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Review

Hydrogen from biomass – Present scenario and future prospects

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ABSTRACT

Hydrogen is considered in many countries to be an important alternative energy vector and a bridge to a sustainable energy future. Hydrogen is not an energy source. It is not primary energy existing freely in nature. Hydrogen is a secondary form of energy that has to be manufactured like electricity. It is an energy carrier. Hydrogen can be produced from a wide variety of primary energy sources and different production technologies. About half of all the hydrogen as currently produced is obtained from thermo catalytic and gasification processes using natural gas as a starting material, heavy oils and naphtha make up the next largest source, followed by coal. Currently, much research has been focused on sustainable and environmental friendly energy from biomass to replace conventional fossil fuels. Biomass can be considered as the best option and has the largest potential, which meets energy requirements and could insure fuel supply in the future. Biomass and biomass-derived fuels can be used to produce hydrogen sustainably. Biomass gasification offers the earliest and most economical route for the production of renewable hydrogen.

1. Introduction

Petroleum-based fuels became the primary source of energy for transportation needs in the 20th century. This has continued in the beginning of the 21st century with almost all vehicles running. On gasoline, diesel or natural gas [1]. The continued use of fossil fuels to meet the majority of the world's energy demand is threatened by increasing concentrations of carbon dioxide (CO_2) in the atmosphere and concerns over global warming [2]. Moreover, the petroleum is a finite source for fuel that is rapidly becoming scarcer and more expensive. Petroleum-based fuels are limited reserves concentrated in certain regions of the world [3]. Environmental, economical and political concerns are generating a growing interest in biofuels. Biofuels produced from natural oils and fats, which can be used as substitutes for gasoline and petroleum diesel fuels. In addition to being biodegradable and non-toxic, they are also essentially free of sulfur and aromatics, producing lower exhaust emissions than conventional gasoline and diesel fuel whilst providing similar properties in terms of fuel efficiency [4].

The term biofuel is referred to as liquid or gaseous fuels for the transport sector that are predominantly produced from biomass. Large-scale production of biofuels offers an opportunity for certain developing countries to reduce their dependence on oil imports. In developed countries there is a growing trend towards employing modern technologies and efficient bioenergy conversion using a range of biofuels, which are becoming cost-wise competitive with fossil fuels [5]. For this reason, alternate transportation fuels such as bioethanol, biodiesel, and hydrogen will play an important role in the world's future.

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Hydrogen production is one of the most promising alternative energy technologies. It is not primary energy existing freely in nature. Hydrogen is a secondary form of energy that has to be manufactured like electricity. It is an energy carrier. The majority of the experts consider that hydrogen has a great role to play as an important energy carrier in the future energy sector [6,7].

Hydrogen is clean fuel with no CO_2 emissions and can easily be used in fuel cells for generation of electricity. Besides, hydrogen has a high energy yield of 122 kJ/g, which is 2.75 times greater than hydrocarbon fuels [8]. The use of hydrogen as a fuel for transportation and stationary applications is receiving much favorable attention as a technical and policy issue [9]. Hydrogen gas is being explored for use in combustion engines and fuel cell electric vehicles. It is a gas at normal temperatures and pressures, which presents greater transportation and storage hurdles than exist for the liquid fuels [10]. Hydrogen can be stored chemically or physiochemically in various solid and liquid compounds (metal hydrides, carbon nanostructures, alanates, borohydrides, methane, methanol, light hydrocarbons) [11].

2. Current status of hydrogen production and use

Hydrogen can be produced from a wide variety of primary energy sources and different production technologies. Most hydrogen is currently produced from nonrenewable sources such as oil, natural gas, and coal. About half of all the hydrogen as currently produced is obtained from thermo catalytic and gasification processes using natural gas as a starting material, heavy oils and naphtha make up the next largest source, followed by coal [12], and only 4% and 1% is generated from water using electricity and biomass, respectively [13]. In short, fossil fuel-based processes account for 95% of global hydrogen production.

The production of hydrogen from fossil fuels causes the co-production of CO_2, which is assumed to be the main responsible for the so-called "greenhouse effect". Hydrogen produced through a range of renewable primary energy sources such as wind, biomass, and solar energy is ideal for gradually replacing fossil fuels [14]. Biomass and biomass-derived fuels can be used to produce hydrogen sustainably. Using biomass instead of fossil fuels to produce hydrogen reduces the net amount of CO_2 released to the atmosphere, since the CO_2 released when the biomass is gasified was previously absorbed from the atmosphere and fixed by photosynthesis in the growing plants [15].

