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Review and evaluation of hydrogen production methods for better sustainability

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ARTICLE INFO

Article history:
Received 18 August 2014
Accepted 6 December 2014
Available online xxx

Keywords:
Efficiency
Energy
Environmental impact
Exergy
Hydrogen production
Renewables

ABSTRACT

This paper examines various potential methods of hydrogen production using renewable and non-renewable sources and comparatively assesses them for environmental impact, cost, energy efficiency and exergy efficiency. The social cost of carbon concept is also included to present the relations between environmental impacts and economic factors. Some of the potential primary energy sources considered in this study are: electrical, thermal, biochemical, photonic, electro-thermal, photo-electric, and photo-biochemical. The results show that when used as the primary energy source, photonic energy based hydrogen production (e.g., photocatalysis, photoelectrochemical method, and artificial photosynthesis) is more environmentally benign than the other selected methods in terms of emissions. Thermochemical water splitting and hybrid thermochemical cycles (e.g. Cu–Cl, S–I, and Mg–Cl) also provide environmentally attractive results. Both photoelectrochemical method and PV electrolysis are found to be least attractive when production costs and efficiencies are considered. Therefore, increasing both energy and exergy efficiencies and decreasing the costs of hydrogen production from solar based hydrogen production have a potential to bring them forefront as potential options. The energy and exergy efficiency comparisons indicate the advantages of fossil fuel reforming and biomass gasification over other methods. Overall rankings show that hybrid thermochemical cycles are primarily promising candidates to produce hydrogen in an environmentally benign and cost-effective way.

Introduction

One of the major challenges of the twenty first century is keeping up with the growth in global energy demand due to increasing population and rising standards of living. For instance, in 2011, 15 TW–energy was consumed by approximately seven billion people world-wide. By 2050, these numbers are expected to escalate to 30 TW and nine billion people, respectively [1]. Fig. 1 demonstrates world's fuel shares of total primary energy supply (TPES), electricity generation, and the resulting CO_2 emissions. From Fig. 1, it can be seen that 85% of the global energy supply was met by fossil fuels in 2011. However, because of their limited nature and nonhomogeneous distribution, fossil fuels are not expected to keep up with the increase in energy demand. Also, fossil fuel

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http://dx.doi.org/10.1016/j.ijhydene.2014.12.035
0360-3199/

