hydrogen manufacturing costs for a specific location. It was determined that these studies were unusual worldwide, particularly in Turkey. Olateju and Kumar (2011) studied the generation of hydrogen in Western Canada using only a 1.9 MW wind turbine. They determined that 250 kW and 370 kW electrolyzers have hydrogen manufacturing costs of $9.8/kg and $6.45/kg, respectively.
examined a wind/electrolyzer system for the energy needs of a chicken farm. Consideration was given to the fact that the chicken farm utilized air-cooling compressors, light bulbs, and equipment for feed processing. The system was comprised of an electrolyzer and a wind turbine, and a compressor was anticipated to transport hydrogen from the electrolyzer to the hydrogen storage tank. This study showed that the size of the electrolyzer, the cost of making energy from turbines, and the height of the turbines all affect how much it costs to make hydrogen.

According to a recent wind map by Douak and Settou (2015), Algeria has the greatest potential for wind energy. The wind probability density function was utilized to examine data collected from various sources for the research. These places make use of the wind energy generated to manufacture hydrogen using water electrolysis. According to the proposed project, employing wind energy at the chosen locations is a potential approach. It is demonstrated that the turbine can provide both hydrogen and power at the lowest possible cost. The manufacture of hydrogen costs as little as €1.25/kg. Gökçek (2010) evaluated the yearly electrical power generation potential from wind and hydrogen in Turkey. In addition, the costs of hydrogen generation for various hub heights were determined. The research showed that the amount of hydrogen made each year was 105.4 kg, the amount of electrical energy made each year was 15,151.3 kWh, and the price of making hydrogen ranged from $0.35/kg to $4.51/kg. Qolipour, Mostafaeipour, and Tousi (2017) investigated the technical-economic viability of constructing a hybrid photovoltaic-wind power plant to generate electricity and hydrogen in Iran southwestern region using the Homer programme. According to the results of the technical-economic feasibility study, the area being looked at makes 3153.8 MWh of energy and 3178 kg/year, which could be used to set up a hybrid system. Greiner, Korpås, and Holen (2007) outlined a methodology for assessing hydrogen production from wind energy, incorporating both time and cost metrics. Their research suggested hydrogen costs ranging between €2.80 and €6.20/kg. Jørgensen and Ropnus (2008) investigated hydrogen production costs using energy electrolyzers under different wind penetration scenarios, revealing a cost range from 0.41 €/N m³ to 0.45 €/N m³. Mathur et al. (2008) delved into the economics of hydrogen production for transportation fuel through offshore wind systems, concluding that although the costs were not yet competitive with gasoline, the outlook was promising for a green transition. Korpås and Greiner (2008) scrutinized the efficiency of wind–hydrogen technologies, emphasizing the role of hydrogen as a manageable load in wind-to-energy systems and its storage capabilities. Bernal-Agustín and Dufo-López (2008) offered a techno-economic analysis of a wind-hydrogen system, indicating that the cost of the hydrogen components was relatively high, with fuel cell electricity costs at $1.7/kWh. Ganjehsarabi (2019) conducted a feasibility study on hydrogen production from wind energy in Ghardaia, finding that more hydrogen was produced at higher hub heights. Honnery and Moriarty (2009) estimated global hydrogen production from wind energy, suggesting that one 2 MW wind turbine per square kilometer could produce 116 EJ of hydrogen worldwide. Mantz and Battista (2008) examined surplus wind energy for hydrogen production, focusing on system configuration and control strategy. Rodríguez et al. (2010) analyzed the potential for hydrogen production from wind energy through water electrolysis, suggesting its application in local automotive transportation. They found that hydrogen prices could be competitive with conventional fuels. Khan and Iqbal (2009) explored simulation and modeling of an independent wind–hydrogen system, concluding that specific controller and electrolyzer characteristics could enhance system performance. Sovacool and Hirsh (2008) discussed the numerous advantages of hydrogen production from wind energy, particularly in island settings, stating that such experimental systems yielded significant energy cost savings. Table 3 presents various studies that have explored wind-based hydrogen production.

The transformation of wind energy into hydrogen involves using water electrolysis equipment to produce hydrogen, which can then be stored for extended periods. This is particularly relevant as the construction costs for both onshore and offshore wind energy projects are on the rise. Shifting from electricity transmission to hydrogen transmission could help reduce the financial burden of installing offshore wind energy systems.

### 2.3 Geothermal-to-hydrogen

Owing to its consistent and reliable nature, geothermal energy is viewed as one of the most dependable forms of renewable energy (Siddiqui, Ishaq, and Dincer 2019). This form of energy is harnessed from heat stored in the Earth subsurface layers. While this energy source has been industrially exploited in areas where accessing these subsurface reservoirs is challenging due to the costs and constraints of drilling, it has been less utilized in regions where geothermal resources are abundant and extraction is more affordable. To bring this natural resource from underground to the surface, a heat transfer medium is necessary. This is achieved in two stages: initially, heat is conducted through rock formations, and subsequently, additional
heat is released to the ground via heat transfer rates (Lourenco Nogueira et al. 2022). Depending on the depth of the geothermal systems—shallow or deep—this resource can serve multiple purposes, including cooling, heating, electricity generation, and energy storage (Mamur et al. 2021). Geothermal energy is also perceived as an environmentally friendly solution, offering a renewable avenue for electricity and hydrogen production at competitive costs (Hand 2008).

Several studies have delved into hydrogen production through high-temperature electrolysis powered by geothermal energy, with thermodynamic analyses indicating an energy efficiency exceeding 80% for hydrogen generation (Kanoglu, Bolatturk, and Yilmaz 2010). Furthermore, geothermal energy can be harnessed not only for hydrogen production but also for its liquefaction. This framework can be optimized to use geothermal energy in the hydrogen liquefaction cycle, absorption cooling systems, and co-generation units that provide both heat and electricity for absorption chillers (Koc, Yuksel, and Ozturk 2022). The predominant technology used in geothermal-assisted hydrogen production is proton exchange membrane electrolyzers, which separate water into hydrogen and oxygen (Gholamian, Habibollahzade, and Zare 2018). In this electrochemical reaction, water temperature emerges as a pivotal factor affecting the output, energy requirements, and cost of the hydrogen production system. Higher reaction temperatures can reduce the energy consumption, thereby lowering the overall production costs of hydrogen (Kanoglu, Dincer, and Rosen 2007). Commonly, geothermal energy is employed in two main ways for hydrogen production: via geothermal power plants that utilize geothermal fluid and residual heat for water heating, and through electricity generation.