Current total annual worldwide hydrogen consumption is in the range of 400–500 billion Nm^3 [16]. Present utilization of hydrogen is equivalent to 3% of the energy consumption and with a growth rate estimated at 5–10% per year [12]. Only a fraction of this hydrogen is currently used for energy purposes; the bulk serves as a chemical feedstock for petrochemical, food, electronics and metallurgical processing industries. The global market for hydrogen is already greater than US$40 billion per year [17]; including hydrogen used in ammonia production (49%), petroleum refining (37%), methanol production (8%), and miscellaneous smaller-volume uses (6%) [18].

Hydrogen can be used as a transportation fuel, whereas neither nuclear nor solar energy can be used directly. It has good properties as a fuel for internal combustion engines in automobiles. Hydrogen can be used as a fuel directly in an internal combustion engine not much different from the engines used with gasoline [19]. Hydrogen has very special properties as a transportation fuel, including a rapid burning speed, a high effective octane number, and no toxicity or ozone-forming potential. It has much wider limits of flammability in air (4%–75% by volume) than methane (5.3%–15% by volume) and gasoline (1%–7.6% by volume) [7].

3. Hydrogen production from biomass

3.1. *Overview of biomass*

Biomass, mainly in the form of wood, is the oldest form of energy used by humans. Traditionally, biomass has been utilized through direct combustion, and this process is still widely used in many parts of the world. The most important biomass energy sources are wood and wood wastes, agricultural crops and their waste byproducts, municipal solid waste, animal wastes, waste from food processing, and aquatic plants and algae. Energy from biomass fuels is used in the electric utility, lumber and wood products, and pulp and paper industries. Currently, much research has been focused on sustainable and environmental friendly energy from biomass to replace conventional fossil fuels.

3.1.1. *Components of biomass*

The chemical structure and major organic components in biomass are extremely important in the development of processes for producing derived fuels and chemicals [19]. The chemical components of lignocellulose can be divided into four major components. They are cellulose, hemicelluloses, lignin and extractives [20]. Generally, the first three components have high molecular weights and contribute much mass, while the last component is of small molecular size, and available in little quantity [21]. Cellulose + hemicellulose contents are more in hardwoods (78.8%) than softwoods (70.3%), but lignin is more in softwoods (29.2%) than hardwoods (21.7%) [22].

Cellulose, which is an abundant component in plants and wood, comes in various forms and a large fraction comes from domestic and industrial wastes [23]. Cellulose is a high molecular weight linear polymer of β-1,4-linked D-glucose units which can appear as a highly crystalline material [24]. Glucose anhydride, which is formed via the removal of water from each glucose, is polymerized into long cellulose chains that contain 5000–10000 glucose units. The basic repeating unit of the cellulose polymer consists of two glucose anhydride units, called a cellobiose unit [25].

Hemicellulose is a mixture of various polymerized monosaccharides such as glucose, mannose, galactose, xylose, arabinose, 4-O-methyl glucuronic acid and galacturonic acid residues [25]. Among the most important sugar of the hemicelluloses component is xylose. In hardwood xylan, the backbone chain consists of xylose units which are linked by β-(1,4)-glycosidic bonds and branched by α-(1,2)-glycosidic bonds with 4-O-methyl glucuronic acid groups [21]. Hemicelluloses exhibit lower molecular weights than cellulose. The number of repeating saccharide monomers is only ~150, compared to the number in cellulose [25].

Lignin is an aromatic polymer synthesised from phenylpropanoid precursors. The basic chemical phenylpropane units of lignin (primarily syringyl, guaiacyl and p-hydroxy phenol) are bonded together by a set of linkages to form a very complex matrix. This matrix comprises a variety of functional groups, such as hydroxyl, methoxyl and carbonyl, which impart a high polarity to the lignin macromolecule [26].

3.1.2. *Importance of biomass*

Biomass energy (bioenergy) utilization has gained particular interest in recent years due to the progressive depletion of conventional fossil fuels that calls for an increased use of renewable energy sources [27]. Growing interest in bioenergy is driven by the following facts among others [28]: (i) it contributes to poverty reduction in developing countries, (ii) it meets energy needs at all times, without expensive conversion devices, (iii) it can deliver energy in all forms that people need (liquid and gaseous fuels, heat and electricity), (iv) it is CO_2-neutral and can even act as carbon sinks, and (v) it helps to restore unproductive and degraded lands, increasing biodiversity, soil fertility and water retention. Importance of biomass will increase as national energy policy and strategy focuses more heavily on renewable sources and conservation.

3.1.3. *Contribution of biomass in global energy supply*

Biomass can be considered as the best option and has the largest potential, which meets energy requirements and could insure fuel supply in the future. Biomass energy resources are potentially the world's largest and most sustainable energy source, a renewable resource comprising 220 billion oven-dry tons (about 4500 EJ) of annual primary production [29]. About 5% of this energy, or 225 EJ, should cover almost 50% of the world's total primary energy demand at present [30]. However, total biomass contributed around 10% to meet the 470 EJ world primary energy demand in 2007, though this was mainly in the form of traditional non-commercial biomass [30,31]. The future potential for biomass could reach 150–400 EJ/yr (up to 25% of world primary energy) by 2050 with the use of forest and urban residues, in addition to growing perennial energy crops [31].

