***Review Article***

**Decarbonizing Energy Systems: A Review of Green Hydrogen Generation Technologies and Their Socio-Economic Impacts**

**Abstract**

As the global demand for clean energy intensifies, hydrogen has emerged as a promising energy carrier capable of addressing both environmental concerns and energy security. The transition to a hydrogen economy is gaining momentum worldwide, with green hydrogen production—particularly from biomass—being viewed as a sustainable and scalable solution. Biomass, an abundant, renewable, and carbon-neutral resource, offers significant potential for hydrogen production through thermochemical processes like gasification. Among the various methods, biomass briquettes serve as an efficient feedstock, contributing to improved energy density and reduced emissions. This paper reviews the stage-wise production of hydrogen from biomass, beginning with feedstock preparation and briquetting, followed by gasification, gas cleanup, and hydrogen separation. Gasification converts carbon-rich biomass into syngas, a mixture of hydrogen, carbon monoxide, and other gases. Advances in gasifier design, such as updraft and fixed-bed reactors, have enhanced gas quality while minimizing contaminants like tar and particulate matter. The subsequent gas purification and desulfurization processes are critical to improving hydrogen yield and equipment longevity. Warm gas cleanup (WGCU) technologies and advanced sorbents, including palladium-based materials, are being developed to increase efficiency and reduce costs. Hydrogen is then separated from purified syngas using techniques like membrane separation and pressure swing adsorption. This review highlights the economic and environmental benefits of biomass-derived hydrogen, especially for countries like India that face energy dependency and pollution challenges. Hydrogen can play a transformative role in industrial decarbonization, clean transportation, and renewable energy storage. Moreover, government initiatives such as India’s National Hydrogen Mission underline the growing policy support for green hydrogen development. The integration of biomass gasification into hydrogen production not only reduces greenhouse gas emissions but also enhances energy security and supports sustainable rural development. Thus, green hydrogen production from biomass presents a viable path toward a low-carbon future.

**Introduction**

 Presently, worldwide research and energy policy is focusing towards the hydrogen economy. Hydrogen is considered as a forecast to become major source of energy in the future. Hydrogen production is likely to play an important role during the development of economy. Biomass is an indigenous, often cheap, and above all renewable fuel. The increasing availability of biomass, combined with the recent development of technologies (Briquettes) to use it efficiently and with low levels of emissions, promise to make biomass an increasingly attractive feedstock option. As biomass is abundant, environment friendly and renewable; the production of hydrogen from biomass is a promising approach. Biomass derived hydrogen is likely to become a fuel of tomorrow. Visualizing the present worldwide scenario of the energy requirements and the concerned pollution, there is an utmost need of an alternative fuel source. This fuel should not only be a potential substitute for the depleting fossil fuels but also should cause least harm to the environment. Hydrogen could be a potential fuel which can meet both the requirements. Hydrogen fuel has been gaining attention worldwide as a potential solution to mitigate climate change and reduce dependence on fossil fuels. India faces severe air pollution issues, especially in major cities. Hydrogen fuel cells produce zero emissions at the point of use, which can help reduce pollution levels. India imports a significant portion of its oil and gas, making it vulnerable to price fluctuations and geopolitical tensions. Hydrogen can be produced domestically using various renewable energy sources, enhancing energy security. Hydrogen can be produced through gasification using renewable energy sources such as biomass briquettes. This can help in balancing the intermittency of renewable energy generation and storing excess energy for later use. Industries such as steel, cement, and chemicals are significant contributors to India's greenhouse gas emissions. Hydrogen can be used as a clean fuel in industrial processes, helping to reduce emissions. Hydrogen fuel cell vehicles offer a promising alternative to conventional internal combustion engine vehicles. With India's burgeoning transportation sector, adopting hydrogen fuel cell vehicles could significantly reduce emissions and dependence on imported oil.

The annual production of hydrogen is estimated to be about 55 million tons with its consumption increasing by approximately 6% per year. Hydrogen can be produced in many ways from a broad spectrum of initial raw materials. Nowadays, hydrogen is mainly produced by the steam reforming of natural gas, a process which leads to massive emissions of greenhouse gases (Balat and Balat, 2009; Konieczny *et al.* 2008). Close to 50% of the global demand for hydrogen is currently generated via steam reforming of natural gas, about 30% from oil/naphtha reforming from refinery/chemical industrial off-gases, 18% from coal gasification, 3.9% from water electrolysis, and 0.1% from other sources (Muradov and Veziroglu, 2005).

