Chapter 2
Hydrogen Production Methods

2.1 Introduction

As hydrogen appears to be a potential solution for a carbon-free society, its production plays a critical role in showing how well it fulfills the criteria of being environmentally benign and sustainable. Of course, hydrogen can be produced from a number of sources, such as water, hydrocarbon fuels, biomass, hydrogen sulfide, boron hydrides, and chemical elements with hydrogen. Because hydrogen is not available anywhere as a separate element, it needs to be separated from the aforementioned sources, for which energy is necessary to do this disassociation. The forms of energy that can drive a hydrogen production process can be classified in four categories: thermal, electrical, photonic, and biochemical energy. These kinds of energy can be obtained from primary energy (fossil, nuclear, and renewable) or from recovered energy through various paths. The literature is quite large and covers many options.

Many researchers have been involved in analyzing the different hydrogen production methods based on energy and exergy analysis. As mentioned by Muradov and Veziroglu [8], ammonia, being rich in hydrogen, can be used as a fuel directly [in internal combustion engines (ICE)] or via on-board decomposition to hydrogen and nitrogen (in ICE and fuel cells). Zamfirescu and Dincer [9] proposed a system that uses ammonia as the source of hydrogen. In their system, the heat recovered from an engine or fuel cell was used to extract hydrogen from ammonia. Yilanci et al. [10] have made a through and up-to-date review on the various hydrogen production systems and analyzed a solar–hydrogen–fuel cell hybrid energy system in terms of energy and exergy efficiencies for stationary applications in Denizli, Turkey. They reported that the overall energy efficiency values of the system vary between 0.88 % and 9.7 %, whereas minimum and maximum overall exergy efficiency values of the system are between 0.77 % and 9.3 %. Balta et al. [11] have analyzed a geothermal-based hydrogen production

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system for Iceland in terms of energy and exergy efficiency and reported that the efficiency varies with the geothermal inlet temperature. This process involves high-temperature steam electrolysis (HTSE) coupled with a geothermal source.

Abanades and Flamant [12] have studied the single-step thermal decomposition (pyrolysis) of methane without catalysts. The process coproduces hydrogen-rich gas and high-grade carbon black (CB) from concentrated solar energy and methane. It is an unconventional route for potentially cost-effective hydrogen production from solar energy without emitting carbon dioxide because solid carbon is sequestered. For the experiment with the 2-m-diameter concentrator, the thermochemical efficiency is in the range of 2–6 % for the maximum conversion (98 %), assuming that the mean temperature in the nozzle is 1,500 K. Liu et al. [13] investigated hydrogen production by integrating methanol steam reforming with a 5-kW solar reactor that can produce 150–300 °C at atmospheric pressure and obtained thermochemical efficiency of solar thermal energy converted into chemical energy in the range of 30–50 %.

Z'Graggen et al. [14] analyzed hydrogen production by steam-gasification of petroleum coke using concentrated solar power and reported a solar energy conversion efficiency of 17 %. Charvin et al. [15] made a process analysis of ZnO/Zn, Fe_3O_4/FeO, and Fe_2O_3/Fe_3O_4 thermochemical cycles and found these to be potentially high-efficiency, large-scale, and environmentally attractive routes to produce hydrogen by concentrated solar thermal energy that operates at a temperature up to 2,000 K. The real energy efficiency of these cycles was reported as 25.2 %, 28.4 %, and 22.6 %, respectively. Falco et al. [16] reported that the application of hydrogen-selective membranes (for example, a Pd/Ag membrane) in steam reforming plants may play an important role in converting natural gas or heavy hydrocarbons into hydrogen in a very efficient way, and by providing the reaction heat by sources such as solar-heated molten salts or a fluid heated in a nuclear reactor may further increase the overall energy efficiency of the system and pave the way for producing large amounts of hydrogen with minimum environmental impact.