In the alternative method, water and steam are separated using a flash splitter. The steam is then used to generate electricity via a steam turbine. Concurrently, heat energy harvested from the hot water through a heat exchanger is used to supplement energy for hydrogen production. This process is illustrated in Figure 5, which provides an industrial flowchart for hydrogen production utilizing geothermal energy (Yilmaz, Kanoglu, and Abusoglu 2015a). Various catalysts can be employed to enhance the separation of oxygen and water. The ability to achieve higher water temperatures also contributes to increased process efficiency (Alizadeh et al. 2022). Geothermal water with a temperature of 200 °C could potentially reduce hydrogen production costs by 19%. Recent studies show that electrolyzers operating at temperatures of 150 °C are highly efficient. However, challenges remain in managing contaminants like hydrogen

### Table 3: A summary of wind to hydrogen production studies.

<table>
<thead>
<tr>
<th>Hydrogen production rate</th>
<th>Assessment objective</th>
<th>Wind turbine Capacity</th>
<th>Hydrogen cost</th>
<th>Electricity production per year</th>
<th>Location</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>Technical</td>
<td>55 kW</td>
<td>€4/kg</td>
<td>50 MWh per year</td>
<td>Mediterranean Sea Iran</td>
<td>Bonacina, Gaskare, and Valenti (2022)</td>
</tr>
<tr>
<td>19.844–19.429 tons/year</td>
<td>Technical &amp; economic</td>
<td>18 kW</td>
<td>€3/kg</td>
<td>900 kWh</td>
<td>Iran</td>
<td>Almutairi et al. (2021b)</td>
</tr>
<tr>
<td>41.4 tons/year</td>
<td>Technical</td>
<td>22 kW</td>
<td>–</td>
<td>2558.4 MWh</td>
<td>Afghanistan Iran</td>
<td>Mostafaipour et al. (2020)</td>
</tr>
<tr>
<td>1665.2 kg/year</td>
<td>Technical</td>
<td>34 kW</td>
<td>–</td>
<td>1300 kWh</td>
<td>Iran</td>
<td>Sorgulu and Dincer (2018)</td>
</tr>
<tr>
<td>–</td>
<td>Technical &amp; economic</td>
<td>100 kW</td>
<td>€2.26/kg</td>
<td>260,610 kWh</td>
<td>Afghanistan</td>
<td>Rezaei, Naghdii-Khozani, and Jafari (2020)</td>
</tr>
<tr>
<td>–</td>
<td>Technical &amp; economic</td>
<td>100 kW</td>
<td>–</td>
<td>–</td>
<td>Iran</td>
<td>Young et al. (2017)</td>
</tr>
<tr>
<td>25,580 kilo tons/year</td>
<td>Technical &amp; environmental</td>
<td>112 kW</td>
<td>–</td>
<td>860 TWh</td>
<td>Sweden</td>
<td>Sial et al. (2015)</td>
</tr>
<tr>
<td>25 kg/day</td>
<td>Technical</td>
<td>12 kW</td>
<td>–</td>
<td>–</td>
<td>Taiwan</td>
<td>Lee and Lee (2008)</td>
</tr>
<tr>
<td>3200 Nm³/year</td>
<td>Technical</td>
<td>10 kW</td>
<td>–</td>
<td>–</td>
<td>Algeria</td>
<td>Aiche-Hamane et al. (2009)</td>
</tr>
<tr>
<td>226.8 m³/year</td>
<td>Technical &amp; economic</td>
<td>2 MW</td>
<td>€1.4/kg</td>
<td>–</td>
<td>South Africa</td>
<td>Ayodele and Munda (2019)</td>
</tr>
<tr>
<td>2100 kg/h</td>
<td>Technical &amp; environmental</td>
<td>264 MW</td>
<td>–</td>
<td>112.7 MW</td>
<td>Canada</td>
<td>Ghorbani, Zendeheboudi, and Moradi (2021)</td>
</tr>
<tr>
<td>49,150 m³/year</td>
<td>Technical &amp; environmental</td>
<td>860 kW</td>
<td>€1.75/kg</td>
<td>–</td>
<td>Iraq</td>
<td>Hasan and Genç (2022)</td>
</tr>
<tr>
<td>15.9 Mega tone/year</td>
<td>Technical</td>
<td>780 TW</td>
<td>–</td>
<td>–</td>
<td>Germany</td>
<td>Jung et al. (2018)</td>
</tr>
</tbody>
</table>
sulfide and other hazardous gases at the electrode ends during hydrogen production from geothermal sources (Karapekmez and Dincer 2018).

Considering the application of renewable energy for hydrogen production, geothermal resources emerge as a feasible option. In countries rich in geothermal energy, harnessing it for hydrogen production could become a notable avenue. While the current heat input for hydrogen production linked to a geothermal source is limited to approximately 200–250 °C, this could evolve in the coming years. Importantly, technologies for hydrogen production and consumption can be conveniently integrated with geothermal energy and distributed power systems. Leveraging geothermal resources for hydrogen manufacturing could further reduce costs (Maack and Skulason 2006).