Presently, worldwide research and energy policy is focusing towards the hydrogen economy. Hydrogen is considered as a forecast to become major source of energy in the future. Hydrogen production is likely to play an important role during the development of economy. As biomass is abundant, environment friendly and renewable; the production of hydrogen from biomass is a promising approach (Saxena et al. 2008). Biomass derived hydrogen is likely to become a fuel of tomorrow. Hydrogen fuel has been gaining attention worldwide as a potential solution to mitigate climate change and reduce dependence on fossil fuels. India faces severe air pollution issues, especially in major cities. Hydrogen fuel cells produce zero emissions at the point of use, which can help reduce pollution levels. India imports a significant portion of its oil and gas, making it vulnerable to price fluctuations and geopolitical tensions. Hydrogen can be produced domestically using various renewable energy sources, enhancing energy security. Hydrogen can be produced through gasification using renewable energy sources such as biomass briquettes (Anonymous, 2021). This can help in balancing the intermittency of renewable energy generation and storing excess energy for later use. Industries such as steel, cement, and chemicals are significant contributors to India's greenhouse gas emissions. Hydrogen can be used as a clean fuel in industrial processes, helping to reduce emissions. Hydrogen fuel cell vehicles offer a promising alternative to conventional internal combustion engine vehicles. With India's burgeoning transportation sector, adopting hydrogen fuel cell vehicles could significantly reduce emissions and dependence on imported oil. The Indian government has shown interest in promoting hydrogen fuel. In November 2020, the Ministry of New and Renewable Energy (MNRE) released the draft National Hydrogen Energy Mission aiming to promote hydrogen production and usage in various sectors. According to reports, India's oil minister announced plans to invest 200 million dollars in hydrogen production over the next five to seven years (Anonymous, 2021). Several pilot projects and collaborations are underway to explore hydrogen production and usage in India. For instance, Indian Oil Corporation (IOC) has announced plans to build a hydrogen production plant at its refinery in Mathura. Indian research institutions and companies are actively involved in research and development related to hydrogen production, storage, and usage technologies. India aims to achieve 10% blending of hydrogen with compressed natural gas (CNG) by 2030 under its National Hydrogen Mission (Anonymous, 2023).While the hydrogen fuel sector in India is still in its nascent stage, there is growing momentum and interest from both the government and private sector, indicating its potential importance in India's future energy landscape. Hydrogen production is increasingly seen as a crucial element in transitioning towards a sustainable energy future.

As the world seeks to reduce greenhouse gas emissions to mitigate climate change, hydrogen is gaining attention as a clean energy carrier. It can be produced without emitting carbon dioxide when generated from renewable sources or through carbon capture and storage (CCS) technologies when produced from fossil fuels (Hassan et al. 2023).Hydrogen can serve as a means of energy storage, especially for intermittent renewable energy sources like wind and solar. Excess energy generated during peak times can be used to produce hydrogen via electrolysis, and this hydrogen can be stored for later use, thus helping to balance energy supply and demand. Hydrogen is a crucial feedstock for various industrial processes, including the production of ammonia for fertilizers, refining petroleum, and manufacturing chemicals like methanol and steel. Transitioning these processes to hydrogen can reduce carbon emissions significantly. Hydrogen fuel cells can power vehicles, offering zero-emission transportation. Although electric vehicles are more prevalent, hydrogen fuel cell vehicles have advantages in terms of range and refuelling time, making them suitable for heavy-duty vehicles and long-haul transport (Cheekatamarla and Praveen, 2024). Hydrogen can play a role in balancing electricity grids by providing flexibility through power-to-gas technologies. During periods of low electricity demand, excess renewable energy can be used to produce hydrogen through electrolysis. This hydrogen can then be stored and converted back to electricity or used as a fuel when demand is high. Hydrogen production can enhance energy independence by diversifying energy sources. Countries with abundant renewable resources can produce hydrogen domestically, reducing dependence on imported fossil fuels. The cost of hydrogen production is a critical factor. Currently, hydrogen production via electrolysis is more expensive compared to conventional methods such as steam methane reforming (SMR) (Katebah et al. 2022).

