Hydrogen Production

Hiroshige Matsumoto, Seiichiro Kimura, Kenshi Itaoka, and Gen Inoue

Abstract Hydrogen production methods to meet hydrogen demand as a future fuel are considered. Current hydrogen production methods are described, and energy efficiency, CO_2 emissions, and cost are discussed. After estimating possible future hydrogen use and demand, various hydrogen production methods meeting future hydrogen demand are addressed and their prospects considered.

A brief conclusion is that future demand for hydrogen fuel cell electric vehicles can be met by conventional fossil fuel-based hydrogen production methods, but novel low-carbon techniques for this production using biomass, renewable energy-based electrolysis, thermochemical methods, and photoelectrochemical water splitting are important to reduce CO_2 emissions. The introduction of hydrogen energy provides benefits of energy saving, renewable energy use, and stabilization of energy security.

Keywords Fossil fuel-based hydrogen • Low-carbon hydrogen • GHG emission • FCEV • Water splitting

1 Introduction

Hydrogen is a multi-aspect chemical species. It is an important raw material in various industries and can work as a fuel. With regard to the latter aspect, hydrogen is a secondary energy, and, accordingly, hydrogen production is a process that converts a primary energy to the chemical energy of hydrogen. Fossil fuel is

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H. Matsumoto (✉) • K. Itaoka
Kyushu University, Fukuoka, Japan
e-mail: matsumoto@i2cner.kyushu-u.ac.jp; k.itaoka@i2cner.kyushu-u.ac.jp

S. Kimura
The Matsushita Institute of Government and Management, Kanagawa, Japan
e-mail: s-kimura@mskj.or.jp

G. Inoue
Kyoto University, Kyoto, Japan
e-mail: ginoue@cheme.kyoto-u.ac.jp

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currently a main primary energy for the production of hydrogen. Hydrogen is produced by reforming hydrocarbons and is generated as a by-product in steel, soda, petroleum refining, and other industries. Renewable energy, such as sunlight, wind, and biomass, can be used as primary energy.

Hydrogen production should be conducted using suitable primary energy with respect to the social background, such as the severity of CO_2 emission, primary energy cost, and others. Hydrogen fuel cell electric vehicles (FCEVs) have recently been put on public sale in Japan. Toyota's FCEV "Mirai" started sales in December 2014 [1], and Honda announced the release of a new FCEV in 2015 [2]. Hydrogen has increased in importance as energy. In this chapter, hydrogen production methods for demand as a fuel and/or energy medium are addressed.

2 Present Status

2.1 Current Hydrogen Usage and Production Methods

Hydrogen is mainly used as a raw material in industries, including petroleum refining, synthesis of ammonia or other chemicals, metal and ceramics, food, semiconductor production, and others. Hydrogen is mostly produced by reforming fossil fuels or as by-products. Water electrolysis is also a production method. The annual amount of hydrogen produced in Japan is 15–20 × 10^9 Nm^3 [3, 4]. Most of the hydrogen is consumed captively, i.e., the consumers produce it.

2.1.1 Reforming

Hydrogen is produced by reforming natural gas, naphtha, and other hydrocarbon-based fuels. Steam reforming and partial oxidation are the two major chemical reactions. These reactions can be written as follows:

$$C_mH_{2n} + mH_2O \rightarrow mCO + (m+n)H_2 (\text{steam reforming}) \tag{1}$$

$$C_mH_{2n} + 0.5mO_2 \rightarrow mCO + nH_2 (\text{partial oxidation}) \tag{2}$$

Steam reforming is endothermic and partial oxidation is exothermic. In both cases, generated CO can be used to produce more hydrogen as

$$CO + H_2O \rightarrow CO_2 + H_2 (\text{water gas shift reaction}) \tag{3}$$

Steam reforming of methane proceeds spontaneously at temperatures >700 °C and is done industrially at 850–950 °C and pressures 1.5–3 MPa. Because the reaction is endothermic, there is a need for heating reaction tubes, determining the upper limit of operation temperature. Partial oxidation has large negative free energy change and can thus proceed non-catalytically. Higher reaction temperatures

(1300–1500 °C) and pressures (4–8 MPa) can be used industrially, enabling use of heavy hydrocarbons such as heavy oil and coal. Lower temperatures are favored by the water-gas shift reaction, and 400–600 °C are typical reaction temperatures. Steam reforming and partial oxidation can be mixed in an appropriate ratio for thermal balance, called the autothermal method.

In these reforming processes, hydrogen is produced as a mixture with CO_2, H_2O, and other impurities, and purification is necessary, usually done with pressure swing adsorption (PSA).

Petroleum refining consumes hydrogen in transforming heavier hydrocarbons to lighter species and in desulfurization. Hydrogen is produced by steam reforming of naphtha and LPG. Ammonium synthesis consumes hydrogen, which is typically produced by steam reforming of natural gas.

2.1.2 By-Product Hydrogen

Hydrogen is generated as a by-product in industrial processes, including sodium hydroxide production, reduction of iron ores to produce steel, petroleum chemistry, and others. In many cases, the by-product hydrogen is consumed captively as fuel and as a chemical raw material, and so the use as fuel other than captive consumption requires an alternative energy resource to replace current usage of such hydrogen.

In petroleum refineries, hydrogen is generated during dehydrogenation of alkanes to produce aromatics. However, more hydrogen is needed and is produced by reforming petroleum-based hydrocarbons. In steelmaking, carbon made from coal, i.e., cokes, is used as a reducing agent of iron ore, and gas from the coke oven contains substantial hydrogen (~55 %). About 16×10^9 Nm^3 of coke oven gas (COG) is produced annually. Large amounts of COG are used for electricity generation or as heat sources and are not used in the form of hydrogen [4]. In the soda industry, NaOH is produced by electrolysis of NaCl aqueous solution and hydrogen, and chlorine is produced as a by-product. Annually, ~1.1×10^9 Nm^3 of hydrogen is generated, accompanied by 4×10^6 tons of NaOH [4]. This hydrogen has high purity and is commercially supplied to other companies.

2.1.3 Electrolysis

Alkaline water electrolysis and polymer electrolyte water electrolysis are the commercial methods. In Japan, the former was used in the past in hydrogen production for ammonia synthesis and is thus technically well established. However, the hydrogen production method for ammonia synthesis has been replaced by cheaper steam reforming of natural gas or other hydrocarbons.