Numerous studies have reported on the production of hydrogen via geothermal energy, as summarized in review articles (Ghazvini et al. 2019; Karayel, Javani, and Dincer 2022; Mahmoud et al. 2021). Typically, a preheater is employed to elevate the temperature of the water that enters the electrolyzer (Yilmaz and Kanoglu 2014). In technologies that couple geothermal power plants with hydrogen production, geothermal water serves dual purposes: it generates electricity in the power plant and also heats water. Initially, the geothermal water drawn from the extraction well is used in the power plant; the residual heat is then utilized for water heating. The air preheater is responsible for capturing this leftover heat from the geothermal fluid and returning it to the Earth. Yilmaz et al. (2019) investigated the influence of temperature on the electrolysis process in a hydrogen production system powered by geothermal energy, utilizing an artificial neural network. Their findings indicate that increasing the temperature from 26 °C to 72 °C reduces the energy required for hydrogen production from 44.5 kW/kg to 43.2 kW/kg, a decrease of nearly 4 %. Further research by Yilmaz, Kanoglu, and Abusoglu (2015b) emphasized the importance of this parameter, revealing that 0.25 g of hydrogen are produced per kilogram of water supplied. At a geothermal supply temperature of 165 °C and a fluid flow rate of 103 kg/s, the rate of hydrogen production was calculated to be 0.026 kg/s.

In a study by Yilmaz et al. (2012), seven different scenarios were explored for hydrogen production and liquefaction using geothermal energy. They developed a methodology for the economic assessment of these scenarios, predicting that the cost of hydrogen production and liquefaction could range between $0.98/kg and $2.62/kg. Their study also scrutinized the effect of geothermal water temperature on these costs, finding that as the temperature increases, the cost of both hydrogen production and liquefaction decreases. However, models that include hydrogen liquefaction have higher capital costs compared to those focused solely on hydrogen production. Balta, Dincer, and Hepbasli (2010) investigated a high-temperature electrochemical method that utilizes geothermal fluid as a heat source. Ingason, Ingolfsson, and Jensson (2008) explored the most cost-efficient techniques for producing hydrogen solely through water electrolysis, leveraging both hydroelectric and geothermal energy. Utilizing a mixed-integer algorithm, they examined 25 potential power plants—12 geothermal and 13 hydroelectric—to identify the best options. Mansilla et al. (2007) conducted a techno-economic evaluation of a high-heat exchanger system in a high-temperature electrochemical reaction for hydrogen production. This system is either coupled to a high-temperature reactor or a geothermal resource for energy recovery. Another study examined the potential for electricity generation from geothermal resources in the western United States and how this power could be utilized for hydrogen production (Ahmadi et al. 2018). Furthermore, Balta, Dincer, and Hepbasli (2009) discussed the technology and potential applications of geothermal hydrogen production units. A thermodynamic assessment was carried out to evaluate the performance of a high-temperature electrochemical reaction powered by a geothermal resource. The overall energy efficiencies of this geothermal hydrogen production process for elevated hydrolysis were found to be 87 % and 85 %, respectively.

Arnason, Sigfússon, and Jonsson (1993) proposed a plan for hydrogen production using geothermal resources on Japan Hachijo Island. This plan is informed by environmental impact studies and aims to serve as a blueprint for expanding geothermal energy use worldwide. Shi et al. (2022) carried out an assessment of three cases involving...
hydrogen production and decompression using geothermal energy. They evaluated a binary geothermal energy plant for power generation and the Linde–Hampson cycle for hydrogen liquefaction, establishing performance metrics for these evaluations. Yuksel and Ozturk (2017) conducted research on a geothermal energy system designed for both energy and hydrogen production. They explored the impact of different operational conditions on the system overall and subsystem efficiencies. Their findings indicate that as the geothermal water temperature increases from 135 °C to 215 °C, the electrical output of the system rises from about 4.5 MW to approximately 8.7 MW. Concurrently, hydrogen production escalates from around 0.03 kg/s to nearly 0.08 kg/s.

Hadjiat et al. (2021) developed a model for hydrogen production utilizing low-enthalpy geothermal resources. This model uses electrical energy generated from the geothermal source to power water electrolysis. The thermal system efficacy was investigated through simulations and tests using the TRNSYS software, based on a spring temperature of 70 °C. The results suggest that the thermal system can generate approximately 0.57 kg of hydrogen per square meter per year. Rahmouni et al. (2014) examined high-temperature electrochemical methods for hydrogen production, using geothermal fluids as the heat source. The study explored the technical and economic viability, as well as the practicality, of various approaches to generating hydrogen through geothermal energy. Yilmaz (2020) developed and evaluated three different models focused on the decomposition of hydrogen using geothermal sources. In a related study, Holdmann and List (2007) investigated the use of geothermal energy for both hydrogen production and liquefaction. Their work included a thermodynamic analysis of four distinct models that utilized geothermal energy. The findings suggest the amount of hydrogen that can be produced from 1 kg of geothermal water at a temperature of 300 °C. Table 4 presents additional studies that have explored the production of hydrogen using geothermal resources.

Undoubtedly, countries with abundant geothermal energy potential can transition from fossil fuels to renewable energy sources more smoothly. However, simply generating power from such renewable resources is not enough without