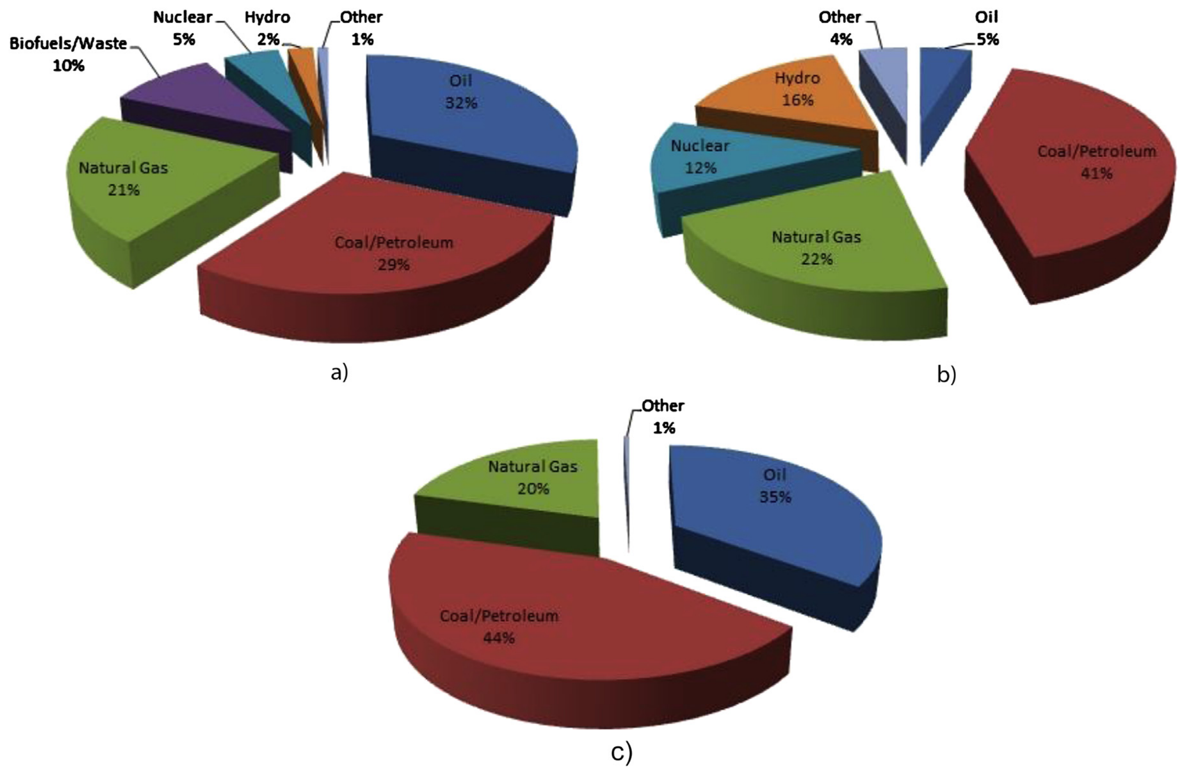

Fig. 1 – World's fuel shares of (a) total primary energy supply (TPES), (b) electricity generation, and (c) CO_2 emissions in 2011 (Other includes geothermal, solar, wind, heat, and waste etc.) (Data from Ref. [1]).

reserves are getting less accessible as the easily-accessible ones are consumed, and the prices of fossil fuels keep increasing due to accessibility loss and political uncertainties of the countries holding worlds' fossil fuel supplies. Along with economic issues, greenhouse gas (mainly CO_2) emissions as a result of fossil fuel utilization, and their contribution to global warming, have been raising serious environmental concerns. Therefore, switching to a non-fossil fuel energy source could greatly reduce the CO_2-related emissions and their adverse effect on global warming.

Reducing the dependence on fossil fuels and minimizing environmentally harmful emissions can be achieved by sustainable energy sources. With near-zero or zero end-use emissions and continually replenished resources, hydrogen can be an ideal sustainable energy carrier. Some of the advantages of hydrogen can be listed as: (i) high energy conversion efficiencies; (ii) production from water with no emissions; (iii) abundance; (iv) different forms of storage (e.g. gaseous, liquid, or in together with metal hydrides); (v) long distance transportation; (vi) ease of conversion to other forms of energy; (vii) higher HHV and LHV than most of the conventional fossil fuels (Table 1). On the other hand, most of the hydrogen production methods are not mature, resulting high production costs and/or low efficiencies [3].

Here, we go further to compare hydrogen with other conventional fuels in terms of Environmental Impact Factor (EIF), Greenization Factor (GF) and Hydrogen Content Factor (HCF) to emphasize the importance of hydrogen as a unique option, through the following equations:

$$EIF = \frac{kg\ CO_2\ product\ of\ combustion\ reaction}{kg\ fuel} \tag{1}$$

$$GF = \frac{EIF_{max} - EIF}{EIF_{max}} \tag{2}$$

$$HCF = \frac{kg\ of\ H_2 in\ the\ fuel}{kg\ fuel} \tag{3}$$

where EIF_{max} is the maximum value of EIF among the evaluated options. In this specific case with 3.6, coal is selected as the EIF_{max}.

As can be seen from Fig. 2, with increasing hydrogen content (HCF), the energy sources become greener (increasing GF) and the environmental impact (EIF) decreases. This is a clear advantage of hydrogen in terms of reducing carbon-related emissions. In order to take full advantage of the hydrogen economy, it needs to be produced from renewable or vast

Table 1 – Higher and lower heating values of hydrogen and common fossil fuels at 25 °C and 1 atm (Data from Ref. [2]).

Fuel	HHV (kJ/g)	LHV (kJ/g)
Hydrogen	141.9	119.9
Methane	55.5	50.0
Gasoline	47.5	44.5
Diesel	44.8	42.5
Methanol	20.0	18.1