Renewable and Sustainable Energy Reviews 57 (2016) 850–866

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development

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ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form
19 October 2015
Accepted 17 December 2015

Keywords:
Hydrogen
Global warming
Solar
Wind
Biomass
Gasification

ABSTRACT

Fossil fuel consumption in transportation system and energy-intensive sectors as the principal pillar of civilization is associated with progressive release of greenhouse gases. Hydrogen as a promising energy carrier is a perfect candidate to supply the energy demand of the world and concomitantly reduce toxic emissions. This article gives an overview of the state-of-the-art hydrogen production technologies using renewable and sustainable energy resources. Hydrogen from supercritical water gasification (SCWG) of biomass is the most cost effective thermochemical process. Highly moisturized biomass is utilized directly in SCWG without any high cost drying process. In SCWG, hydrogen is produced at high pressure and small amount of energy is required to pressurize hydrogen in the storage tank. Tar and char formation decreases drastically in biomass SCWG. The low efficiency of solar to hydrogen system as well as expensive photovoltaic cell are the most important barriers for the widespread commercial development of solar-based hydrogen production. Since electricity costs play a crucial role on the final hydrogen price, to generate carbon free hydrogen from solar and wind energy at a competitive price with fossil fuels, the electrical energy cost should be four times less than commercial electricity prices.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.12.112
1364-0321/

1. Introduction

Modernization is in energy consumption debt and the majority of the world's energy demand is supplied by fossil fuel resources. The continued use of finite fossil fuel resources have shifted thinking towards the future energy scenario of the world in the scarcity of fossil fuels [1]. In this regard, the alarm of accelerated global warming shifts the energy focus of the world to clean and renewable energies [2,3]. Today, various weather related calamities such as drought, heat waves on the Earth, deluge and hurricanes are obvious warning signs from nature that exacerbate mankind's concerns about climate change. Based on the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC), since the mid-20th century, anthropogenic greenhouse gas (GHG) concentration is responsible for augmentation of global warming (GW) [4]. Today, impending depletion of fossil fuel resources exacerbated by rising demand for energy and the obscure prospect of climate change have become the main challenges of humankind [5,6]. To establish an environmentally friendly energy for the future of the world, these dilemmas should be solved by development of carbon-neutral energy systems [7]. It was projected that to supply the energy demand of the world and support economic development, and maintain atmospheric carbon dioxide (CO_2) levels at an acceptable level, approximately 10 TW (terawatt) of carbon-neutral power should be generated by the mid-century [8]. Hoffert et al., [9] stipulated that generation of 12, 25 and 30 TW of carbon-free power is required to stabilize atmospheric CO_2 concentrations at 550, 450 and 350 ppm levels respectively by 2050. This outstanding goal requires a revolution in energy production, conversion, storage, and distribution technologies toward clean development policies. Economic and environmental concerns are generating a growing interest in alternative fuels. Hydrogen is one of the most promising alternative energy carriers, which does not exist freely in nature. Same as electricity, hydrogen is not a source of energy and it is assumed as a secondary form of energy, which is generated from natural and bioresources. It has been projected that hydrogen plays a great role in the future scenario of energy sectors [10]. Hydrogen as the lightest element with density of 0.0695 with respect to air is an odorless, tasteless and colorless gas [11].

Hydrogen is a clean fuel without toxic emissions and can easily be applied in fuel cells for electricity generation. Indeed, the energy yield of hydrogen is about 122 kJ/g, which is 2.75 times greater than hydrocarbon fuels [12]. Application of hydrogen in transportation system whether as a fuel in combustion engines or fuel cell in electric has received much favorable attention as an energy policy issue [13,14]. Hydrogen utilization is free of toxic gas formation as well as CO_2 emission and the only product is water vapour. Vehicles fuelled by hydrogen drastically decrease dependence on fossil fuel and conspicuously mitigate tailpipe emissions [15]. Table 1 displays characteristics of combustion and detonation of hydrogen [11].