Steam Ethanol Reforming (SER) process by integrating palladium-based membrane separation within key reaction stages to enhance hydrogen yield and purity. Three alternative architectures—Open, Membrane Reactor, and Hybrid—were evaluated, demonstrating improved thermal efficiency and reduced specific CO₂ emissions compared to both the baseline SER and conventional SMR processes. The membrane integration not only shifts equilibrium to favour hydrogen production but also enables in-situ separation, thereby increasing overall process performance. Furthermore, the study includes an economic assessment indicating that despite higher capital costs, membrane-assisted systems offer lower operational expenditures and better environmental compliance, making them a viable pathway for large-scale, centralized green hydrogen production (Mosca et al. 2020). The hydrogen production system utilizes SOEC stacks supported by essential Balance of Plant (BoP) components. A shell-and-coil condenser and evaporator manage heat exchange and steam generation. Steam and air pre-heaters, along with a shell-and-tube heat exchanger (using the LMTD method), ensure thermal efficiency. A centrifugal pump and compressor operate based on fluid dynamics and defined efficiencies. A three-way mixer balances mass flow, while a Water Treatment and Recovery Unit (WTRU) produces high-pressure steam. Lastly, a separator removes residual water from flue gas using a mist extractor, optimizing overall system performance (Akinlabi et al. 2022). Green hydrogen, produced via electrolysis powered by floating photovoltaic platforms, and grid hydrogen, derived from conventional electricity sources, are evaluated alongside grey and blue hydrogen, which are both produced from natural gas, with blue hydrogen incorporating carbon capture using hot potassium carbonate. Using process simulation tools, the authors assess material and energy balances, capital and operating expenditures, and three critical performance indicators: Energy Return on Energy Invested (EROEI), Levelized Cost of Hydrogen (LCOH), and Life Cycle Assessment (LCA). While green hydrogen showed a slightly higher LCOH (8.76) than blue hydrogen (5.50), it demonstrated significantly lower environmental impacts and superior EROEI values (13.39–14.29), underscoring its potential as the most sustainable option. This literature contributes valuable insights into the techno-economic and environmental performance of hydrogen production pathways, especially within the context of maritime transport electrification (Mio et al. 2023). Hydrogen should be strategically implemented in sectors where decarbonization alternatives are limited, such as heavy-duty transportation, industrial chemical feedstocks, building heating, and seasonal energy storage. The authors outline a three-phase implementation strategy and forecast a global need of 2.3 Gt of hydrogen annually, which could enable an 18% reduction in emissions across energy-related sectors. They conclude that while hydrogen may not dominate the energy landscape, it is crucial in complementing renewable electricity systems and achieving a fully renewable energy future (Oliveira et al. 2021). Analysis of thermochemical water-splitting cycles (TWSCs) for sustainable hydrogen production, emphasizing the use of cerium-based redox reactions due to their favourable thermodynamic properties. The study highlights the primary technical challenges such as high activation temperatures, thermal stress on materials, and the need for efficient heat and mass transfer. Various innovations like metal oxide foams, inert gases, and vacuum-based reactors are discussed as strategies to enhance performance and reduce environmental impact. Simulation models, both commercial and in-house, are explored to evaluate dynamic system behaviour, yet the authors note a significant gap in georeferenced and weather-responsive simulations. Economically, the levelized cost of hydrogen from metal oxide cycles remains high, indicating a need for further technological and economic advancements to compete with solar electrolysis methods (Barone et al. 2023).

As technology advances, electrolyser efficiency is projected to improve significantly—from 61% in 2030 to 76% by 2050—indicating growing feasibility and energy efficiency in hydrogen production. Biomass gasification stands out with the lowest CAPEX at approximately €11 million, while pyrolysis and coal gasification demand higher investments, ranging from €170 million to over €280 million. Steam Methane Reforming (SMR) and photo fermentation fall in between, with costs varying depending on the scale and method applied. A consistent decline in cost and increase in efficiency is anticipated for each type, reinforcing the trend towards cost-effective green hydrogen solutions. The indicative hydrogen demand by 2030, with the United States (5.1–7.7 MtH₂), Korea (2.8–4.2 MtH₂), China (1.8–2.7 MtH₂), and Russia (1.5–2.2 MtH₂) expected to be major consumers (Kelvin Edem Bassey & Chinedu Ibegbulam, 2023; Sharma and Kumar 2024).

Hydrogen production through the gasification pathway involves converting carbon-containing feedstocks, such as coal, biomass, or municipal solid waste, into hydrogen-rich gas through a chemical process known as gasification. This method offers several advantages, including the potential to utilize a variety of feedstocks, high hydrogen yield, and the ability to capture and sequester carbon dioxide emissions.