Ni et al. [17], have conducted energy and exergy analyses of the thermodynamic-electrochemical characteristics of hydrogen production by a PEM electrolyzer plant and found that the energy and exergy efficiencies of the system are same and influenced by the operating temperature, current density, and the thickness of the polymer electrolyte membrane (PEM). With an increase in current density from 2,000 to 10,000 A/m^2, an operating temperature of 353 K, and a PEM electrolyte thickness of 100 μm, the efficiency decreases from 0.64 to 0.58. They also claimed that with an increase in the thickness of the PEM electrolyte and the operating temperature, the efficiency of the plant is reduced. For the three different PEM electrolyte thicknesses, that is, 50, 100, and 200 μm (and at 10,000 A/m^2 current density), the energy efficiency is 0.6, 0.58, and 0.56 respectively. For three different operating temperatures (300, 323, and 353 K) the energy efficiency is 0.55, 0.57, and 0.58 at a current density of 10,000 A/m^2. For higher current densities the difference in efficiency is more evident than for lower current densities.

Zedtwitz et al. [18] have produced hydrogen via solar thermal decarbonization of fossil fuels using three different routes and reported an exergy efficiency of 32 %

for solar decomposition of natural gas, 46 % for solar steam reforming of natural gas, and 46 % for solar steam gasification of coal. Although the exergy efficiency of the first route is less as compared to the latter two, it is a zero carbon dioxide emission method of producing hydrogen.

2.2 Classification of Hydrogen Production Methods

Hydrogen can be produced by both renewable and nonrenewable sources of energy. The former has the advantage of being environmentally friendly whereas the latter has either carbon dioxide or some other form of carbon residue in the end product other than hydrogen. Hydrogen production using conventional sources, that is, coal, oil, and natural gas, is in practice these days, and research is ongoing to minimize the environmental damage caused by greenhouse gas emissions. One method by which greenhouse gases can be minimized is by using solar or some other form of renewable energy source as the primary energy requirement for the hydrogen production chemical reaction. Therefore, it is important to understand the renewable energy sources first and then how these energy sources can be used for hydrogen production. Dincer [19] has summarized various green hydrogen production methods that use renewable energy sources (Table 2.1).

Careful reading of Table 2.1 shows that the primary energy required for the chemical reactions is generally electrical and thermal energy. The materials or chemicals used to generate hydrogen are principally water and fossil fuels. Organic biomass and inorganic compounds such as hydrogen sulfide are also used to produce hydrogen. Therefore, it is important to identify the sources of energy that can be used to fulfill the primary energy demands for environmentally benign hydrogen production.

The energy conversion from energy sources to process energy is equally important, as summarized by Dincer [19] in Table 2.2. It is important to see that electricity may be produced by all the renewable energy sources. High-grade thermal energy can be produced by concentrated solar energy, biomass and recovery gas from landfills, etc., and low-grade thermal energy can be produced geothermally.

Taking the foregoing discussion further, this section considers hydrogen production using renewable and sustainable energy resources, for example, solar, wind, and geothermal. Hydrogen production mainly involves thermal and electrical energy as the input energy; therefore, different renewable sources are used to provide input energy. Because most of the renewable sources are used to produce electricity first and the electricity is then further utilized to produce hydrogen, for example, in an electrolyzer unit, different electricity production methods are also discussed briefly here. Some renewable sources, for example, geothermal, can also be used to produce heat that can be used in thermochemical and hybrid cycles for hydrogen production. Discussion of different modes of hydrogen production, that is, via electricity and via thermal, appears in this chapter as necessary.

Table 2.1 Classification of green hydrogen production methods

Primary energy	Hydrogen production method	Material resources	Brief description	
Electrical energy	Electrolysis	Water	Water decomposition into O_2 and H_2 by passing a direct current which drives electrochemical reactions	
	Plasma arc decomposition	Natural gas	Clean natural gas (methane) is passed through an electrically produced plasma arc to generate hydrogen and carbon soot	
Thermal energy	Thermolysis	Water	Steam is brought to temperatures of over 2,500 K at which water molecule decomposes thermally	
	Thermo-catalysis	H_2S cracking	Hydrogen sulfide	H_2S extracted from sea or derived from other industrial processes is cracked thermo-catalytically
		Biomass conversion	Biomass	Thermo-catalytic biomass conversion to hydrogen
	Thermochemical processes	Water splitting	Water	Chemical reactions (including redox reactions or not) are conducted cyclically with overall result of water molecule splitting
		Gasification	Biomass	Biomass converted to syngas; H_2 extracted
		Reforming	Biofuels	Liquid biofuels converted to hydrogen
		H_2S splitting	Hydrogen sulfide	Cyclical reactions to split the hydrogen sulfide molecule
Photonic energy	PV electrolysis	Water	PV panels generate electricity to drive electrolyzer	
	Photo-catalysis	Water	Complex homogeneous catalysts or molecular devices with photo-initiated electron collection are used to generate hydrogen from water	
	Photo-electrochemical method	Water	A hybrid cell is used to generate photovoltaic electricity, which drives the water electrolysis process	
	Bio-photolysis	Water	Biological systems based on cyanobacteria are used to generate hydrogen in a controlled manner	