Currently, much research has been focused on sustainable and environmental friendly energy from biomass to replace conventional fossil fuels. Biomass can be converted to a number of secondary energy carriers (electricity, gaseous, liquid and solid fuels and heat) using a wide range of conversion routes. The conversion routes to fuels and electricity can be distinguished in thermal, chemical and biochemical conversion routes [32]. There have been developed thermo chemical conversion technologies such as pyrolysis [33], gasification [34], liquefaction [35], and supercritical fluid extraction [36] for maximizing liquid yields. Direct combustion is the old way of using biomass. Biomass thermo chemical conversion technologies such as pyrolysis and gasification are certainly not the most important options at present; combustion is responsible for over 97% of the world's bioenergy production [37]. In industrialized countries, the main biomass processes utilized in the future are expected to be the direct combustion of residues and wastes for electricity generation [38].

3.2. *Biomass feedstocks for hydrogen production*

The use of renewable biomass as a major feedstock for hydrogen production has received considerable attention in recent years. Hydrogen can be generated from biomass, but this technology urgently needs further development. The production of hydrogen from biomass is already economically competitive today. Hydrogen from biomass has many advantages [39]: (i) independence from oil imports, (ii) net product remains within the country, (iii) stable pricing level, (iv) peace keeping, and (v) the CO_2 balance can be improved by around 30%.

Two types of biomass feedstock are available to be converted into hydrogen [40]: (i) dedicated bioenergy crops, and (ii) less expensive residues, such as organic waste from regular agricultural farming and wood processing (biomass residues). The list of some biomass material used for hydrogen production is given in Table 1 [41]. In general, biomass from energy crops, such as sweet sorghum, can be used as raw material for hydrogen production [42]. Biomass, especially organic waste, offers an economical, environmental-friendly way for renewable hydrogen production [43].

3.3. *Hydrogen production routes from biomass*

The methods available for the hydrogen production from biomass can be divided into two main categories: thermo chemical and biological routes. The major biomass-to-hydrogen pathways are shown in Fig. 1 [44]. Hydrogen can be produced from biorenewable feedstocks via thermo chemical conversion processes such as pyrolysis, gasification, steam gasification, steam reforming of bio-oils, and supercritical water gasification. Biological production of hydrogen can be classified into the following groups: (i) biophotolysis of water using green algae and blue-green algae (cyanobacteria), (ii) photo-fermentation, (iii) dark-fermentation, and (iv) hybrid reactor system.

The advantage of the thermo chemical process is that its overall efficiency (thermal to hydrogen) is higher ($\eta \sim 52\%$) and production cost is lower [45]. The yield of hydrogen that can be produced from biomass is relatively low, 16–18% based on dry biomass weight [46]. Hydrogen yields and energy contents,

Table 1 – List of some biomass material used for hydrogen production.

Biomass species	Main conversion process
Bio-nut shell	Steam gasification
Olive husk	Pyrolysis
Tea waste	Pyrolysis
Crop straw	Pyrolysis
Black liquor	Steam gasification
Municipal solid waste	Supercritical water extraction
Crop grain residue	Supercritical fluid extraction
Pulp and paper waste	Microbiol fermentation
Petroleum basis plastic waste	Supercritical fluid extraction
Manure slurry	Microbiol fermentation

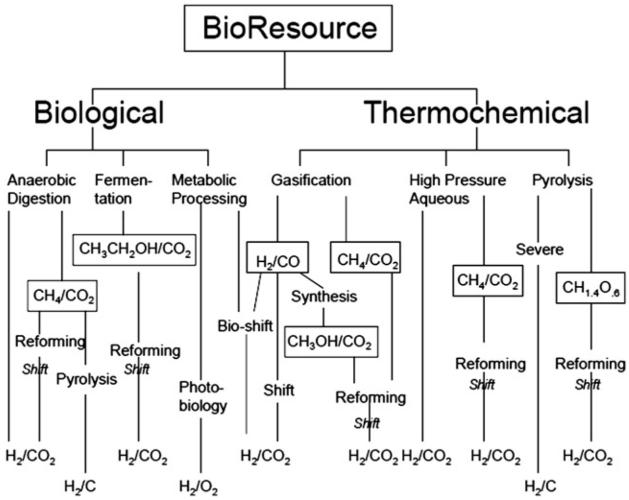

Fig. 1 – Pathways from biomass-to-hydrogen. Source: Ref. [44].

compared, with biomass energy contents obtained from processes with biomass, are shown in Table 2 [47]. In the pyrolysis and gasification processes, water gas shift is used to convert the reformed gas into hydrogen, and pressure swing adsorption is used to purify the product. Comparison with other biomass thermo chemical gasification such as air gasification or steam gasification, the supercritical water gasification can directly deal with the wet biomass without drying, and have high gasification efficiency in lower temperature [48]. The major disadvantage of these processes is the decomposition of the biomass feedstock leading to char and tar formation [49]. In order to optimize the process for hydrogen production, a number of efforts have been made by researchers to test hydrogen production from biomass gasification/pyrolysis with various biomass types and at various operating conditions, an example of oil palm shell compared with physic nut waste is listed in Table 3 [50].