### Table 4: A summary of geothermal to hydrogen production studies.

<table>
<thead>
<tr>
<th>Hydrogen production rate</th>
<th>Assessment objective</th>
<th>Energy efficiency (%)</th>
<th>Solver</th>
<th>Annual electricity production</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.42 g/s</td>
<td>Hydrogen and heating fluid production</td>
<td>14.8</td>
<td>Equation solver</td>
<td>2050 kWh</td>
<td>Ebadollahi et al. (2019)</td>
</tr>
<tr>
<td>0.06 kg/s</td>
<td>Hydrogen and hot water production</td>
<td>39.46</td>
<td>Equation solver</td>
<td>–</td>
<td>Yuksel, Ozturk, and Dincer (2018a)</td>
</tr>
<tr>
<td>0.06 kg/s</td>
<td>Hydrogen, oxygen, hot water, and power production</td>
<td>42.5</td>
<td>Equation solver</td>
<td>–</td>
<td>Yuksel, Ozturk, and Dincer (2018b)</td>
</tr>
<tr>
<td>0.0558 kg/s</td>
<td>Hydrogen production and liquefaction</td>
<td>–</td>
<td>Equation solver</td>
<td>7937 kWh</td>
<td>Yuksel, Ozturk, and Dincer (2018c)</td>
</tr>
<tr>
<td>335 ton/day</td>
<td>Hydrogen production and liquefaction</td>
<td>26.74</td>
<td>Aspen plus</td>
<td>130 MWh</td>
<td>Seyam, Dincer, and Agelin-Chaab (2020)</td>
</tr>
<tr>
<td>–</td>
<td>Hydrogen production and liquefaction</td>
<td>4.94</td>
<td>Equation solver</td>
<td>1571.1 kWh</td>
<td>Ratlamwala and Dincer (2012)</td>
</tr>
<tr>
<td>15.9 kg/h</td>
<td>Hydrogen production and desalination</td>
<td>–</td>
<td>Equation solver</td>
<td>3804 kWh</td>
<td>Kianfar, Khaililyara, and Jafarmadar (2018)</td>
</tr>
<tr>
<td>–</td>
<td>Hydrogen production and thermoelectric generation</td>
<td>–</td>
<td>Equation solver</td>
<td>37.26 kWh</td>
<td>Khanmohammadi et al. (2020)</td>
</tr>
<tr>
<td>0.37 kg/h</td>
<td>Hydrogen production and thermoelectric generation</td>
<td>18.9</td>
<td>MATLAB</td>
<td>–</td>
<td>Han et al. (2020)</td>
</tr>
<tr>
<td>3.4 Mkg/year</td>
<td>Hydrogen production and CO₂ capturing</td>
<td>–</td>
<td>Geographical information system</td>
<td>–</td>
<td>Gouareh et al. (2015)</td>
</tr>
<tr>
<td>1.12 kg/s</td>
<td>Hydrogen and heating fluid production</td>
<td>3.51</td>
<td>Equation solver</td>
<td>–</td>
<td>Ghaebi et al. (2018)</td>
</tr>
<tr>
<td>24.8 L/s</td>
<td>Hydrogen, power production and ice-making</td>
<td>38.33</td>
<td>Equation solver</td>
<td>414.10 kWh</td>
<td>Cao et al. (2018)</td>
</tr>
<tr>
<td>–</td>
<td>Hydrogen, power production</td>
<td>–</td>
<td>MATLAB</td>
<td>1060 kWh</td>
<td>Calise et al. (2020)</td>
</tr>
</tbody>
</table>
a feasible plan for storing or transporting the energy. The technology that converts geothermal energy to hydrogen showcases promising capabilities for hydrogen production.

2.4 Biomass-to-hydrogen

Initially conceived as an ecological term, biomass has broadened its scope with the emergence of renewable energy discussions, particularly during the oil crisis. It is now considered a sustainable material that is abundantly available and cost-effective, and it has been widely used in the production of fuels and other natural resources (Wang et al. 2022b). Biomass comprises various organic materials—both degradable and non-degradable—formed through photosynthetic processes. This includes plants, animals, and microorganisms, as well as their waste products. The term also encompasses forestry and agricultural residues like crop leftovers, wood scraps, biofuels, agro-industrial waste, and municipal waste. The production of hydrogen from biomass has been a topic of increasing interest (Guo et al. 2022; Wang, Le, and Sun 2022a).

In classifying biomass, categories such as algae, solid municipal waste, and wood are often included (Cao et al. 2020). Because biomass absorbs carbon dioxide during its growth phase, it is considered a largely carbon-neutral resource (Ahn and Kim 2020). For instance, wood biomass has been found to have a lower ash content compared to microalgae biomass (Yang et al. 2013). Furthermore, integrating biomass feedstocks like food waste (from municipal solid waste) has shown not only to enhance hydrogen production but also to reduce emissions of pollutants (Park et al. 2021). As a result, a substantial body of research has focused on hydrogen generation methods using wood biomass.

Sattar et al. (2014) found that while the particle size of biomass feedstock had minimal influence on gas composition and the rate of gasification, the flow of steam was a significant factor. Similarly, de Sales et al. (2017) carried out studies examining the roles of air and steam flow on hydrogen production. The studies showed that higher air concentrations led to a decrease in hydrogen levels, whereas the introduction of saturated steam boosted hydrogen production. Heat was also identified as a crucial factor in hydrogen synthesis from biomass feedstock. Research by Li et al. (2014) indicated that an initial increase in temperature led to a rise in hydrogen concentration, which later declined.

Optimizing technology and equipment is essential for efficient hydrogen production, particularly under optimal biomass materials and operational conditions (Pandey, Prajapati, and Sheth 2019). Due to the irregular structure of biomass, burners with small and simple structures were particularly sought after (Ueki et al. 2011). Advancements like the compact design of the double-layer boundary layer burner and self-organizing thermal heat recirculation greatly improved the combustion characteristics (Dai and Dai 2022; Dai and Zhu 2022). The presence of an inert medium further facilitated heat transfer and fluid dispersion, enhancing the utility of biomass fuel (Gharehghani et al. 2021). Manelis et al. (2011) showed that the use of porous media mixed with solid fuel could elevate production levels. Additionally, Araus, Reyes, and Toledo (2014) proposed a combined filtration combustion method using wood pellets and inert medium, achieving a near-perfect hydrogen conversion rate of 99.9%. It should be noted that biomass can be segmented into various feedstocks.

2.4.1 Solid municipal waste-to-hydrogen

Compost increasingly, compost derived from solid municipal waste is utilized in agriculture as both a fertilizer and soil enhancer. While proponents view this as an essential recycling strategy that diverts waste from landfills (Vyas et al. 2022), critics express concern over its typically high metal content. The compost is frequently applied in large amounts to meet crop requirements and add organic matter to the soil. The primary concern is the potential for these metals to accumulate in crops and, in rare instances, infiltrate groundwater through the soil. Studies indicate that municipal solid waste compost can be high in salt content, which poses risks to soil structure and plant growth.

The processing of solid municipal waste has advantages, including reduced spatial, oxygen, and time requirements (Koumaki et al. 2021). One major challenge is the generation of a large volume of sludge. However, elevating the organic content of the sludge can make it more conducive to fermentation processes (Guven et al. 2019). Numerous studies have explored the potential of using this sludge for methane and hydrogen production (Sancho et al. 2019). While treatment waste is not inherently a suitable substrate due to the presence of both live and dead microbes that have consumed easily biodegradable organic materials (Tawfik et al. 2021), it may also contain substances like toxic metals and bio-inhibitors that hinder the fermentation process (Jin et al. 2018). Therefore, solid municipal waste has been employed to both increase the organic matter content of the substrate and mitigate the inhibitory effects on the fermentation process.