2.2 Hydrogen Production Capability of Current Facilities

In steel production, the total amount of hydrogen contained in generated COG is 9×10^9 Nm^3/year in Japan. Only about a tenth is used as hydrogen gas [4], and the remaining 8×10^9 Nm^3/year can be used as fuel. In addition, COG contains methane and CO that can be reformed to produce another 17×10^9 Nm^3/year of hydrogen. If we assume 60 % recovery of hydrogen through purification by PSA, in principle, 5×10^9 Nm^3/year and 10×10^9 Nm^3/year of hydrogen can be produced, respectively. At present, COG is not a surplus but is used as fuel for thermal power and other heat sources. Therefore, COG can be considered economically as a hydrogen source only when cheaper fuel is available to substitute COG utilization.

COG is a product of coal through coke production, which is a CO_2-emiting process and must be accommodated by CO_2 separation to avoid such emission. As mentioned in Sect. 2.1.2, about 1.1×10^9 Nm^3 of hydrogen is generated as a by-product in the soda industry with high purity and can be used as a hydrogen source. Petroleum refineries are equipped with hydrogen production facilities that are capable of excess hydrogen production (i.e., planned hydrogen production capability minus actual hydrogen consumption) using steam reforming of naphtha and LPG, owing to the closing of oil refineries and suspension of ethylene production facilities [5]. The estimated capability is as much as 4–6 $\times 10^9$ Nm^3/year [3, 4]. Steam reforming of natural gas can be used to produce hydrogen, as explained in Sect. 2.1.1. The Mizuho Information and Research Institute estimates that hydrogen that can be newly produced is 7–8 $\times 10^9$ Nm^3/year [4].

The amounts of hydrogen that can be generated by the methods discussed above are summarized in Table 1. Given the hydrogen demand assumed later in Table 6, the hydrogen need of FCEVs would be 13.5×10^9 Nm^3/year even in 2050 and is affordable because of the by-product steam-reformed hydrogen shown in Table 1. These conventional hydrogen production methods can address the assumption of FCEV hydrogen demand. However, this production is accompanied by CO_2 emission, because fossil fuel is the energy source. For reduction of this emission, hydrogen production should shift to non- or low-carbon hydrogen in the future, and related production techniques are explained in the following sections.

Table 1 Hydrogen production/supply capability of by-product hydrogen and steam reforming

Hydrogen source	Hydrogen production capability [10^9 Nm^3/year]
Steel industry	5 (15[a])
Soda industry	1.1
Petroleum refineries	4–6
Steam reforming of natural gas	7–8
Total	17–20 (30[a])

[a] CO and CH_4 contained in COG are considered hydrogen sources

2.3 Comparison of Hydrogen Production Methods

To compare energy efficiency, CO_2 emissions, and costs, the following energy pathways from natural gas, crude oil, coal, biomass, and electricity as primary energy for vehicle fuel tanks are considered for hydrogen production. Energy efficiency is defined as process efficiency of hydrogen production. CO_2 emissions and costs should include those associated with all processes from the well to hydrogen production. Hydrogen purification is not considered, because the required hydrogen purity varies with use. Hydrogen compression and filling are also not included in Fig. 1.

2.3.1 Energy Efficiency

Energy efficiency of steam reforming is defined as (hydrogen energy)/[(feedstock energy)+(input energy)] and that of water electrolysis as (hydrogen energy)/[(electricity)+(input energy)]. Values were collected from reference data of the Mizuho Information and Research Institute [6], US Department of Energy Hydrogen Analysis Project (H2A) [7], and Japan Hydrogen and Fuel Cell Demonstration Project (JHFC) [8]. Largest and smallest mean values are summarized in Fig. 2. Data in reference [8] include those under research, and these are included in the figure. In steam reforming, energy efficiencies are higher for reforming of methanol, dimethyl ether (DME), and natural gas than those for reforming of others. Efficiency is lowest for kerosene and Fischer-Tropsch (FT) synthetic fuel. The energy efficiency of alkaline and proton exchange membrane (PEM) water electrolysis is comparable to that of steam reforming.

2.3.2 CO_2 Emissions

CO_2 emissions are defined as the total amount of CO_2 emitted in feedstock production, transportation, and hydrogen production. Greenhouse gases (GHG) other than CO_2 are also taken into account as CO_2 equivalent values. The Institute of Energy Economics Japan [9], Mizuho Information and Research Institute [6], H2A [7], and JHFC [8] have estimated CO_2 emissions with different feedstock, and these are summarized in Figs. 3 and 4. Data in reference [8] include those under research and these are included in the figure. Reference [7] deals with the situation in the USA, but its data are used in the figures because the percentage of CO_2 emissions in feedstock production and transportation of the total are not significantly different from those in the other references dealing with Japan (e.g., in natural gas reforming, CO_2 emissions from mining, and transportation are 12 % in the USA [4] and 14 % in Japan [5]). For water electrolysis, CO_2 emissions for electricity production are included, which is assumed to be conducted in Japan even using the data of H2A [7]. CO_2 emissions of construction and maintenance equipment are not considered.