Biological hydrogen production processes are found to be more environment friendly and less energy intensive as compared to thermo chemical and electrochemical processes [51]. Researchers have started to investigate hydrogen production with anaerobic bacteria since 1980s [52]. Biological production of hydrogen (biohydrogen) as a byproduct of microorganism metabolism is an exciting new area of technology development that offers the potential production of usable hydrogen from a variety of renewable resources [53]. There are three types of microorganisms of biohydrogen generation: cyano-bacteria, anaerobic bacteria, and fermentative bacteria. A promising method is the biological production of hydrogen by fermentation. The production of hydrogen from biomass by fermentation is one of the routes that can contribute to a future sustainable hydrogen economy. The amount of hydrogen produced from glucose is affected by fermentation pathways and liquid end-products [54]. Butyric acid and acetic acid constituted more than 80% of total end-products [55]. Theoretically, 4 mol of H_2 are produced from 1 mol of glucose in acetate type fermentation, however only 2 mol of H_2 produced when butyrate is the main fermentation product. To date, many studies have been done on fermentative hydrogen production from pure sugars and from feedstocks, such as byproducts from the agricultural and food industry, municipal waste, or wastewaters [56]. Anaerobic digestion of solid organic waste, including municipal and agricultural wastes and wastewater sludge, is one such renewable source for H_2 production. However, continual H_2 production using this process has limitations one of which is the low yields of hydrogen currently realized from the fermentation of even the simplest sugars [57]. A combination of dark and photo-fermentation in a two-stage hybrid system can improve the overall yield of hydrogen [58]. Anaerobic bacteria decompose glucose or starch via acetate fermentative metabolism as the first step, and photosynthetic bacteria convert the resultant acetate to hydrogen in another reactor as the second stage. The hydrogen yield is increased two-fold in comparison to that using only dark-fermentation [59].

Table 2 – Comparison of hydrogen yields were obtained by use of three different processes.

Processes	Hydrogen yield(wt%)	Hydrogen energy contents/biomass energy content
Pyrolysis + catalytic reforming	12.6	91
Gasification + shift reaction	11.5	83
Biomass + steam + except heat (theoretical maximum)	17.1	124

Table 3 – Hydrogen production from conversion of oil palm shell and physic nut waste.

Type biomass/Temperature	Gas production (vol.%)
Oil palm shell	
773 K	3.56
973 K	12.58
1173 K	33.49
Physic Nut	
773 K	8.22
973 K	9.29
1173 K	11.63

Source: Ref. [50].

3.4. *Hydrogen production costs*

The major problem in utilization of hydrogen gas as a fuel is its unavailability in nature and the need for inexpensive production methods [8]. Steam methane reforming (SMR) is currently the most common and least expensive process for producing hydrogen from natural gas. In this method, natural gas feedstock costs generally contribute approximately 52–68% to the final hydrogen price for larger plants, and 40% for smaller plants, with remaining expenses composed of capital charges [60]. Large-scale centralized power plants give way to small-scale distributed generation systems that operate nearer the point of use [61]. Hydrogen production costs from natural gas using SMR range from about 1.50 US$/kg at large-scale facilities (1.2 Gg/d) to about 3.75 US$/kg at a 500 kg/d facility (assumes 7

Table 4 – Hydrogen costs used in long-term scenario modelling.

Method	Feedstock price	Feedstock cost [$/GJ H_2]	Other prod. cost [$/GJ H_2]	Transport cost [$/GJ H_2]	Refueling cost [$/GJ H_2]	Total cost at fuel pump [$/GJ H_2]
Natural gas with CCS	3–5 $/GJ	3.8–6.3	1.2–2.7	2	5–7	12–18
Coal with CCS	1–2 $/GJ	1.3–2.7	4.7–6.3	2	5–7	13–18
Biomass gasification	2–5 $/GJ	2.9–7.1	5–6	2–5	5–7	14–25
Onshore wind	3–4 cents/kWh	9.8–13.1	5	2–5	5–7	22–30
Offshore wind	4–5.5 cents/kWh	13.1–18.0	5	2–5	5–7	27–37
Solar thermal elec.	6–8 cents/kWh	19.6–26.1	5	2–5	5–7	32–42
Solar PV	12–20 cents/kWh	39.2–65.4	5	2–5	5–7	52–82
Nuclear	2.5–3.5 cents/kWh	8.2–11.4	5	2	5–7	20–27

Source: Ref. [72].