According to a study by Tunay et al. (2022), the inflow waste from wastewater treatment was examined for hydrogen synthesis from organic material. High-rated denitrification treatment was employed to enhance the organic content while conserving energy. The findings suggest that
the approach not only lowers the energy demands of the wastewater treatment plant but also enables the generation of green energy through the reduction of greenhouse gas emissions. Santos and Hanak (2022) evaluated the technoeconomic feasibility of sorption-enhanced gasification, a technique that includes in-situ CO₂ capture and augmented gasification of solid wastes for hydrogen production. While the method showed environmental benefits, the capital costs need to be reduced to make it competitive with traditional gasification techniques. Chen et al. (2020) investigated the interaction of experimental factors to optimize hydrogen production from combusted municipal solid waste. Their results indicated an optimal hydrogen generation rate of 15.963 mol/kg at a 41.36 mol% concentration, with the data aligning well with the projected statistical model. Utilizing heat to vaporize the waste was found to be an effective method for qualitative and quantitative hydrogen recovery from municipal solid waste.

Gasification of municipal solid waste is increasingly being viewed as a sustainable avenue for electricity generation (Liu et al. 2018). Numerous facilities for waste gasification are either in operation or under development worldwide (Arena 2012). Compared to incineration, gasification is both effective and less harmful to the environment, although it shares some emission-related challenges with incinerators (Basu 2010). Compounds such as hydroxides, tars, and halogens are released during the gasification process, posing environmental and operational problems (Sharma et al. 2008). These issues are often attributable to the diverse nature and characteristics of municipal solid waste. Therefore, it is vital to develop and apply optimal strategies to mitigate these pollutants across various scales of application. The primary chemical processes involved in gasification are outlined in reactions 14–20 (Bonilla and Gordillo 2017).

\[
\begin{align*}
C + O_2 &= CO_2 \text{ combustion process} \quad (14) \\
C + 0.5O_2 &= CO \text{ reduction process} \quad (15) \\
C + 2H_2 O &= 2H_2 + CO_2 \text{ gas–water reaction} \quad (16) \\
C + CO_2 &= 2CO \text{ Boudouard reaction} \quad (17) \\
C + 2H_2 &= CH_4 \text{ fermentation} \quad (18) \\
C + H_2 O &= CO_2 + H_2 \text{ gas shift combining water} \quad (19) \\
CH_4 + H_2 O &= CO + 3H_2 \text{ methane–steam} \quad (20)
\end{align*}
\]

Table 5 shows the gasification of municipal solid waste and solid fuels for hydrogen production.

Effective gasification of municipal solid waste results in the production of hydrogen-rich gas. Utilizing heat to vaporize this solid waste appears to be an efficient method for both qualitatively and quantitatively generating hydrogen.

### 2.4.2 Food waste-to-hydrogen

Food waste represents a significant portion of municipal solid waste, generated at various stages from production to consumption. Globally, it is estimated that approximately 1.3 billion tonnes of food are wasted each year. In China alone,
around 140 million tonnes of food waste are produced annually, with 98% of this waste being directly sent to landfills and incinerators, leading to considerable environmental challenges (Zheng et al. 2019b).

Food waste forms a considerable portion of overall solid waste (Saqib et al. 2019). Annually, countries like Japan, India, and South Korea generate a staggering 624–635 million tonnes of food waste (Valizadeh et al. 2021). Managing this waste effectively for resource optimization remains a challenging endeavor. Common disposal methods include decomposition, anaerobic digestion, incineration, and landfiling (Kim et al. 2011). Notably, food waste is rich in organic matter, comprising more than 90% of its dry weight (Singh et al. 2020), and it also has a high moisture content (Xiong et al. 2020). Traditional management methods such as landfills, incineration, and anaerobic digestion have their drawbacks. Landfills consume valuable land resources, incineration requires significant amounts of additional fuel and incurs high costs, and anaerobic digestion suffers from low efficiency, prolonged processing times, and environmental pollution concerns (Caton et al. 2010).

Numerous studies have delved into hydrogen production from food waste. Xu et al. (2022) explored the interplay between salinity and inoculum preparation on the genomic and physiological behaviors of thermophilic lactobacillus in hydrogen generation from food waste. Their experiments revealed that pretreated inoculum produced 7–56% more hydrogen than untreated ones. They also found that different bacterial strains dominated hydrogen production at varying salinity levels. In a separate study, McCaffery et al. (2019) evaluated the gas composition from a fluidized gasifier using air and steam as oxidizing agents, emphasizing the significant role of the type of gasification agent in determining syngas hydrogen concentration. Ahmed and Gupta (2010) found steam gasification to be more efficient than pyrolysis for food waste, suggesting a greater hydrogen yield.

Park et al. (2022) assessed the impact of agitator types in anaerobic fermenters and catalysts for methane reforma-

<table>
<thead>
<tr>
<th>Additive substance</th>
<th>Additive</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchen biochar</td>
<td>8.3 mL/L</td>
<td>Suryoto et al. (2016)</td>
</tr>
<tr>
<td>Olive peel</td>
<td>330 g</td>
<td>Pagliaccia et al. (2016)</td>
</tr>
<tr>
<td>Kitchen waste</td>
<td>2 mL/L</td>
<td>Tawfik, El-Qelish, and Salem (2015)</td>
</tr>
<tr>
<td>White clay and paper</td>
<td>215 g</td>
<td>Zhang and Wang (2013)</td>
</tr>
<tr>
<td>Lime clay and paper</td>
<td>205 g</td>
<td>Zhang, Wang, and Jiang (2013)</td>
</tr>
<tr>
<td>Paper and pulp</td>
<td>15 g/L</td>
<td>Lin, Wu, and Wang (2013)</td>
</tr>
<tr>
<td>Kitchen biochar</td>
<td>10 g/L</td>
<td>Suryoto et al. (2017)</td>
</tr>
<tr>
<td>and paper</td>
<td>7.1 g/L</td>
<td>Cao and Zhao (2009)</td>
</tr>
</tbody>
</table>

This section highlights the advantages of utilizing food waste as a potential source for renewable hydrogen energy. This approach serves dual purposes: it lessens the burden of managing municipal waste while also making the technology more financially viable through revenue generation from excess food waste. Several factors can be identified that influence the efficiency and stability of this application.