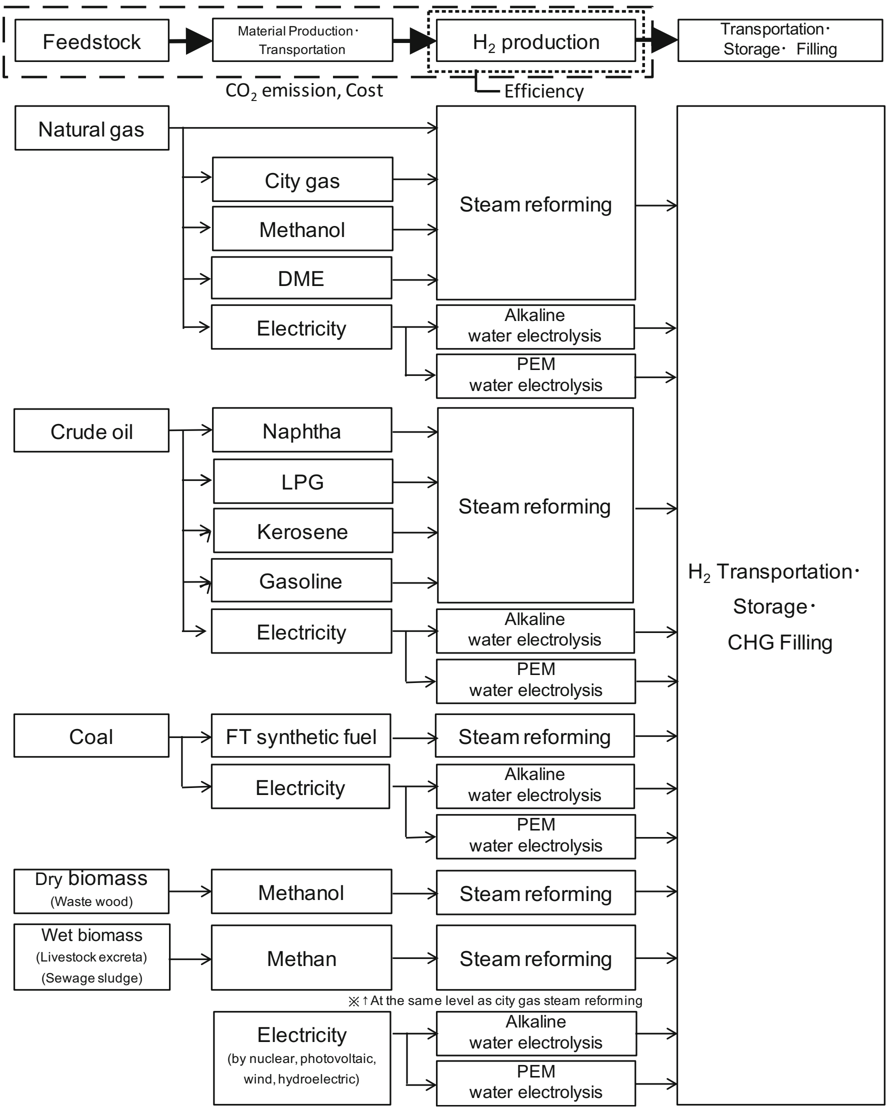


Fig. 1 Energy paths of assumed hydrogen production for comparing efficiency, CO_2 emissions, and costs

2.3.2.1 Steam Reforming

CO_2 emissions for hydrogen production from various feedstocks are shown in Fig. 3. Autothermal reforming is not included. The breakdown of total CO_2 emission, such as natural gas reforming, is ~10 % from material production and transportation, 60 % from derivation from fuel, and 30 % from operation of hydrogen production equipment. In steam reforming, except in the case of biomass, CO_2

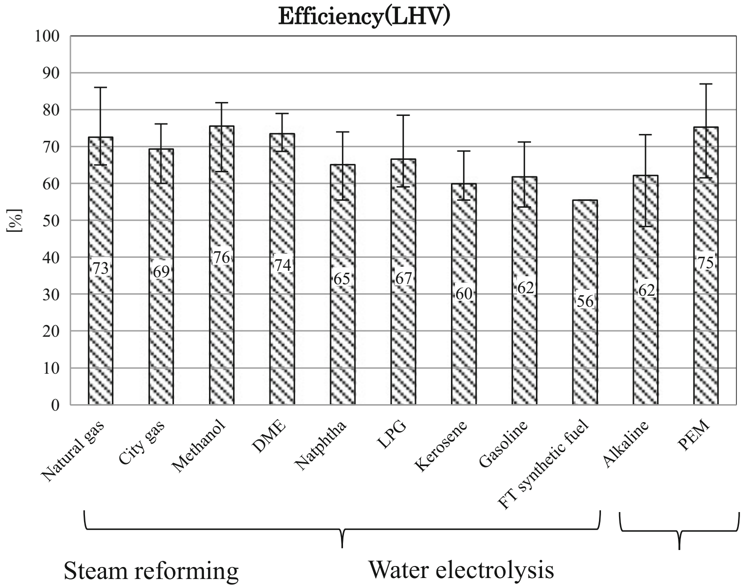


Fig. 2 Efficiency of hydrogen production from various fuel-reforming processes and electrolysis

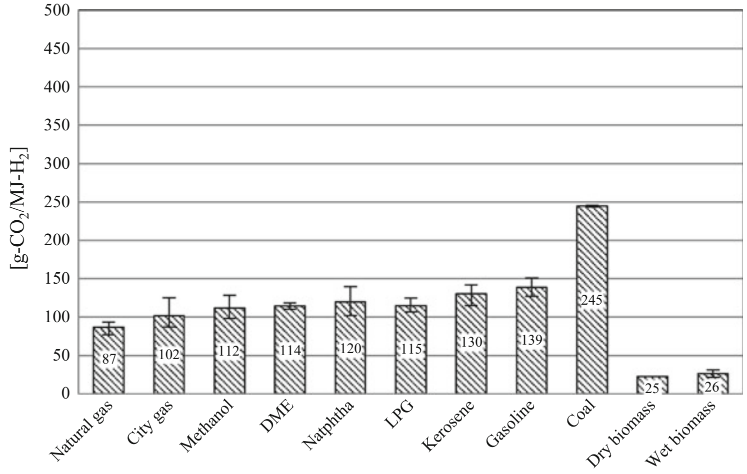


Fig. 3 CO_2 emissions for hydrogen production from various feedstocks by steam reforming

emitted from natural gas reforming is the least, and that from reforming of coal is the greatest. Emissions from biomass are less than from other fuels and are only 30 % of those from natural gas. Challenges include efficiency improvement in hydrogen production, increased biomass use, and technology development in CO_2 capture and storage for further emissions reduction.

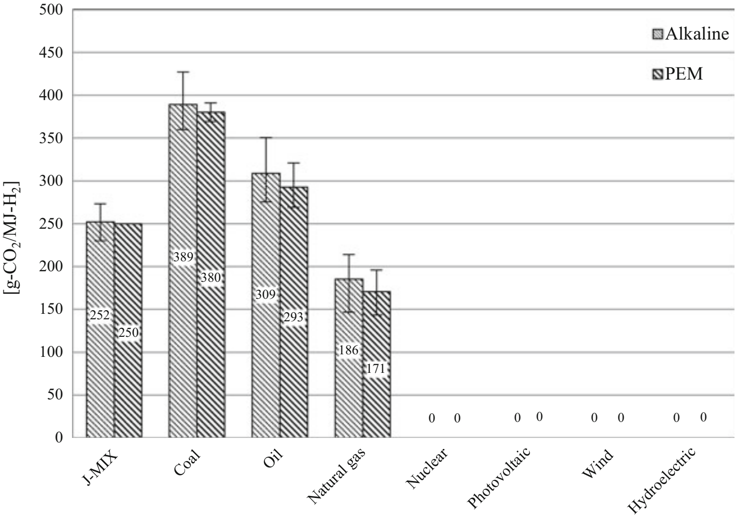


Fig. 4 CO_2 emission from electricity for unit water electrolysis, derived from various fuels/ primary energy sources

2.3.2.2 Water Electrolysis

CO_2 emissions from water electrolysis using electricity derived from various fuels/ primary energy sources are shown in Fig. 4. For J-Mix, the Japanese average electricity mix in 2013 reported in Electricity Generation by Source (2014) [10] is assumed to consider the effect of cessation of nuclear power plants. The breakdown of CO_2 emissions, such as alkaline water electrolysis derived from natural gas, is ~60 % from electricity production from natural gas, 10 % from derivation from fuel, and 30 % from operation of hydrogen production equipment. In water electrolysis, CO_2 emission is slight compared with steam reforming if electricity from renewable energy is used.