US$/GJ natural gas price) [62]. The SMR process produces CO and CO_2, the primary greenhouse gas. According to Muradov and Veziroglu [63], a typical SMR hydrogen plant with the capacity of approximately 1 million m^3 of hydrogen per day produces 0.3–0.4 million standard cubic meters of CO_2 per day, which is normally vented into the atmosphere. Several studies [64,65] showed that capturing CO_2 adds about 25–30% to the cost of producing hydrogen by SMR.

Hydrogen production by gasification and pyrolysis of biomass are not generally considered economically competitive with SMR processes. The price of hydrogen obtained by direct gasification of lignocellulosic biomass, however, is about three times higher than that for hydrogen produced by SMR [66]. According to Hamelinck and Faaij [67], the cost of producing hydrogen from biomass ranges from 10 to 14 US$/GJ, with a net higher heating value (HHV) energy efficiency of 56–64%.

It is believed that in the future biomass can become an important sustainable source of hydrogen. The future prospects for hydrogen economy or economic hydrogen production are the basic point of many articles [68]. Biomass residues are the cheapest feedstocks. Because of the low sulfur content of biomass, a sulfur removal system is not likely to be required. Several studies have shown that the cost of producing hydrogen from biomass is strongly dependent on the cost of the feedstock [69]. Hydrogen from biomass gasification is not expected to develop in the near term due to costs, lack of demonstrated technology and lack of widespread hydrogen market and infrastructure [70]. For a more long-term view of price competition, it is necessary to include both the variability in feedstock prices and the likely use of CO_2 capture and storage (CCS) in fossil based processes [71]. As shown in Table 4, according to IEA's long-term scenario [72], hydrogen from biomass via gasification is expected to become quite competitive with the fossil routes including CCS, and the lowest cost of all the renewable routes in the next 40 years.

4. Hydrogen production from biomass gasification

4.1. *Principles of biomass gasification*

The gasification of biomass is a thermal treatment, which results in a high production of gaseous products and small quantities of char and ash. Gasification generally involves pyrolysis as well as combustion to provide heat for the endothermic pyrolysis reactions [35]. Gasification is carried out at high temperatures in order to optimize the gas production. The resulting gas, known as producer gas, is a mixture of carbon monoxide, hydrogen and methane, together with carbon dioxide and nitrogen [73]. Most biomass gasification systems utilize air or oxygen in partial oxidation or combustion processes. At temperatures of approximately 875–1275 K, solid biomass undergoes thermal decomposition to form gas-phase products that typically include H_2, CO, CO_2, CH_4, H_2O, and other gaseous hydrocarbons (CHs) [74]. Gas composition of product from the biomass gasification depends heavily on the gasification process, the gasifying agent, and the feedstock composition [75]. Gasification of biomass is generally observed to follow the reaction:

$$\text{Biomass} + O_2\ (\text{or } H_2O) \rightarrow CO,\ CO_2,\ H_2O,\ H_2,\ CH_4 + \text{other CHs} + \text{tar} + \text{char} + \text{ash} \quad (1)$$

Assuming a gasification process using biomass as a feedstock, the first step of the process is a thermo chemical decomposition of the cellulose, hemicelluloses and lignin compounds with production of char and volatiles [76]. Further the gasification of char and some other equilibrium reactions occur. Possible products obtained from gasification process are given in Fig. 2 [77].

4.2. *Hydrogen from biomass via gasification*

Gasification of biomass has been identified as a possible system for producing renewable hydrogen, which is beneficial to exploit biomass resources, to develop a highly efficient clean way for large-scale hydrogen production, and has less dependence on insecure fossil energy sources [41]. Most of the research spurred by this interest has been of economic technology in nature, based on gasifier performance data acquired during system proof of conceptual tests. Less emphasis has been given to experimental investigation of hydrogen production via biomass gasification. Until now, all process equipment needed to produce hydrogen is well established in commercial use, except for the gasifiers [78].

Biomass gasification can be considered as a form of pyrolysis, which takes place in higher temperatures and

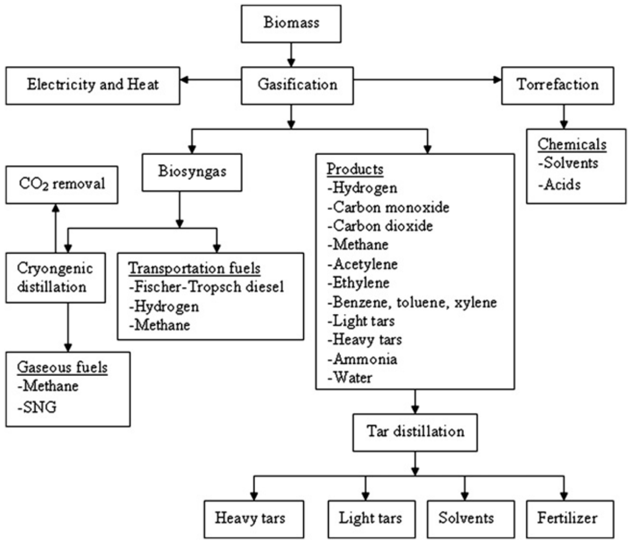

Fig. 2 – Products from gasification process.