Biochemical energy	Dark fermentation	Biomass	Anaerobic fermentation in the absence of light
	Enzymatic	Water	Uses polysaccharides to generate the required energy
Electrical + thermal	High-temperature electrolysis	Water	Uses a thermal source and electrical power to split water in solid oxide electrolyte cells
	Hybrid thermochemical cycles	Water	Use thermal energy and electricity to drive chemical reactions cyclically with the overall result of water splitting
	Thermo-catalytic fossil fuel cracking	Fossil fuels	A thermo-catalytic process is used to crack fossil hydrocarbons to H_2 and CO_2, whereas CO_2 is separated/sequestrated for the process to become green
	Coal gasification	Water	Coal is converted to syngas, then H_2 extracted and CO_2 separated/sequestrated (electric power spent)
	Fossil fuels reforming	Fossil fuels	Fossil hydrocarbons are converted to H_2 with CO_2 capture and sequestration (electric power spent)
Electrical + photonic	Photo-electrolysis	Water	Photo-electrodes + external source of electricity
Biochemical + thermal	Thermophilic digestion	Biomass	Uses biomass digestion assisted by thermal energy for heating at low-grade temperature
Photonic + biochemical	Bio-photolysis	Biomass, water	Uses bacteria and microbes to photo-generate hydrogen
	Photo-fermentation	Biomass	The fermentation process in facilitated by light exposure
	Artificial photosynthesis	Biomass, water	Chemically engineered molecules and associated systems to mimic photosynthesis and generate H_2

Modified from Dincer [19]

Table 2.2 Production methods and energy conversion paths to produce "green hydrogen"

Hydrogen production method		Green energy source	Conversion path
Electrolysis (green energy generates electricity for water electrolysis) or *plasma arc decomposition* (green energy generates electricity for plasma arc decomposition of natural gas)		Solar	PV power plant or concentrated solar power (CSP) to generate electricity
		Geothermal	Power plant [organic Rankine cycle (ORC), flash cycle, etc.]
		Biomass	Biomass power plant, internal combustion engines, fuel-cell plants
		Wind	Wind power plants (grid-connected or autonomous)
		Ocean heat	OTEC (ocean thermal energy conversion) plants
		Other renewable	Tides, ocean currents, and wave energy converted into electricity
		Nuclear	Nuclear power plants
		Recovery	Landfill gas combusted in diesel generators
			Industrial/other heat recovery used to drive ORC or other heat engines
			Incineration with pollutant capture drives Rankine power plant
Thermolysis		Solar	Concentrated solar heat used to generate ultrahigh-temperature steam
Thermo-catalysis	H_2S cracking	Solar	Concentrated solar heat used to drive the process at high temperature
		Biomass	Low-grade biomass combustion generates the process heat
		Recovery	Landfill gas combustion, high-temperature industrial heat recovery
	Biomass conversion	Solar	Concentrated solar heat at high temperature drives the process
		Biomass	Auto-thermal process: reaction heat comes from biomass combustion
Thermochemical processes	Water splitting	Solar	Concentrated solar radiation generates high-temperature heat
		Geothermal	Geothermal-generated electricity to drive high-temperature heat pumps
		Biomass	Dried biomass is combusted to generate high-temperature heat
		Nuclear	Nuclear electric power used to drive high-temperature heat pumps
		Recovery	Landfill gas combustion
	Gasification	Solar	Concentrated solar heat at high temperature drives the process
		Biomass	Auto-thermal process: reaction heat comes from biomass combustion
	Fuel reforming	Solar	Concentrated solar heat at high temperature drives the process
		Biofuels	Auto-thermal process: reaction heat comes from biomass combustion
	H_2S splitting	Solar	Concentrated solar heat used to drive the process at high temperature
		Geothermal	High-temperature geothermal heat at ~200 °C drives the process