2.3.3 Costs

In the present study, cost is based on hydrogen production at 70 MPa onsite and a 300 Nm^3/h direct-filling commercial hydrogen station operated by JHFC [11]. Tables 2, 3, and 4 show presumed hydrogen production conditions. Costs related to hydrogen compression and filling are not included.

Table 2 Presumed conditions

Scale of hydrogen station[a]	Onsite 300 Nm^3/h
Operating condition[a]	365 day/y, 13 h/day
Annual hydrogen production volume[a]	1,538,396 Nm^3
Construction cost of hydrogen production equipment (including PSA)[a]	186 million yen
Hydrogen purity[a]	99.99 % (4 N)

[a] JHFC [11]

Table 3 Variable costs

		Unit price		Annual usage	
City gas[a,b]		114	Yen/kg	441,890	kg
Clean water[a]		300	Yen/ton	3428	ton
Waste water[a]		200	Yen/ton	1714	ton
Electricity[a]				1,141,251	kWh
	J-Mix[c]	16	Yen/kWh		
	Wind[d]	14	Yen/kWh		
	Hydro[d]	21	Yen/kWh		
	Solar[d]	36	Yen/kWh		

[a] JHFC [11]

[b] Calculated from major contracts of city gas (Osaka gas, Tokyo gas, Saibu gas)

[c] Calculated from the Federation of Electric Power Companies of Japan [10]

[d] Calculated from the Energy and Environment Council [12]

Table 4 Fixed cost

Labor[a]	7 million yen annually per person, 1.5 persons employed
Book value[a]	55 % of construction cost
Depreciation[a]	10 years
Repair[a]	3 % of construction cost
Insurance[a]	0.77 % of book value
Fixed assets tax[a]	1.4 % of book value
Overhead[a]	0

[a] JHFC [11]

Table 5 compares estimated costs for hydrogen production via steam reforming and alkaline water electrolysis with various operation rates. Hydrogen produced via water electrolysis is more expensive than via steam reforming. For this electrolysis, percentages of electricity versus total costs are 72 % at 100 % operation rate and 61 % at 60 % operation rate. The price of the electricity is a key factor determining the cost of this electrolysis and is the reason for its higher cost of hydrogen production relative to steam reforming.

Table 5 Estimation of cost for hydrogen production via steam reforming and electrolysis

Technology	Operation rates (100 % = 365 day/year, 13 h/day)	Production cost [yen/Nm^3]
Steam reforming (city gas)	100 %	Approx. 60
	80 %	Approx. 66
	60 %	Approx. 76
Alkaline water electrolysis	100 %	Approx. 109 (J-Mix)
		Approx. 99–208 (wind, hydro, solar)
	80 %	Approx. 116 (J-Mix)
		Approx. 107–215 (wind, hydro, solar)
	60 %	Approx. 130 (J-Mix)
		Approx. 118–226 (wind, hydro, solar)

3 Technology Road Map

3.1 Perspectives on Future Hydrogen Demand in Transportation and Large-Scale Energy Conversion Sectors

Use of hydrogen as energy will increase in the future, with FCEVs as an example. FCEVs have recently been introduced in Japan. Assuming that an FCEV is driven 12,000 km/year (an estimate from ordinary cars in the country) and consumes 1 kg of hydrogen per 100 km distance driven [13], the amount of hydrogen is estimated at 1.35×10^9 Nm^3/year/million-FCEVs. The Fuel Cell Commercialization Conference of Japan (FCCJ) published a scenario for the commercialization of FCEVs [14]. The scenario specifies two million FCEVs and construction of ~1000 hydrogen stations by 2025. Table 6 shows an estimation of hydrogen demand as fuel for FCEVs by 2020, 2030, and 2050. The numbers of FCEVs are estimated from the FCCJ scenario.

Another use of hydrogen is for electricity generation. Economic efficiency may be a problem, however. Hydrogen is considered a potential option for use as a fuel for thermal power plants in the form of either a mixture with other fuels or pure hydrogen [3, 4]. There is an estimate that hydrogen demand will increase by another 22×10^9 Nm^3/year by 2030, assuming that all newly built thermal power plants adopt a fuel mixture containing 50 % hydrogen [4]. If this is realized, such hydrogen demand for thermal power would exceed the demand of FCEVs (Table 6). However, hydrogen use by thermal power plants results in the reduction of CO_2 emission, so hydrogen should be produced from low-carbon energy sources or accompanied by carbon capture and sequestration (CCS).

Table 6 Estimated hydrogen demand in 2020, 2030, and 2050

Year	Hydrogen demand [10^9 Nm^3/year]	Breakdown
2020	0.5–1.1	
	0.5–1.1	0.4–0.8 million FCEVs[a]
2030	2.7–27.0	
	2.7–5.4	2–4 million FCEVs[1]
	0–21.6	Hydrogen turbine (mixed at 50 %)[b]
2050	13.5–35.1	
	13.5	10 million FCEVs[a]
	0–21.6	Hydrogen turbine (mixed at 50 %)[b]

[a] FCEV: 120 kg-H_2/car/year, giving 1.35×10^9 Nm^3/year/million-FCEVs

[b] According to a report from the Mizuho Information and Research Institute [4]

3.2 Hydrogen Production Methods Under Development

3.2.1 Membrane Reactor Reformer

For technical advancement of reforming, a membrane reformer equipped with a palladium-based alloy membrane is an advanced method for steam reforming of methane (Fig. 5) [15]. The aim is to conduct steam-reforming reactions and hydrogen separation processes simultaneously, without shift converters and purification systems. This results in greater energy efficiency (~80 %) and more compact equipment size than those of conventional technologies and is in the validation phase.

3.2.2 Biomass

Biomass, i.e., wood from forestry, arboricultural activities or from wood processing, agricultural residues, food waste, industrial waste and coproducts from manufacturing and industrial processes, and sewage sludge, can be used as an energy source for hydrogen production. Figure 3 shows that hydrogen derived from biomass has low CO_2 emissions relative to fossil fuel-based hydrogen. In the case of woody biomass, autothermal reforming is used in hydrogen production. Anaerobic fermentation is conducted to produce methane followed by steam reforming.