**Stage by Stage Process of Hydrogen Production**

**Figure 1. Flowchart of Biomass to Hydrogen**

**a. Feedstock Preparation:** The feedstock, which can be coal, biomass, or other carbon-containing materials, is prepared by drying and sometimes grinding it into small particles to improve the efficiency of the gasification process. Feedstocks that have incompatibly small particle sizes (such as saw dust) can potentially be made usable by being pressed into briquettes or pellets, especially if they are subsequently torrefied. Pellet mills compress the raw feedstock through a plate under extremely high pressure, often resulting in enough heat to fuse the lignin content of wood. Briquetting systems compress the raw feedstock or a feedstock slurry into a Mold, often with a binder mixed in the feedstock material then binds together to form larger pieces (Bion et al., 2012; Blohm & Dettner, 2023; Das et al., 2001; Dawood et al., 2020).

Briquetting is – like pelletising – a process in which the raw material is compressed under high pressure, which causes the lignin in the wood or biomass to be liberated so that it binds the material into a firm briquette. The most appropriate water content in the raw material for briquetting varies and depends on the raw material. However, the normal water content is between 6% and 16%. If the water content is over 16% the quality of the briquettes will be reduced, or the process will not be possible. There are hydraulic presses for small capacities from 50 to 400 kg/hour. The raw material is fed into the press by a time-controlled dosing screw, which means that it is the volume of the raw material and not the weight, which is controlled. Briquettes have a fairly good uniform length (square briquettes) and they are mainly used by domestic consumers. Mechanical presses are available with capacities from 200 kg/hour up to 1800 kg/hour (Barone et al., 2023, Naqvi et al., 2024; Oliveira et al., 2021). Briquettes from these presses are normally round and short and they are used in heating plants for larger industries and for district heating plants. A mechanical press is built like an eccentric press. A constantly rotating eccentric connected to a press piston presses the raw material through a conic nozzle. The required counter pressure can be adjusted only by using a nozzle with a different conicity. A mechanical press receives raw material from a speed-controlled dosing screw. The speed of the dosing screw determines the production rate of the press. A change in the specific gravity of the raw material will change the hardness of the briquettes. A mechanical briquetting press will produce a long length of material – a briquette string – which, however, breaks into random lengths depending on the binding capacity of the raw material. A saw or cutter is used to cut the briquette string into briquettes of uniform length. The briquette string pushed out of the press is very hot because of the friction in the nozzle. The quality of the briquettes depends mainly on the cooling and transport line mounted on the press.

**b. Technology refinement for production of hydrogen rich producer gas using briquettes as feedstock.**

Gasification is the thermal conversion of any carbon containing materials at elevated temperatures (650-1200oC) in the presence of gasification agents (air, oxygen, carbon dioxides, or a combination of these). The resulting product is synthesis gas “syngas” which is suitable for producing heat, power generation, industrial applications, and liquid fuels production. Syngas consists primarily of carbon dioxide (CO2), carbon monoxide (CO), hydrogen (H2), methane (CH4), and other contaminants including ash, char, tar, gaseous metals, sulphur compounds, and chlorine traces. The type of feedstock composition, gasification process, and gasification agent determines the main component and contaminants in the syngas. Contaminants in syngas are treated and removed to ensure high-quality syngas for use in fuel and power generation.

C6H12O6 + O2 + H2O → CO + CO2 + H2 + other species

Updraft gasifiers in this type of reactor, biomass is fed downward from the top and gasifying agents is fed upward from the bottom in a counter flow arrangement. Ash is collected at the bottom of the equipment with air-lock design. This counter flow process also makes syngas from updraft gasifiers carries less contamination. In contrast, the operation of updraft gasifiers is the easiest among other types of fix-bed gasifiers above. Its design is also simple and available for multi-feed stock purpose. Fixed bed reactors and fluidized bed are the most commonly used reactor configurations. In fixed bed gasifiers, two types stand out, using counter current and concurrent flows. In the counter current gasifier, the feed is carried out at the top and the gassing agent (O2/air) is inserted at its base. In the concurrent gasifier, the feed is carried out from the top, while the gassing agent is inserted from the side or even from the top. One of the advantages of the concurrent fixed bed gasifier is that approximately 99% of the tar is consumed, requiring a minimum of tar removal in the gas. The gas produced in a concurrent gasifier has lower amounts of tar (<1%), higher temperature (700 ◦C) and more particulate matter than that obtained using a counter current gasifier. The composition of the gas, determined for an air coefficient of 0.287, was 24% of CO, 12% of H2, 14% of CO2, 2% of CH4 and 45% of N2. The influence of the air/fuel ratio on the composition of the gas, on its heating value and on the overall efficiency.