	Biomass	Low-grade biomass combustion generates the process heat
	Recovery	Landfill gas combustion, high-temperature industrial heat recovery
PV electrolysis	Solar	Solar radiation generates electricity through PV panels
Photo-catalysis	Solar	UV and upper spectrum visible solar radiation drives the process
Photo-electrochemical	Solar	All solar spectrum used by photo-electrochemical cell
Bio-photolysis	Solar	All solar spectrum can be used
Dark fermentation	Biomass	Biogas reactors are used for dark fermentation to generate hydrogen
Enzymatic	Biomass	Polysaccharides are manipulated by special enzymes to extract hydrogen
High-temperature electrolysis	Solar	Concentrated solar power generates high-temperature heat and electricity
	Geothermal	Geothermal electricity coupled to high-temperature heat pumps
	Biomass	Biomass combustion generates power and high-temperature heat
	Nuclear	Nuclear power used to generate electricity and high-temperature heat
	Recovery	Recovered energy generates electricity and high-temperature heat
Hybrid thermochemical cycles	Solar	Concentrated solar power generates high-temperature heat and electricity
	Geothermal	Geothermal electricity coupled to high-temperature heat pumps
	Biomass	Biomass combustion generates power and high-temperature heat
	Nuclear	Nuclear power used to generate electricity and high-temperature heat
	Recovery	Recovered energy generates electricity and high-temperature heat
Photo-electrolysis	Solar	PV or CSP + electrolysis bath with photo-electrodes
Thermophilic digestion	Biomass + other	Biomass energy drives the process; heat recovery or solar provides heat
Bio-photolysis	Biomass + solar	Biomass + photonic energy drive the process
Photo-fermentation	Biomass + solar	Biomass + photonic energy drive the process
Artificial photosynthesis	Solar	Solar energy drives the hydrogen generation process directly

A classification of solar hydrogen production systems based on energy input [that is, sunlight (photo) and solar thermal, and type of chemical reactants, for example, H_2O, natural gas, oil, coal] and for the different hydrogen production processes involved, for example, electrolysis, reforming, gasification, and cracking, is also presented. Thermochemical cycles, such as the hybrid-sulfur cycle, metal oxide-based cycle, and electrolysis of water are the most promising processes for environmentally benign future hydrogen production. The concept of sustainable and environmentally benign hydrogen production by artificial photosynthesis is also discussed. For a case study, sustainability of a solar hydrogen system through exergy efficiency and sustainability index is investigated. The various processes associated with solar hydrogen production in terms of exergy efficiency and sustainability index are also compared.

2.3 Renewables for Hydrogen Production

In this section, hydrogen production via renewable sources is discussed. As already mentioned, thermal and electrical energy are the input energy sources; therefore, in this section a brief discussion about these is included. Electricity can be produced by various renewable resources, such as solar, wind, geothermal, tidal, wave, ocean thermal, hydro, and biomass. Generally, with these technologies, the electricity produced is supplied to the grid, but with some technologies, for example, solar photovoltaic, the electricity can also be supplied to small standalone systems. Renewable sources of energy are known as eco-friendly and sustainable energy resources, in contrast to fossil fuels (coal, oil, natural gas) that produce greenhouse gases such as carbon dioxide, which are responsible for global warming on this planet Earth. Moreover, fossil fuels are finite sources and they are depleting fast. Some established renewable technologies for electricity and thermal energy production are discussed briefly here. Also, the various processes involved in hydrogen production, such as electrolysis, thermolysis, photo-electrolysis, and photosynthesis, are discussed in connection with renewable energy sources.