There is an estimate for the domestic hydrogen production potential of wood, livestock waste, and agricultural residue that indicates ~1300 hydrogen stations can be operated based on these types of biomass across Japan [16]. Assuming 1000 FCEVs per hydrogen station, the estimated number of stations could manage 1.3 million FCEVs. Dispersion of locations and small amounts of generated biomass per location are the major drawbacks of this biomass. Accordingly, mass production of hydrogen from biomass corrected for a wide area will increase cost because of transportation of the biomass feedstock. Onsite hydrogen production from sewage

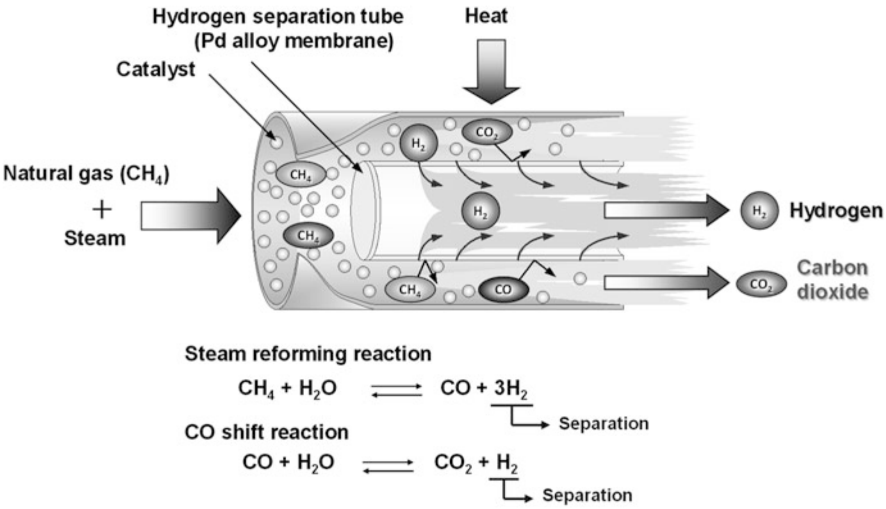


Fig. 5 Principle of a hydrogen separation reformer [15]

sludge for hydrogen stations will be an effective use of biomass. The Ministry of Land, Infrastructure, Transport and Tourism estimates a hydrogen production potential ~0.13×10^9 Nm^3/year [17]. There is an ongoing validation plant of hydrogen production from sewage sludge in the city of Fukuoka [13], which is an effective means of supply to hydrogen stations by locating stations near sewage treatment plants; the estimated hydrogen costs are 80–85 yen/Nm^3.

3.2.3 Thermochemical Water Splitting

One-step thermodynamic water splitting needs an extremely high temperature. The same molar amounts of steam, hydrogen, and oxygen are chemically in equilibrium at ~4100 °C [18]. However, the sequence of multiple chemical reactions combined with hydrogen separation enables complete water splitting at much lower temperatures [19, 20]. The iodine-sulfur (IS) process is one example and works when 900 °C heat is available (Fig. 6) [20, 21]. The Japan Atomic Energy Agency (JAEA) is verifying a combined system of the IS process and a high-temperature gas-cooled reactor (HTGR), which is a nuclear reactor using helium as the coolant [21]. A test plant with hydrogen production capability 200 NL/h has been constructed and tested. In *Nuclear Energy Vision 2100* proposed by the JAEA, hydrogen produced by an HTGR will be supplied to industries from around 2040 [22]. An HTGR with thermal output of 600 MW can produce 0.6×10^9 Nm^3/year of hydrogen.

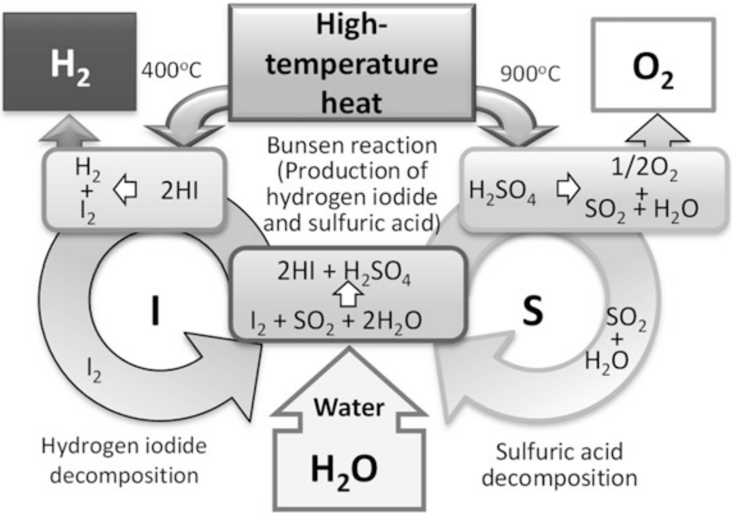


Fig. 6 Iodine-sulfur process. The full process is divided into three sections, Bunsen, H_2SO_4, and HI [21]. $SO_2 + I_2 + 2H_2O \rightarrow H_2SO_4 + 2HI$ (Bunsen reaction). $H_2SO_4 \rightarrow H_2O + SO_2 + 0.5O_2$ (sulfuric acid decomposition). $2HI \rightarrow H_2 + I_2$ (hydrogen iodide decomposition)

3.2.4 Water/Steam Electrolysis

Comparing CO_2 emissions from various hydrogen production methods (Fig. 4), water electrolysis can produce low-carbon hydrogen when low-carbon electricity is used. Therefore, water electrolysis based on low-carbon or renewable electricity is an important direction for future hydrogen production. A power-to-gas project in Germany is based on such a concept, using excess electricity for the production of hydrogen and methane [23]. In this case, the operation rate cannot be sufficiently high to affect the hydrogen production cost, because electrolyzers function only on sunny or windy days. In the case of Japan, as mentioned in Sect. 2.3.3, the price of electricity is the most significant in hydrogen production cost via water electrolysis; 61–72 % of that cost is from electricity for operation rates of 60–100 %. However, facility cost is another important contributor at 21 % (operation rate, 100 %) and 30 % (operation rate, 60 %). Further, the price of hydrogen varies with the operation rate (Table 5).

Electrolysis is an electrochemical water-splitting process and occurs on inputting electric energy greater than Gibbs free energy of water formation ($\Delta_f G$). Either liquid water or steam can be electrolyzed depending on the operation temperature. Figure 7 shows a thermodynamic breakdown of the energy for electrolysis conducted at 25 °C and 600 °C, in the cases of liquid water and steam electrolysis, respectively [24]. Alkali water electrolysis and polymer electrolyte water electrolysis are the two technically established methods. These typically operate at around 2 V, corresponding to 75 % energy efficiency (based on high heat value, HHV). There is a NEDO research project for hydrogen utility that has targeted electrolysis

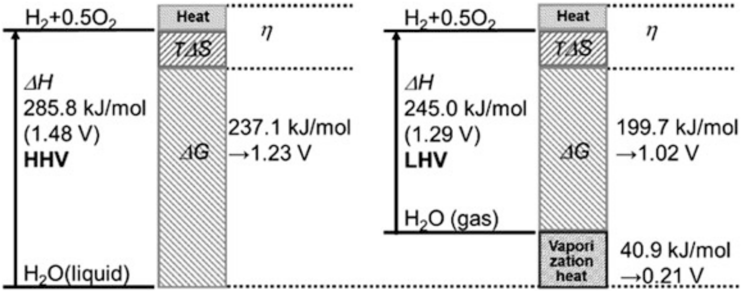


Fig. 7 Comparison of thermodynamics of water/steam electrolysis operated at 25 °C and 600 °C [20]. Minimum required electrolysis voltage is $\Delta_f G/2\ F$, where F is Faraday's constant and is a function of temperature, i.e., 1.23 V at 25 °C and 1.02 V at 600 °C

voltage 1.8 V (at 0.6 A/cm^2) to improve efficiency and thereby reduce hydrogen production cost [25]. As suggested by Fig. 7, steam electrolysis will need less electrolysis voltage. The NEDO project targets 1.6 V for steam electrolysis [25]. This type of effort should make water/steam electrolysis a practical hydrogen production method in combination with renewable energy.