### 2.4.3 Biomass of algae-to-hydrogen

The International Agriculture Organization estimates that global production of fresh algae ranges between 150 and 600 tonnes per hectare annually, amounting to 12 million tonnes of dry matter each year (Adnan et al. 2019). Algal biomass has been suggested as a viable alternative biomass source for immediate conversion into biofuels or for further refinement into industrial energy sources like biogas and hydrogen through gasification or similar processes (Panwar, Kaushik, and Kothari 2011). Recent scientific literature has...
emphasized the potential of using algae as a fuel source, citing benefits such as enhanced photosynthetic activity and rapid growth rates compared to terrestrial ecosystems (Naik et al. 2010). Algae also have the advantage of thriving in wastewater conditions. One key distinction that sets algae apart from other energy sources is its status as a continuous, limitless, and pollutant-free energy supply. Unlike hydrocarbon-based fuels, algae utilize excess atmospheric CO₂ implying that their use would not result in a net increase in carbon dioxide emissions, thereby contributing to the stabilization of the Earth climate (Vyas, Verma, and Subrahmanyam 2010; Xia et al. 2015). Table 7 presents data on hydrogen yields and concentrations derived from algal biomass.

Chen (2022) outlines a strategy for continuous and sustainable hydrogen production using algae, providing both scientists and policymakers with a framework for evaluating its economic feasibility at the local level. To illustrate the advantages and disadvantages of algae-based hydrogen production, a prospective technology concept focused on biotechnological utility. These materials offer a raw material base for diverse industries, including hydrogen production (Van Fan et al. 2021). They are also rich in energy-dense compounds. A novel method for the concurrent synthesis of hydrogen and furfural from raw lignocellulose was developed by Lyu (2022). The study showed that the biomass substrates generated both furan and pure hydrogen, with production levels varying based on substrate type, content, volume, and particle size. A maximum conversion rate of 67% was attained for residual acetaldehyde, and a new electrochemical method yielded 336 mL of liquid hydrogen per gram of furfural waste with a peak efficiency of 99.3% (Lyu 2022). To reduce carbon dioxide emissions and meet fossil fuel needs, it is imperative to innovate using renewable feedstocks like biomass-based thermochemical methods. Figure 6 outlines the process for hydrogen production utilizing lignocellulosic biomass.

### Table 7: The hydrogen outputs and concentrations of algal biomass.

<table>
<thead>
<tr>
<th>Algal family</th>
<th>Classification</th>
<th>Stoichiometric hydrogen content (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenedesmus</td>
<td>Aquatic</td>
<td>47.8–64.8</td>
<td>Demirbas (2010); Park et al. (2013)</td>
</tr>
<tr>
<td>Chlorella</td>
<td>Micro</td>
<td>48.0–63.5</td>
<td>Sialve, Bernet, and Bernard (2009); Xia et al. (2013a)</td>
</tr>
<tr>
<td>Nannochloropsis</td>
<td>Micro</td>
<td>57.5–66.1</td>
<td>Efremenko et al. (2012); Xia et al. (2013b)</td>
</tr>
<tr>
<td>Eichhornia</td>
<td>Aquatic</td>
<td>64.2–65.1</td>
<td>Su et al. (2010); Cheng et al. (2010)</td>
</tr>
<tr>
<td>Chlamydomonas</td>
<td>Micro</td>
<td>54.1</td>
<td>Sialve, Bernet, and Bernard (2009)</td>
</tr>
<tr>
<td>Tetraselmis</td>
<td>Micro</td>
<td>46.2–64.1</td>
<td>Dismukes et al. (2008)</td>
</tr>
<tr>
<td>Laminaria</td>
<td>Micro</td>
<td>65.2–67.1</td>
<td>Shi et al. (2011)</td>
</tr>
<tr>
<td>Dunaliella</td>
<td>Aquatic</td>
<td>34.3–60.1</td>
<td>Lakaniemi et al. (2011)</td>
</tr>
<tr>
<td>Arthospira</td>
<td>Micro</td>
<td>33.1–64.3</td>
<td>Cheng et al. (2012)</td>
</tr>
<tr>
<td>Anabaena</td>
<td>Micro</td>
<td>55.2–59.8</td>
<td>Wei, Quarterman, and Jin (2013)</td>
</tr>
<tr>
<td>Euglena</td>
<td>Micro</td>
<td>49.1–58.2</td>
<td>Sialve, Bernet, and Bernard (2009)</td>
</tr>
<tr>
<td>Gelidium</td>
<td>Aquatic</td>
<td>66.0–67.3</td>
<td>Park et al. (2011)</td>
</tr>
</tbody>
</table>

culturing algae was compared to the world largest solar electrolysis hydrogen facility. A global temporal dynamic map and a scalability analysis were also conducted to explore the potential for algal hydrogen production in various geographic locations. In a related study, Chen et al. (2022) demonstrated that chemical emulsification of green algae can serve as a basis for chemiluminescence hydrogen production. The research found that products derived from Nannochloropsis could directly form indices in their initial liquid cultures when treated with a conventional chemical dispersant, a cationic etherified carbohydrate. This resulted in 11 days of sustained hydrogen production under constant light exposure, with an average chemiluminescence production rate of 0.37%.