The efficiency of hydrogen fuel cell (HFC) vehicles is three times more than gasoline engines [16]. Being a gas at normal pressures and temperatures, hydrogen presents greater storage and transportation barriers than exist for the liquid fuels. The unavailability in nature and the expensive production process of hydrogen are the other hurdles that make hydrogen gas an uneconomic fuel. Compared to methane (CH_4) and propane (C_3H_8) by energy density of 32.6 and 86.7 MJ/m^3 (at 15 °C and 1atm) respectively, the energy density of hydrogen is 10 MJ/m^3, which means that utilization of hydrogen fuel in the vehicles requires larger fuel tank [17]. Moreover, the small size of hydrogen molecules causes hydrogen to be leaked from the vessel. If significant amounts of hydrogen escape to the environment, free radicals of hydrogen can be constituted due to ultraviolet radiation, which leads to ozone depletion [18].

Table 1
Characteristics of combustion and detonation of hydrogen.

Density at STP (Kg/m^3)	0.084
Heat of vaporization(J/g)	445.6
Lower heating value (KJ/g)	119.93
High heating value (KJ/g)	141.8
Thermal conductivity at std. condition (mW/cm/K)	1.897
Diffusion coefficient in air at std. condition (cm^{2}s)	0.61
Flame ability limits in air (vol%)	4.0–75
Detonability limits in air (vol%)	18.3–59
Limiting oxygen index (vol%)	5.0
Stoichiometry composition in air (vol%)	29.53
Minimum energy of ignition in air (Mj)	0.02
Auto-ignition temperature (K)	858
Flame Temperature in air (K)	2318
Maximum burning velocity in air at std. condition (m/s)	3.46
Detonation velocity in air at std. condition (Km/s)	1.48–2.15
Energy of explosion mass related g TNT(g)	24.0
Energy of explosion volume related g TNT (m3) (STP)	2.02

Nevertheless, the future prospect of economic hydrogen production is the basic point of many researches. Hydrogen is produced from different primary energy sources and various production technologies. Currently, hydrogen production from nonrenewable resources such as coal, oil and natural gas is dominant in the world [19]. Around 95% of the produced hydrogen is from fossil fuel-based methods and hydrogen production from water using electricity and biomass is only 4% and 1% respectively [20]. About half of all produced hydrogen is achieved from gasification and thermo catalytic processes of natural gas (NG), followed by heavy oils, naphtha and coal [21]. The reaction between NG and steam in a catalytic converter strips away the hydrogen atoms and carbon dioxide (CO_2) is generated as the byproduct. Application of fossil fuel for hydrogen production should be associated with carbon capture systems (CCS). Hydrogen can also be produced from methanol or gasoline, though again CO_2 is an unwanted byproduct. Hydrogen production from carbon-lean and carbon-free energy sources, including renewable electricity, biomass and nuclear energy could be the long-term aim of the hydrogen utopia [13]. However, in the medium term, fossil fuels are projected to be applied in hydrogen production scenario. At present, biomass is not anticipated to play a conspicuous role in hydrogen production as its use for biodiesel in transportation system and for combined heat and power generation is likely to become a priority. Nevertheless, the significant resources of biomass as well as other renewable resources has attracted attention to produce renewable hydrogen. Under the premise that the supremacy of renewable and sustainable energy (RSE) in the energy mix of the world in immediate future is unavoidable, development of hydrogen production from wealthy RSE resources could be the best policy to achieve clean environment. The low price of hydrogen production as well as environmentally friendly manner play a crucial role in the further development of the hydrogen-including economy [22].

Since CO_2 which is responsible for greenhouse effect is one of the main byproducts of the fossil fuel based hydrogen production process, hydrogen produced from renewable sources such as biomass, geothermal, solar and wind energy is ideal for gradually replacing fossil fuels [23]. Chemical conversion of energy sources such as coal and biomass gasification as well as NG steam reforming with CCS is one of the available processes with great potential to contribute to hydrogen production. Moreover, water electrolysis by electricity from fossil fuel resources, nuclear power and RSE known as electro-chemical conversion, has great capacity to be developed for hydrogen production. Some hydrogen production processes such as fermentation, thermo-chemical water