-Solar. Solar energy is an abundant source of energy that can be utilized in two ways: (i) to convert sunlight into electricity through a photovoltaic system and (ii) to generate heat using concentrating collectors. The estimated potential of the direct capture of solar energy is enormous. When solar energy strikes the Earth's atmosphere, approximately 30 % is reflected. After reflection by the atmosphere, Earth's surface receives about 3.9×10^{24} MJ incident solar energy per year, which is almost 10,000 times more than current global energy consumption. Thus, the harvesting of less than 1 % of photonic energy would serve all human energy needs [1]. Photovoltaic systems, as already discussed, are a novel approach to electricity generation as these use solar energy, which is freely available. Although the intermittent nature of solar radiation limits the use of this technology to some extent, for off-sunshine periods energy can be stored in a battery bank. Photovoltaic

Table 2.3 Different solar collectors with their operating temperatures, concentration factors, and power capacities

Solar collector	Concentration factor	Temperature (°C)	Power capacity
Flat-plate collector	1	<200	<1 MW (thermal)
Vacuum-tube collector	3	<300	<1 MW (thermal)
Concentrating solar collector (trough type)	40–80	<350	<50 MW (electrical)
Field mirror collector	200–700	<1,500	<150 MW (electrical)
Parabolic collector	1,000–2,500	<2,500	<100 kW (thermal)/E_{inh}

Modified from Brown et al. [20] and Friberg [21]

systems can be used not only as standalone systems but also connected to a grid to supply continuous electricity throughout the day. The efficiency of the solar cell typically ranges from 12 % to 15 % for a silicon solar cell. However, it is as high as 25–30 % for GaAs solar cells. The cost of the former is less as compared to the latter, and the latter is used mostly for space applications. The efficiency of the photovoltaic (PV) system can also be calculated from the product of the efficiencies of its various components such as the solar cell, module, and battery. From a health perspective, the potential benefits of solar energy applications seem very desirable. The two disadvantages of the PV technology can be low conversion efficiency and high cost of the solar cells, but these drawbacks can be overcome by intense research. On the other hand, solar thermal technology is at its maturity stage. Depending upon the temperature needed, different types of solar collectors can be used. Table 2.3 gives information about different solar collectors, their temperatures, concentration factors, and power capacities.

The flat-plate collector (FPC) is the simplest one: solar radiation incident on a flat transparent surface is transmitted to an equal-size absorbing/collecting surface generally composed of Cu or Al metal. Cu or Al metal is preferred because of high thermal conductivity (Cu) and comparatively reasonable cost (Al) of the material. Construction of a flat-plate collector is simple: various parts of a FPC are shown in Fig. 2.1.

A riser made of several metal tubes is attached to a black metallic surface called the receiver surface and placed between a metal box and a glazed surface. The metal box is thermally insulated by a suitable insulator (for example, glass wool). The glazed surface is exposed to sun to receive solar flux. To receive maximum solar flux, the metal box is tilted at an angle from the horizontal that is about the latitude of the location/city/village where it is being installed. The incident solar flux passes through the glazing gets absorbed on the receiver surface. The heat is transmitted to the water inside the riser, and the hot water goes up from the riser to a storage tank. The storage tank is connected to the riser from both ends, that is, top and bottom. Circulation of water inside the riser kicks in as soon as hot water rises up from the bottom to the top of the riser and goes to the storage tank by a combined effect of thermo-siphoning and gravity. It is important to note that the larger the area of receiver surface, the larger would be the thermal energy received. The concentration factor of a FPC is 1 and a thermal power up to 1 MW can be