The cost of hydrogen is estimated in Table 5. This cost is primarily a function of the price of electricity and energy efficiency of electrolysis. Therefore, electrolysis will become effective via cost reduction of renewable electricity, and improved energy efficiency of photovoltaic cells is crucial.

3.2.5 Photoelectrochemical Water Splitting

Water splitting can occur on the surface of a semiconductor in contact with water with the incidence of light when the semiconducting material is appropriately selected. This process is similar to photosynthesis that uses light to produce a chemical, i.e., sugar in natural photosynthesis. Since the discovery of photoelectrochemical water-splitting catalysis in anatase TiO_2 [26], extensive research has been conducted. The advantage of photoelectrochemical water splitting is its simplicity. The action of a combination of photovoltaic cells and water electrolyzers can be conducted simultaneously with only water, a catalyst, and sunlight. The drawback is energy efficiency; state-of-the-art efficiency is currently 2 % [27]. Such a low efficiency necessitates large areas of land.

3.2.6 Summary of Hydrogen Production Methods Under Development

The hydrogen production methods addressed in Sect. 3.2 are summarized in Table 7, with an assumed capability of hydrogen production. The most important feature is

Table 7 Low-carbon hydrogen production methods

Methods	Potential hydrogen production [10^9 Nm^3/year]	Remarks
Biomass	1.9[a]	Effective when used for local hydrogen stations
Thermochemical hydrogen	0.6	600-MW thermal HTGR is assumed as thermal source: 0.6×10^9 Nm^3/year/nuclear reactor
Water/steam electrolysis with renewable electricity	NA	Available for renewable electricity hydrogen conversion
Photoelectrochemical water splitting	NA	Direct conversion of solar energy to hydrogen

[a] 1.75×10^9 Nm^3/year from wood, livestock waste, and agricultural residue and 0.13×10^9 Nm^3/year from sewage sludge (Sect. 3.2.2)

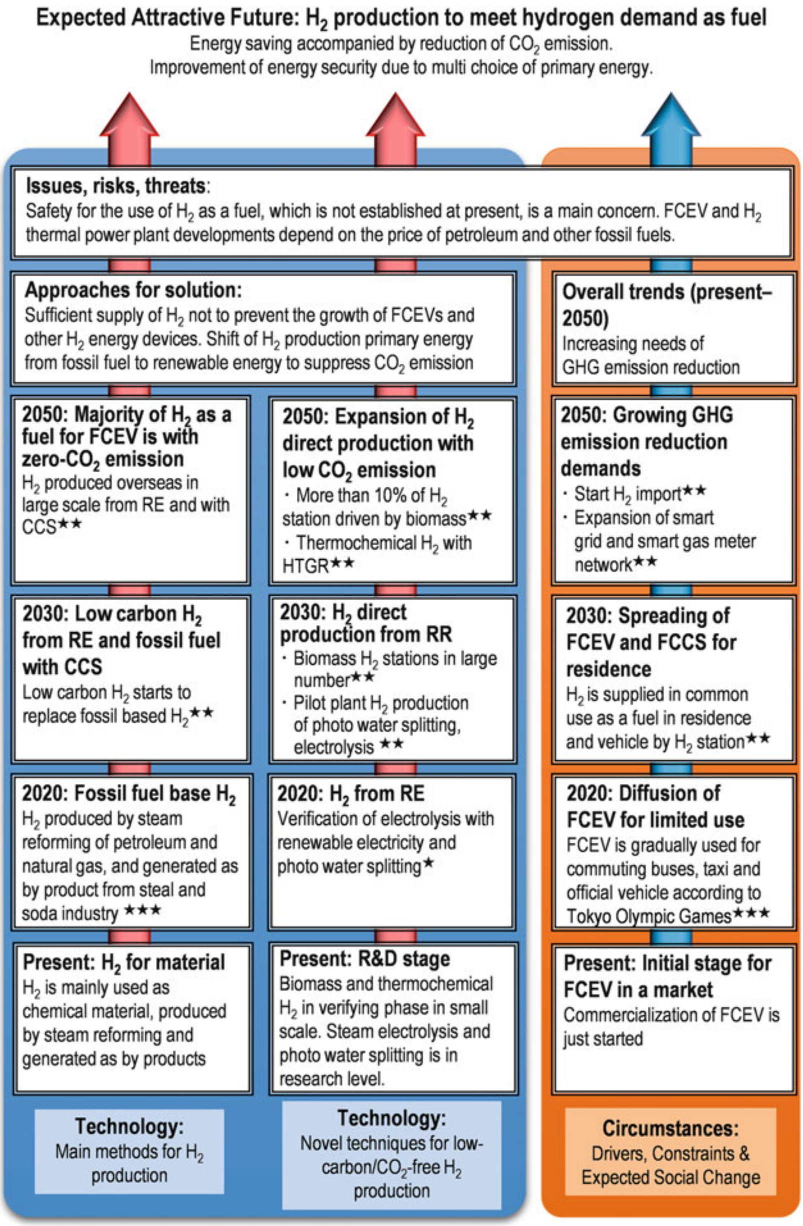
that they are low-carbon hydrogen production methods. This feature is of primary importance for the sustainability of daily life and is discussed in the next section.

3.3 Road Map

A road map for hydrogen production is summarized in Fig. 8 and is discussed here.