produces a mixture of gases with H_2 content ranging 6–6.5% [79]. The synthetic gas produced by the gasification of biomass is made up of H_2, CO, CH_4, N_2, CO_2, O_2, and tar. When gasifying biomass, tar that is formed together with the synthetic gas is difficult to remove with a physical dust removal method [80]. The product distribution and gas composition depends on many factors including the gasification temperature and the reactor type [81]. The most important gasifier types are fixed bed (updraft or downdraft fixed beds), fluidized bed, and entrained flow gasifiers. All these gasifiers need to include significant gas conditioning along with the removal of tars and inorganic impurities and the subsequent conversion of CO to H_2 by water gas shift reaction. Table 5 shows typical gas composition data as obtained from commercial wood and charcoal downdraft gasifiers operated on low to medium moisture content fuels [82].

Gasification technologies provide the opportunity to convert renewable biomass feedstocks into clean fuel gases or synthesis gases. The synthesis gas includes mainly hydrogen and carbon monoxide (H_2 + CO) which is also called as bio-syngas [83]. Bio-syngas is a gas rich in CO and H_2 obtained by gasification of biomass. Hydrogen production is the largest use of syngas. Biomass can be converted to bio-syngas by non-catalytic, catalytic, and steam gasification processes. Steam gasification is a promising technology for thermo chemical

Table 5 – Typical gas composition data as obtained from commercial wood and charcoal downdraft gasifiers operated on low to medium moisture content fuels (wood 20%, charcoal 7%).

Component	H_2 (%)	CO_2 (%)	CH_4 (%)	CO (%)	N_2 (%)	Heating value (MJ/m^3)
Wood gas	12–20	9–15	2–3	17–22	50–54	5–5.9
Charcoal gas	4–10	1–3	0–2	28–32	55–65	4.5–5.6

Source: Ref. [82].

hydrogen production from biomass. Steam reforming and so-called dry or CO_2 reforming occur according to the following reactions and are usually promoted by the use of catalysts.

$$C_nH_m + nH_2O \leftrightarrows n\,CO + (n + m/2)\,H_2 \quad (2)$$

$$C_nH_m + nCO_2 \leftrightarrows (2n)\,CO + (m/2)\,H_2 \quad (3)$$

Modeling of biomass steam gasification to synthesis gas is a challenge because of the variability (composition, structure, reactivity, physical properties, etc.) of the raw material and because of the severe conditions (temperature, residence time, heating rate, etc.) required [84]. The yield of H_2 from steam gasification increases with increasing water-to-sample (W/S) ratio [85]. The yields of hydrogen from the pyrolysis and the steam gasification increase with increasing of temperature. In general, the gasification temperature is higher than that of pyrolysis and the yield of hydrogen from the gasification is higher than that of the pyrolysis [86]. Demirbas [87] investigated the yields of hydrogen from pyrolysis and steam gasification of corncob at different temperatures. The yield of hydrogen from conventional pyrolysis of corncob increased from 33 to 40% with increasing of temperature from 775 to 1025 K. The yield of hydrogen from steam gasification of corncob increased from 29 to 45% for (W/S) = 1 and from 29 to 47% for (W/S) = 2 with increasing of temperature from 975 to 1225 K.

The effect of catalyst on gasification products is very important. The use of the catalyst did not affect the gas yields, but the composition of the gases was strongly influenced. The content of H_2 and CO_2 increased, while that of CO decreased; a drastic reduction in the content of organic compounds could also be observed. Because the char yields remained almost constant compared to an equivalent no catalytic thermal run, the increase in the content of hydrogen was probably due to the influence of the catalyst on the water gas shift reaction [85]. Dolomite, Ni-based catalysts and alkaline metal oxides are widely used as gasification catalysts [88]. Mg-promoted catalysts showed a greater difficulty for Ni precursor's reduction besides different probe molecules (H_2 and CO) adsorbed states. In the conversion of cyclohexane, Mg inhibited the formation of hydrogenolysis products. Nonetheless, the presence of Ca did not influence the metallic phase. The impregnated Ni/MgO-catalyst performed better than the other types [79].