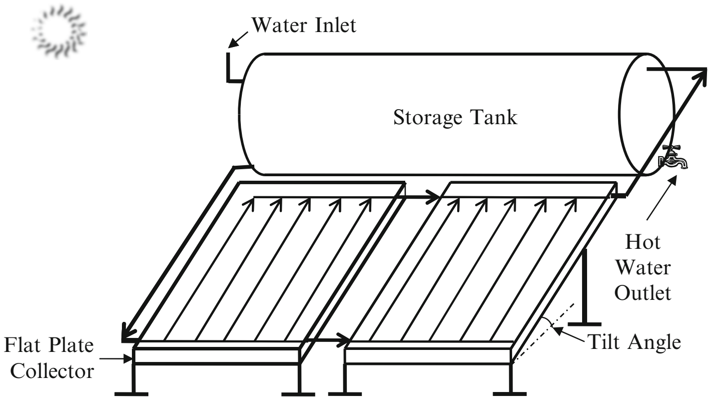

Fig. 2.1 A flat-plate collector system

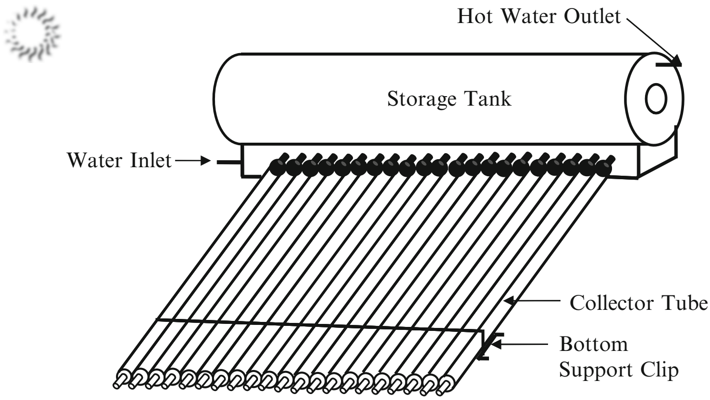

Fig. 2.2 Evacuated tube solar water heater

generated for a temperature range up to 200 °C by connecting flat-plate collectors in series. The other collectors shown are concentrating collectors. Their concentration factor, power, and operating temperature are higher. The application of solar energy in hydrogen production is discussed in the subsequent sections.

The vacuum-tube collector differs from the flat plate as it involves some tubes instead of a riser (Fig. 2.2). An evacuated tube is also shown in Fig. 2.3. An absorber plate gets heated when exposed to the sun transfers heat to a chemical via a heat pipe. The chemical tends to change phase from liquid to gas. Heat carried by the hot vapor/gas is then transmitted to water in the tank. Vacuum is created within the evacuated tube so as to minimize convective heat losses from absorber surface to ambient. The number of tubes can be increased or decreased depending upon the temperature of the hot water to be maintained. Some advantages include easy maintenance as tubes can be easily detached from the water heater.

Fig. 2.3 Evacuated tube

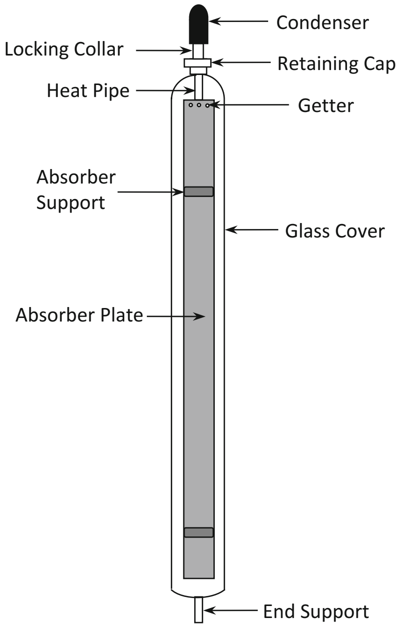

Table 2.4 Classification of geothermal sources

Temperature range	Application
Low (<90 °C)	Heating, cooling
Moderate (90–150 °C)	Heating, cooling, power generation
High (150–350 °C)	Heating, cooling, power generation, hydrogen production

Modified from Balta et al. [11]

In the present book, the input energy source to produce hydrogen is taken to be solar energy; therefore, a brief introduction to solar energy is presented in the next section.

-Geothermal. Geothermal energy is limited to appropriate geographic sites or locations where the resource is present; however, there are many such sites worldwide, spread over 24 countries with an operating potential of 57 TWh/year [22]. Geothermal energy is attractive for its ability to provide base load power 24 h per day. Extraction rates for power production will always be higher than refresh rates; reinjection helps restore the balance and significantly prolongs purpose only. Geothermal emissions are most significantly impacted by technology choices. Waste gases are more than 90 % CO_2 by weight [23], so if directly released, emissions will be high. Balta et al. [11] classified geothermal energy sources, based on temperature range for possible applications (Table 2.4).