#### 2.4.4 Lignocellulosic biomass-to-hydrogen

Bioenergy stands as one of the globe most abundant and efficient carbon sources. Key raw materials for bioenergy production encompass agricultural crop residues, micro-algae, forestry resources, and by-products from wood processing. Lignocellulosic material has emerged as a preferable option for extraction processes tailored to specific applications. The complex matrix of lignocellulose consists of a dense arrangement of phenolic and hemicellulose structures that envelop the cellulose chains (Ma et al. 2019). Components such as petroleum extracts, ash, and carbohydrates are also found in lignocellulosic biomass residues. Owing to the distinct chemical properties of these components, lignocellulosics serve as a substrate with high biotechnological utility. These materials offer a raw material base for diverse industries, including hydrogen production (Van Fan et al. 2021). They are also rich in energy-dense compounds. A novel method for the concurrent synthesis of hydrogen and furfural from raw lignocellulose was developed by Lyu (2022). The study showed that the biomass substrates generated both furan and pure hydrogen, with production levels varying based on substrate type, content, volume, and particle size. A maximum conversion rate of 67% was attained for residual acetaldehyde, and a new electrochemical method yielded 336 mL of liquid hydrogen per gram of furfural waste with a peak efficiency of 99.3% (Lyu 2022). To reduce carbon dioxide emissions and meet fossil fuel needs, it is imperative to innovate using renewable feedstocks like biomass-based thermochemical methods. Figure 6 outlines the process for hydrogen production utilizing lignocellulosic biomass.

Analytical assessments of lignocellulosic biomass have identified the presence of ammonia, oxygen, carbon, hydrogen, water, and sulfur. This suggests that agricultural biomass could adequately fulfill the requirements of
combustion systems, making it a viable and sustainable raw material for hydrogen production through gasification techniques. Depending on the season, agricultural waste may consist of either field remnants or forestry by-products left over after harvest or processing (Mondal and Denich 2010). The core structural elements of lignocellulosic biomass are mucilage, viscose, and phenol (Hoang et al. 2021b). These components can vary in concentration depending on the conversion methods employed, which can, in turn, influence the characteristics of the final products. When examining the composition for bioenergy applications, it is crucial to consider biomass sources that

![Diagram of hydrogen production process](image)

**Figure 6:** Process for producing hydrogen using lignocellulosic biomass (Hoang et al. 2021a).

<table>
<thead>
<tr>
<th>Sources of biomass</th>
<th>Correlative mass (%)</th>
<th>Components of lignocellulosic mass (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Condensation</td>
<td>Volatile compounds</td>
<td>Ash</td>
</tr>
<tr>
<td>The almond stone</td>
<td>12.2</td>
<td>78.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Peeled cassava</td>
<td>13.7</td>
<td>58.5</td>
<td>4.6</td>
</tr>
<tr>
<td>Bamboo</td>
<td>14.6</td>
<td>71.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Shell of a coconut</td>
<td>9.1</td>
<td>78.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Durian clamshell</td>
<td>10.8</td>
<td>–</td>
<td>4.9</td>
</tr>
<tr>
<td>Cotton sprigs</td>
<td>5.9</td>
<td>71.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Fiber of palm mesocarp</td>
<td>10.9</td>
<td>85.2</td>
<td>7.8</td>
</tr>
<tr>
<td>Husk of rice</td>
<td>7.1</td>
<td>68.1</td>
<td>17.2</td>
</tr>
<tr>
<td>Shelled palm kernel</td>
<td>7.8</td>
<td>73.2</td>
<td>1.05</td>
</tr>
<tr>
<td>Shelled walnut</td>
<td>9.1</td>
<td>78.6</td>
<td>1.01</td>
</tr>
<tr>
<td>Bagasse derived of sugarcane</td>
<td>7.8</td>
<td>87.0</td>
<td>3.9</td>
</tr>
<tr>
<td>General wood</td>
<td>6–22</td>
<td>75–83</td>
<td>0.25–4.4</td>
</tr>
</tbody>
</table>
have diverse chemical compositions. Table 8 provides a summary that includes the varying levels of proximate, ultimate, and lignocellulosic components across different types of biomasses.

To meet the biomass requirements for hydrogen production, different kinds of feedstock should be considered: specialized crops and lignocellulosic biomass residues. Lignocellulosic waste is an attractive option due to its affordability and availability, especially towards the end of harvest seasons. However, challenges exist in terms of land utilization and the timing of crop growth for dedicated energy production. To facilitate the required processing, different biomass types could be classified based on their chemical makeup. Table 9 provides a summary of research findings on hydrogen production using lignocellulosic biomass.

The production of hydrogen offers the benefit of utilizing a diverse range of cost-effective and sustainable raw materials. However, the complex structure of lignocellulose poses a significant hurdle in the efficient conversion of biomass to hydrogen. Economical production remains challenging due to the necessity for extensive pretreatments or a combination of processing steps and detoxification methods to remove receptor antagonists.

### Table 9: A summary of hydrogen production from lignocellulosic biomass.

<table>
<thead>
<tr>
<th>Lignocellulosic raw materials</th>
<th>Hydrogen production (%)</th>
<th>Generators of inhibitors</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty fruit cluster of oil palms</td>
<td>11</td>
<td>No synthesis of polyphenolic and furanics from hydrochloric and acetic acidity</td>
<td>Abdul et al. (2016)</td>
</tr>
<tr>
<td>Grain straw</td>
<td>68.7</td>
<td>No synthesis of polyphenolic and furanics from hydrochloric and acetic acidity</td>
<td>Cao et al. (2013)</td>
</tr>
<tr>
<td>Rice husk</td>
<td>7.55</td>
<td>Furanic compounds</td>
<td>Asadi and Zilouei (2017)</td>
</tr>
<tr>
<td>Biomass of grass</td>
<td>31.8</td>
<td>Possible formation of furfural</td>
<td>Yang and Wang (2019)</td>
</tr>
<tr>
<td>Bagasse from cotton</td>
<td>30.5</td>
<td>Weak barriers such as acetic, no furan production</td>
<td>Dong et al. (2018)</td>
</tr>
<tr>
<td>Rice husk</td>
<td>162.1</td>
<td>–</td>
<td>Kumar and Das (2016)</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>42</td>
<td>–</td>
<td>Sheng et al. (2018)</td>
</tr>
<tr>
<td>Rice husk</td>
<td>84</td>
<td>–</td>
<td>Wathiq and Hassein (2020)</td>
</tr>
</tbody>
</table>