Hydrogen production from biomass has major challenges. There are no completed technology demonstrations. The yield of hydrogen is low from biomass since the hydrogen content in biomass is low to begin with (approximately 6% versus 25% for methane) and the energy content is also low due to high oxygen content (about 40 wt% of biomass). Since over half of the hydrogen from biomass comes from spitting water in the steam reforming reaction, the energy content of the feedstock is an inherent limitation of the process [44,89]. The yield of hydrogen as a function of oxygen content is shown in Fig. 3.

However, the cost for growing, harvesting and transporting biomass is high. Thus, even with reasonable energy efficiencies, it is not presently economically competitive with natural gas steam reforming for stand-alone hydrogen without the advantage of high-value co-products. Additionally, as with all sources of hydrogen, production from biomass will require

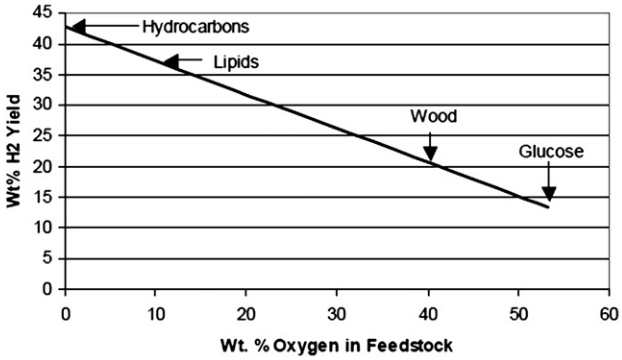

Fig. 3 – Theoretical yield of H_2 as a function of the oxygen content in the feed. Source: Ref. [44].

Table 6 – Share of individual primary energy sources in meeting final energy needs (%).

Source of energy	1998	2025	2050
Fossil fuels	88	62	29
Nuclear energy	10	2	2
Hydrogen from solar energy	–	7	31
Electricity from solar energy	–	11	16
Heat from solar energy	–	18	22
Energy from solar energy	2	25	35
Hydrogen	–	11	34

Source: Ref. [100].

appropriate hydrogen storage, transport infrastructure and utilization systems to be developed and deployed [44].

4.3. *Role of biomass gasification in the future hydrogen supply*

Today, hydrogen is mainly produced from natural gas via steam methane reforming, and although this process can sustain an initial foray into the hydrogen economy, it represents only a modest reduction in vehicle emissions as compared to emissions from current hybrid vehicles, and ultimately only exchanges oil imports for natural gas imports [90]. It is clearly not sustainable. Biomass has been recognized as a major world renewable energy source to supplement declining fossil fuel resources [91,92]. It will play an important role in the future global energy infrastructure for the generation of power and heat, but also for the production of chemicals and fuels. The dominant biomass conversion technology will be gasification, as the gases from biomass gasification are intermediates in the high-efficient power production or the synthesis from chemicals and fuels [93]. Biomass gasification offers the earliest and most economical route for the production of renewable hydrogen.

IIASA's Environmentally Compatible Energy Strategies (ECS) project has developed a long-term hydrogen-based scenario (B1-H_2) of the global energy system to examine the future perspectives of fuel cells [94]. The scenario illustrates the key role of hydrogen in a long-term transition towards a clean and sustainable energy future. According to this scenario, biomass gasification will become a dominant technology in the future (Fig. 4).

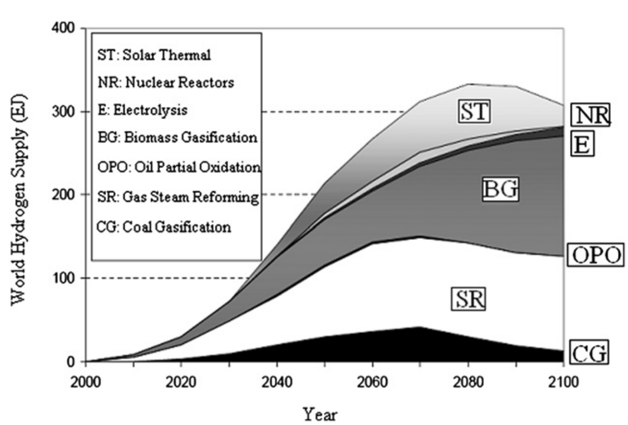

Fig. 4 – Global hydrogen supply mix for the period 2000–2100 in the B1-H_2 scenario. Steam reforming of natural gas and gasification of biomass are the dominant technologies. Source: Ref. [61].

5. Role of hydrogen in the future global energy supply

Energy demand has grown strongly and will continue to increase, particularly in developing countries where energy is needed for economic growth and poverty alleviation. In the beginning of this new century, the rational use of energy becomes a keyword for the world sustainable development both in developed and developing countries [95]. Projected world primary energy demand by 2050 is expected to be in the range of 600–1000 EJ (compared to about 500 EJ in 2008) [96]. At the present time primary energy sources are dominated by fossil fuels, with nearly 80% of global energy demand supplied from crude oil, natural gas, and coal [97].