An assumed technological goal for hydrogen production is a supply of hydrogen meeting the demand of FCEVs and other hydrogen energy devices. Reduction of CO_2 (GHG) emissions is mandatory for the sustainability of society, so primary energy for the hydrogen production should be shifted from fossil fuel to renewable energy. The right-hand column in the roadmap chart (Fig. 8) explains social status relevant to hydrogen energy. At present, hydrogen energy is viewed from the perspective of energy saving and reduction of CO_2 emissions. Hydrogen-fueled FCEVs have been commercialized since 2014 [1] in Japan, and the number of FCEVs is assumed to increase as mentioned in Sect. 3.1. If we assume ten million FCEVs by 2050, this number will roughly correspond to 15–20 % of total automobiles nationwide. Accordingly, around 5000 hydrogen stations should be operated, assuming an average capacity of 2000 FCEVs per hydrogen station. When the above technological goal is fully achieved, hydrogen will be used in society as an energy medium for transportation and other potential hydrogen devices.

Based on the assumed social situation above, increasing demand of hydrogen as fuel can be defined and is not very different from the assumption of future hydrogen demand outlined in Sect. 3.1 and Table 6. That is, hydrogen is currently produced at $15–20 \times 10^9$ Nm^3/year, and this will need to increase by 100–200 % by 2050 for hydrogen fuel, as mentioned in Sect. 2.1. As addressed in Sect. 2.2 and Table 1, hydrogen needed by FCEVs can be supplied by the conventional types even in 2050, i.e., steam reforming and by-product hydrogen, as long as the supply of fossil



Expected Attractive Future: H_2 production to meet hydrogen demand as fuel

Energy saving accompanied by reduction of CO_2 emission.
Improvement of energy security due to multi choice of primary energy.

Issues, risks, threats: Safety for the use of H_2 as a fuel, which is not established at present, is a main concern. FCEV and H_2 thermal power plant developments depend on the price of petroleum and other fossil fuels.

Approaches for solution: Sufficient supply of H_2 not to prevent the growth of FCEVs and other H_2 energy devices. Shift of H_2 production primary energy from fossil fuel to renewable energy to suppress CO_2 emission

Overall trends (present–2050) Increasing needs of GHG emission reduction

Technology: Main methods for H_2 production	**Technology:** Novel techniques for low-carbon/CO_2-free H_2 production	**Circumstances:** Drivers, Constraints & Expected Social Change
2050: Majority of H_2 as a fuel for FCEV is with zero-CO_2 emission H_2 produced overseas in large scale from RE and with CCS★★	**2050: Expansion of H_2 direct production with low CO_2 emission** · More than 10% of H_2 station driven by biomass★★ · Thermochemical H_2 with HTGR★★	**2050: Growing GHG emission reduction demands** · Start H_2 import★★ · Expansion of smart grid and smart gas meter network★★
2030: Low carbon H_2 from RE and fossil fuel with CCS Low carbon H_2 starts to replace fossil based H_2★★	**2030: H_2 direct production from RR** · Biomass H_2 stations in large number★★ · Pilot plant H_2 production of photo water splitting, electrolysis ★★	**2030: Spreading of FCEV and FCCS for residence** H_2 is supplied in common use as a fuel in residence and vehicle by H_2 station★★
2020: Fossil fuel base H_2 H_2 produced by steam reforming of petroleum and natural gas, and generated as by product from steal and soda industry ★★★	**2020: H_2 from RE** Verification of electrolysis with renewable electricity and photo water splitting★	**2020: Diffusion of FCEV for limited use** FCEV is gradually used for commuting buses, taxi and official vehicle according to Tokyo Olympic Games★★★
Present: H_2 for material H_2 is mainly used as chemical material, produced by steam reforming and generated as by products	**Present: R&D stage** Biomass and thermochemical H_2 in verifying phase in small scale. Steam electrolysis and photo water splitting is in research level.	**Present: Initial stage for FCEV in a market** Commercialization of FCEV is just started

*1 Estimated from FCCJ scenario

Abbreviations:

FCEV: Fuel Cell Electric Vehicle, FCS: Fuel Cell Cogeneration System, HTGR: High Temperature Gas-cooled Reactor, R&D: Research and Development, RE: Renewable Electricity, RS: Renewable Resources

Fig. 8 Roadmap of hydrogen production fuel is sufficient. However, these conventional hydrogen production methods are fossil fuel-based and accompanied by CO_2 emissions. To reach the technical goal for hydrogen production shown in Fig. 8 and mentioned above, development of production methods of low-carbon hydrogen discussed in Sect. 3.2 is important for reducing CO_2 emissions. In the next 20–30 years, hydrogen may be used in electricity generation in a fuel mixture with natural gas for thermal power plants. In this case, the need for hydrogen is greater than that of FCEVs, and the hydrogen should be low carbon as discussed in Sect. 3.1. Steam reforming of brown coal together with CCS and water electrolysis combined with solar or other renewable electricity can be assumed as overseas hydrogen production schemes [3, 4, 28, 29].

According to the above discussion on the quantity and quality of hydrogen necessary as a future fuel, substantial progress in methods producing low-carbon or CO_2-free hydrogen is mandatory. Hydrogen production methods of this kind with the potential capability of hydrogen production were explained in Sect. 3.2 and Table 7. The statuses of these techniques are different, as described in the following.

Biomass is currently in the verification phase. As mentioned in Sect.. 3.2.2 and shown in Table 7, a hydrogen production capability of 1.9×10^9 Nm^3/year is predictable, corresponding to 1.4 million FCEVs (14 % to the total expected number of FCEVs in 2050). As thermochemical hydrogen production, the IS process with HTGR at a small-scale hydrogen production facility (~200 NL/h) is operating for technology verification, as mentioned in Sect. 3.2.3. An HTGR with thermal output 600 MW can produce 0.6×10^9 Nm^3/year of hydrogen (corresponding to 0.44 million FCEVs), and its utilization from around 2040 is proposed [22].

Water electrolysis (alkaline and PEM) is technically nearly established, and improvement of energy efficiency is being studied [25]. Steam electrolysis and photoelectrochemical water splitting are under research, but could move into the verification stage in the next 10 years. Water/steam electrolysis (Sect. 3.2.4) is the only technique that produces hydrogen from electricity, and will be important in hydrogen production methods using renewable energy, because the main form of energy available from that energy is electricity. Photoelectrochemical water splitting is more beneficial, because it directly produces hydrogen from sunlight (Sect. 3.2.5). For practical use, however, the energy efficiency should be increased from the current state-of-the-art 2 % [27] to ~20 % or higher, comparable to the combination of photovoltaic cells and water electrolysis, which make up ~21 % of hydrogen production. State-of-the-art commercial energy efficiencies of these two technologies are 25 % [30] and 87 % [31], respectively.

Future expansion of these low-carbon hydrogen production methods will reduce CO_2 emissions and is the technological goal of hydrogen production.