### 3 Conclusions

Outside In light of the pressing need to transition to sustainable energy systems for mitigating climate change, this review underscores the importance of green hydrogen as a versatile and sustainable energy vector. Beyond its conventional role in industrial processes for manufacturing ammonia and methanol, hydrogen is increasingly seen as a new frontier in energy technology (Ajaj and Hassein 2020; DhahirTaher and Salem 2020). Its production from renewable sources like solar, wind, and hydro via electrolysis technologies: Polymer Electrolyte Membrane (PEM), Solid Oxide Electrolyzers (SOE), and Alkaline Electrolyzers (AE) offers a pathway to achieve not only zero greenhouse gas emissions but also the capability to stabilize energy grids and integrate seamlessly into existing infrastructures (Mathew et al. 2016; Hassan et al. 2022c). The paper conducts a meticulous comparative evaluation of these production methods, considering variables such as system design, cost, infrastructural facilities, and efficiency improvements. Although the review acknowledges the significant upfront investment required, it highlights the manifold long-term benefits, including the potential for grid stabilization and greater compatibility with existing energy systems. Significant advances in catalyst materials and system integration are leading to enhanced efficiencies and declining operational costs, making the large-scale production of green hydrogen increasingly viable (Hassan et al. 2022e, 2023a). Moreover, sectors like transportation, industry, and energy storage are rapidly embracing hydrogen-based solutions, thereby amplifying the imperative for scaling up green hydrogen production (Hassan et al. 2022a).

The review also offers a comprehensive assessment of the practical aspects surrounding green hydrogen, such as its use, storage, transportation, and redistribution, while acknowledging the challenges that remain. Due to its clean-burning properties and versatility, hydrogen is gaining global attention as both a fuel and a unique energy carrier, with the potential to revolutionize sectors from transportation to grid energy storage (Hassan et al. 2023b, 2023e). In particular, unpredictable renewable energy sources like solar and wind find a natural complement in hydrogen, which can act as a buffer, storing excess energy for later use (Hassan et al. 2023c, 2023d). The study explores these dynamics in detail, emphasizing the synergistic relationship between renewable energy and hydrogen production. While there are complexities in developing a robust storage and transportation infrastructure for hydrogen, given its low energy density and high-pressure requirements, advancements in material science and engineering solutions are
progressively overcoming these barriers. Additionally, the paper explores the possibility of retrofitting existing fossil fuel-based hydrogen production facilities with carbon capture and storage systems as a transitional measure toward producing green hydrogen (Hoisang and Sakaushi 2022). In summary, while challenges exist, the technological and systemic advancements in hydrogen production, storage, and transportation make it an increasingly compelling component of a sustainable energy future. Therefore, the momentum is clearly shifting towards a large-scale, global application of green hydrogen as an indispensable element in combating climate change and achieving energy sustainability.

List of abbreviations

AC alternative current
DC direct current
EV electric vehicles
FC fuel cell
IRENA International Renewable Energy Agency
NOCT nominal operation cell temperature
PV photovoltaic
RES renewable energy sources
WT wind turbine

List of symbols

- \( P_{\text{pv}} \) PV array power (kW)
- \( C_{\text{pv}} \) PV array capacity (kW)
- \( D_{\text{pv}} \) PV array derating factor (%)
- \( T_{\text{a}} \) ambient temperature (C)
- \( T_{\text{c}} \) PV cell temperature (C)
- \( H_{\text{s}} \) incident solar radiation (kW/m²)
- \( H_{\text{r}, \text{NOCT}} \) incident solar radiation at standard test conditions (kW/m²)
- \( T_{\text{a}, \text{NOCT}} \) ambient temperature at NOCT (C)
- \( T_{\text{c}, \text{NOCT}} \) Cell temperature at NOCT (C)
- \( T_{\text{c}, \text{NOCT}} \) solar radiation temperature at which NOCT (kW/m²)
- \( \alpha_{\text{P}} \) temperature coefficient of power (%/°C)
- \( \eta \) solar transmittance of any cover over the PV array [%]
- \( \beta \) solar absorptance of the PV array [%]
- \( \eta_{\text{PV}} \) PV efficiency
- \( \eta_{\text{h}} \) coefficient of heat transfer to the surrounding
- \( Q_{\text{H}_2} \) rate of hydrogen generated by the electrolyzer
- \( A_{\text{p}, \text{B}} \) coefficient of the consumption curve (kW/kg/h)
- \( \eta_{\text{f}} \) friction co-efficient
- \( N_{\text{c}} \) number of cells in series
- \( I_{\text{e}} \) electrolyzer current
- \( F \) Faraday efficiency
- \( m_{\text{H}_2} \) hydrogen mass flow (kg/h)
- \( m_{\text{H}_2} \) nominal hydrogen mass flow (kg/h)
- \( Q_{\text{H}_2} \) rate of hydrogen generated by the electrolyzer
- \( R \) Gas constant
- \( P_{\text{hto}} \) Hydrogen tank outlet pressure
- \( P_{\text{htc}} \) Hydrogen tank compressor inlet pressure
- \( \eta_{\text{h}, \text{t}} \) Hydrogen tank compressor efficiency
- \( P \) Pressure of hydrogen
- \( \eta_{\text{t}, \text{tan}} \) Volume of hydrogen tank
- \( P_{\text{con}} \) Converter input power
- \( P_{\text{con}} \) Converter output power
- \( \varphi \) Stefan–Boltzmann constant
- \( LHV_{\text{H}_2} \) lower heating value of the hydrogen output
- \( Q_{\text{h}} \) heat inter
- \( i \) process step
- \( Q_{\text{solar},i} \) total solar energy supplied to the solar collector
- \( \eta_{\text{opt}} \) optical efficiency
- \( \sigma \) Stefan–Boltzmann constant
- \( T_{\text{s}} \) solar heat collection temperature
- \( I \) thermal solar intensity
- \( C_{\text{i}} \) solar concentration ratio

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