Petroleum-based fuels are limited reserves concentrated in certain regions of the world. These sources are on the verge of reaching their peak production. Known petroleum reserves are estimated to be depleted in less than 50 years at the present rate of consumption [98]. As supplies of fossil fuels dwindle and concerns about continued contributions of additional carbon dioxide to the atmosphere intensify, there is an increasing need for new sources of energy from renewable carbon-neutral sources with minimal negative environmental impact [99]. Renewable energy is expected to play a major role in the global future energy provision.

Hydrogen and fuel cells are often considered as a key technology for future sustainable energy supply. Renewable shares of 36% (2025) and 69% (2050) on the total energy

Table 7 – Percentage point shares of alternative fuels in total automotive fuel consumption in the EU under the 'optimistic development scenario' of the European Commission.

Year	Biofuel	Natural gas	Hydrogen	Total
2010	6	2	–	8
2015	7	5	2	14
2020	8	10	5	23

Source: Ref. [105].

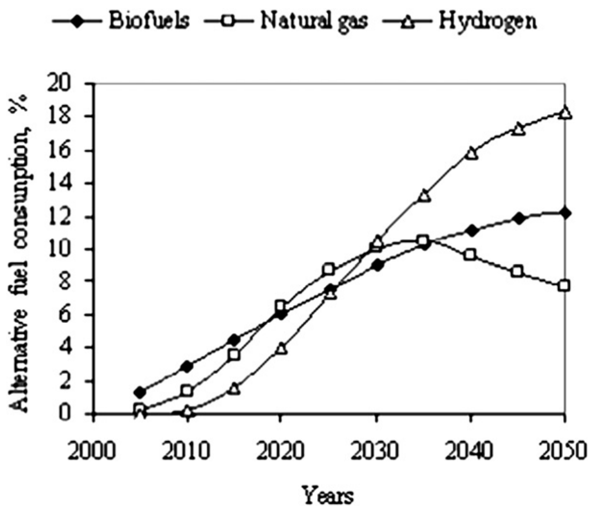

Fig. 5 – Shares of alternative fuels compared to the total automotive fuel consumption in the world. Source: Ref. [107].

demand will lead to hydrogen shares of 11% in 2025 and 34% in 2050 [100]. The share of individual primary energy sources in meeting final energy needs are given in Table 6.

Carbon dioxide is main greenhouse gas associated with global warning, is produced in all combustion processes involving fossil fuels as well in other industrial processes such as cement production and sweetening of natural gas [101]. One-fifth of global carbon dioxide emissions are created by the transport sector, which accounts for some 60% of global oil consumption [102]. For that reason, alternate transportation fuels, such as ethanol, biodiesel, and hydrogen, will play an important role in the world's future.

Due to the increasing mobility of people and goods, the transport sector accounts for more than 30% of final energy consumption in the European Union (EU) and is expanding [103]. The European Commission White Paper [104] calls for dependence on oil in the transport sector to be reduced by using alternative fuels such as biofuels. An increasing use of biofuels for transport is emerging as an important policy strategy to substitute petroleum-based fuels [103]. Regarding fuel substitution, the Commission stakes mainly on biofuels, natural gas (CNG), and hydrogen/fuel cells and envisages the following scenario, dubbed by the Commission herself the 'optimistic development scenario'(Table 7) [105].

As is evidenced by several funded programs from many national government agencies all over the world, hydrogen is being promoted as the fuel for the future [106]. Fig. 5 shows the shares of alternative fuels compared to the total automotive fuel consumption in the world as a futuristic view [107].

6. Conclusion

Today, hydrogen is mainly produced from natural gas via steam methane reforming, and although this process can sustain an initial foray into the hydrogen economy, it represents only a modest reduction in vehicle emissions as compared to emissions from current hybrid vehicles, and ultimately only exchanges oil imports for natural gas imports. It is clearly not sustainable. Hydrogen produced through a range of renewable primary energy sources such as wind, biomass, and solar energy is ideal for gradually replacing fossil fuels. The use of renewable biomass as a major feedstock for hydrogen production has received considerable attention in recent years.

Hydrogen can be generated from biomass, but this technology urgently needs further development. The production of hydrogen from biomass is already economically competitive today. Hydrogen production from biomass has major challenges. There are no completed technology demonstrations. It is believed that in the future biomass can become an important sustainable source of hydrogen. Due to its environmental merits, the share of hydrogen from biomass in the automotive fuel market will grow fast in the next decade.

Gasification of biomass has been identified as a possible system for producing renewable hydrogen, which is beneficial to exploit biomass resources, to develop a highly efficient clean way for large-scale hydrogen production, and has less dependence on insecure fossil energy sources. Steam reforming of natural gas and gasification of biomass will become the dominant technologies by the end of the 21st century.

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