4 Benefit and Future Vision

A hydrogen energy society using hydrogen as an energy medium has the following benefits:

1. Energy saving accompanied by reduction of CO_2 emissions
2. Facilitating a CO_2-free energy system and substantial reduction of CO_2 emissions by producing hydrogen from renewable energy
3. Improvement of energy security via multiple choices of primary energy

FCEV is a good example of benefit (1). Even when hydrogen fuel is produced conventionally from fossil fuels, well-to-wheel CO_2 emission can be roughly 0.5–0.6 that of a conventional internal-combustion engine vehicle (based on representative values, comparing a FCEV fueled with hydrogen produced by onsite reforming of town gas and a gasoline or diesel internal-combustion engine vehicle) [3]. Benefit (2) is more important to dramatically decrease CO_2 emission over its present status. CCS is one method to reduce CO_2 emission, but the use of large portions of renewable energy is essential for the sustainability of society. In contrast, hydrogen is an energy medium suitable for the use of renewable energy, which can be enhanced by the spread of hydrogen energy. This characteristic can stabilize the energy situation in Japan, which has long suffered from poor energy resources. We can produce hydrogen within Japan in the future via biomass, water electrolysis with renewable electricity, and photoelectrochemical water splitting, which are advantageous to fossil fuel-based hydrogen from an energy security standpoint.

Such low-carbon techniques of hydrogen production are in various stages toward practical applications and are currently studied and developed both scientifically and technologically. We can even assume the emergence of novel techniques that are presently unknown. As mentioned above, progress of these techniques is required to realize a hydrogen energy society. Resources should be spent on their research and development to realize the benefits of hydrogen energy.

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References

1. Press release on Nov. 18, 2014 from Toyota Motor Corporation (in Japanese). http://newsroom.toyota.co.jp/en/detail/4197769
2. Press release on Nov. 17, 2014 of Honda Motor Co., Ltd. (in Japanese). http://www.honda.co.jp/news/2014/4141117.html
3. New Energy and Industrial Technology Development Organization (NEDO) Hydrogen energy white paper (*Suiso Energy Hakusho*), July 28, 2014 http://www.nedo.go.jp/news/press/AA5_100292.html

4. Mizuho Information and Research Institute, FY2012 report: a study on present and future status of hydrogen demand and supply http://www.nedo.go.jp/library/seika/shosai_201311/20130000000462.html
5. Agency for Natural Resources and Energy. Hydrogen production, transportation and storage. http://www.meti.go.jp/committee/kenkyukai/energy/suiso_nenryodenchi/suiso_nenryodenchi_wg/pdf/006_s02_00.pdf
6. Mizuho Information and Research Institute. Yusouyou nenryou no well-to-weel hyouka. (2004). http://www.mizuho-ir.co.jp/publication/report/2004/pdf/wtwghg041130.pdf
7. U.S. Department of Energy. Production case studies. http://www.hydrogen.energy.gov/h2a_prod_studies.html. Accessed 7 Nov 2014
8. Japan Hydrogen and Fuel Cell Demonstration Project, Japan Automobile Research Institute (2011) Sougou kouritu to GHG haisyutu no bunnseki houkokusyo. http://www.jari.or.jp/Portals/0/jhfc/data/report/2010/pdf/result.pdf
9. Institute of Energy Economics Japan (2009) Zidousyayou nennryou tositeno suiso enerugi- no gennzyou to konngo no doukou ni tuite. http://eneken.ieej.or.jp/data/2523.pdf
10. Federation of Electric Power Companies Japan (2014) Denjiren kaicyou teirei kaiken yousi. http://www.fepc.or.jp/about_us/pr/kaiken/__icsFiles/afieldfile/2014/05/23/kaiken_20140523.pdf,pp.5
11. Japan Hydrogen and Fuel Cell Demonstration Project (2011) Nenryou denchi sisutemu tou zissyou kennkyuu houkokusyo. http://www.jari.or.jp/Portals/0/jhfc/data/report/pdf/tuuki_phase2_01.pdf
12. Energy and Environment Council (2011) kosuto tou kenshou iinkai houkokusho. http://www.cas.go.jp/jp/seisaku/npu/policy09/pdf/20111221/hokoku.pdf
13. http://www.hydrogennet.dk/fileadmin/user_upload/PDF-filer/Aktiviteter/Afholdte_aktiviteter/Transportworkshop%20d.%201.%20dec%202011/4_Sloth.pdf
14. Fuel Cell Commercialization Conference of Japan (2010) Commercialization scenario for FCVs and H_2 stations. http://fccj.jp/pdf/22_cse.pdf
15. Shirasaki Y, Tsuneki T, Ota Y, Yasuda I, Tachibana S, Nakajima H, Kobayashi K (2009) Int J Hydrog Energy 34(10):4482–4487
16. Tajima M (n.d.) Fukuoka strategy conference for hydrogen energy, presentation slides, p 29. http://www.f-suiso.jp/wp-content/uploads/2012/12/H24bunkakai4-21.pdf
17. A report from Ministry of Land, Infrastructure, Transport and Tourism. http://www.meti.go.jp/committee/kenkyukai/energy/suiso_nenryodenchi/suiso_nenryodenchi_wg/pdf/006_s02_00.pdf
18. NIST-JANAF Tables. http://kinetics.nist.gov/janaf/janaf4pdf.html
19. Funk JE (2001) Int J Hydrog Energy 26(3):185–190
20. Kameyama H, Sakurai M, Masuda A, Fukui T (2012) Hydrogen Energy System, 37 3-10 (in Japanese)
21. Kasahara S, Tanaka N, Noguchi H, Iwatsuki J, Takegami H, Yan X L, Kubo S (2014) Proceedings of the HTR 2014, Weihai, China, October 27-31, ,Paper HTR2014-21233
22. JAEA. Nuclear energy vision 2100 -towards a low carbon society-, 2008 (in Japanese). http://www.jaea.go.jp/03/senryaku/seminar/08-4-2.pdf
23. Germany Energy Agency. Power to gas strategy platform. http://www.dena.de/en/projects/renewables/power-to-gas-strategy-platform.html
24. Matsumoto H, Kwati Leonard (2014) Catalyst (Shokubai), 56:296–299
25. NEDO, project on hydrogen utiliation. http://www.nedo.go.jp/activities/ZZJP_100068.html
26. Fujishima A, Honda K (1972) Nature 238:37–38
27. NEDO, news release, March 31, 2015. http://www.nedo.go.jp/news/press/AA5_100372.html
28. Yoshino Y, Harada E, Inoue K, Yoshimura K, Yamashita S, Hakamada K (2012) Energy Procedia 29:701–709
29. Okada Y, Sasaki E, Watanabe E, Hyodo S, Nishijima H (2006) Int J Hydrog Energy 31:1348–1356
30. Nayak PK, Cahen D (2014) Adv Mater 26:1622–1628
31. Haryu E et al (2011) Honda R&D Tech Rev 23(2):90–97