**c. Development/ adoption of technology to separate tar from the producer gas.**

The raw gas produced from the gasification process typically contains impurities such as sulphur compounds, particulates, and tars. These impurities must be removed to prevent equipment fouling and ensure the quality of the hydrogen product. Gas cleanup processes may include scrubbing, filtering, and chemical treatment to remove contaminants.

**Figure 2. Classification of Desulfurization technologies**

**Warm Gas Cleanup**

The production of clean synthesis gas (syngas)—free of contaminants such as particulates, sulphur, ammonia, chlorides, mercury and other trace metals, and possibly carbon dioxide—is crucial to final product quality, to protecting downstream units such as gas turbines, catalytic reactors, and fuel cells, and to ensuring low environmental emission levels. Therefore, gas cleanup steps are indispensable, but do have a sizeable impact on plant economics. Although raw syngas leaving the gasifier is at high temperature, conventional gas cleaning is typically carried out at low temperature by scrubbing the syngas using chemical or physical solvents (these require cooling the gas to typically below 100°F). The cooling equipment required, and the need to reheat the syngas before making use of it in a combustion turbine or synthesis reactor, result in economic and thermodynamic penalties that decrease the efficiency of a gasification plant.

Preliminary efforts of the so-called "hot gas" cleanup focused on a maximum operating temperature of about 1000°F so that the alkalis in the hot syngas could be condensed out on the particulates so as not to cause corrosion problems with downstream equipment. WGCU technology tends to remove a significant portion of trace metal contaminants such as mercury along with the major gas contaminants (sulphur, etc.) found in syngas. In conventional syngas cleanup systems operated at low temperatures, activated carbon is used for complete removal of trace species, but at the elevated temperatures of the WGCU conventional activated carbon cannot be utilized. Accordingly, alternative sorbents are required. Palladium-based sorbents are among the most promising candidates for the high-temperature, one-step capture or polishing to extremely low levels of trace elements from coal-derived fuel gases.

**d. Production of hydrogen from the purified producer gas through absorption**

**Hydrogen Separation:** After the gas cleanup stage, the hydrogen-rich gas mixture is further processed to separate hydrogen from the other gases. Various separation methods can be employed, including pressure swing adsorption (PSA), membrane separation, or cryogenic distillation. One pathway for the separation of H2 from the syngas is found in membrane technologies. Advances in H2 membrane separation are critical to the development of advanced energy systems based on coal/biomass processing with CO2 capture. The membrane-based separation of H2 from biomass-derived syngas using an improved palladium (Pd)-based membrane technology (De Risi et al., 2023; Eicke et al., 2022; Jolaoso et al., 2022).

Renewable energy sources like biomass generation is indigenous and can help to a large extent in reducing the dependency on fossil fuels. It also provides national energy security when depleting global reserves of fossil fuels threatens sustainability of Indian Economy. Hydrogen production costs from natural gas, coal gasification and electrolysis are very sensitive to the cost of the primary feedstock and the economy of scale. On the basis of these considerations, it seems reasonable tom say that hydrogen may become competitive as an energy carrier if the current best-practice production costs are reduced by a factor of three by utilizing biomass as feedstock. In terms of greenhouses gases, therefore, coal when converted to electricity typically produces around 830g CO2/kWh of electricity generated, oil 600 g CO2/kWh and natural gas 400g CO2/kWh. But for biomass the carbon is recycled through the next crop, so the emissions are not an issue, and the CO2/ kWh is in effect zero. Presently, worldwide research and energy policy is focusing towards the hydrogen economy. Hydrogen is considered as a forecast to become major source of energy in the future. Hydrogen production is likely to play an important role during the development of economy.

**Conclusion**

Green hydrogen as a key enabler of a low-carbon, sustainable energy future. Technological advancements, particularly in electrolyser efficiency and cost reduction are paving the way for broader adoption across sectors such as transportation, industry, and energy storage. Despite notable challenges, such as high initial capital costs, the need for high-temperature materials, and region-specific limitations, promising solutions are emerging, including thermochemical water-splitting cycles, biomass-based systems, and hybrid solar technologies. The global map of projected hydrogen demand by 2030 underscores the urgency for coordinated international strategies, robust investment, and supportive policies to drive the hydrogen economy forward. With continued innovation, integration of renewable resources, and cross-sector collaboration, green hydrogen can become a central pillar in achieving global decarbonization and energy security goals.

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