It can be seen from Table 2.4 that the high geothermal resource temperature is about 350 °C, which is suitable for hydrogen production; however, recent research carried out by Landsvirkjun, Iceland's national power company, on deep drilling in

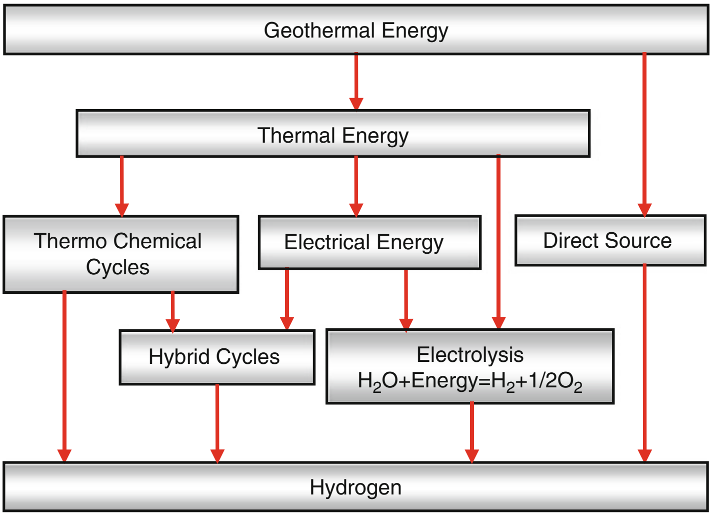

Fig. 2.4 Hydrogen production via geothermal energy (Modified from Balta et al. [11])

Iceland shows the possibility of extracting 500–600 °C of steam at a depth of 4–5 km for various applications, ranging from power production to hydrogen production. Presently, deep drilling is purely experimental, but it could become a possibility within the next decades [24–26]. Figure 2.4 shows various geothermal hydrogen production routes, which are mainly via thermal energy and direct application of geothermal energy.

Thermal energy application further depends upon the available temperature range. For example, if it is at a high temperature (350 °C), it can be used to provide heat in thermochemical cycles and hybrid cycles, and if it is in a moderate temperature range, electricity can be produced first, and it can then be used in electrolysis of water for hydrogen production. High temperature can also be used for high-temperature electrolysis of water whereas electricity can also be used in hybrid cycles. Some gases rich in hydrogen, for example, hydrogen sulfide (H_2S), also come from the geothermal well and can be used for hydrogen production. This route is shown as "direct source" in Fig. 2.4.

-Hydro. Hydroelectric power generation is an established technology that uses the potential energy of water to generate electricity. The main components of the hydropower plants are a dam/retaining wall, water turbine, and electrical generator. A dam or retaining wall is made across the width of a river so that the water level may rise on one side of the wall. On the other side of the dam/retaining wall, water turbines coupled with electricity generators are installed. The potential energy of water is then used to run turbines, and the turbines run generators and produce electricity. Water turbines are available in large variety, and selection depends upon the different water heads and flow rates. The Pelton wheel and Francis turbines are generally used for high water heads, and the Kaplan turbines can be used for low water heads.

Some intermediate water head turbines that can be used for both high and low water heads are Michel Banki and Deriaz turbines. The electricity produced is then supplied to the grid, from where it is distributed to its users. Mini hydro and hydel power stations can also be built to fulfill the electrical demands of a community living near small rivers and where the water head is not sufficient for a big hydropower plant. Hydro energy is essentially used to produce electricity, and then the electricity can be used for hydrogen production via electrolysis. Hydropower plants are more eco-friendly then thermal power plants as they cause less harm to the environment, but because these require very large civil structures and community relocation for those who live near the river, substantial public resistance sometimes occurs.

-Biomass. Biomass can also be used as an alternative as it has a large stored potential of renewable energy, which can be utilized to produce power by combustion or by thermochemical or biochemical conversion to liquid (ethanol, methanol) or gaseous fuels (methane, hydrogen) [27]. However, the inherent inefficiency of photosynthesis, which captures only a small percentage of solar energy reaching the Earth's surface, limits its usefulness as a major energy source [28]. Some high-yielding crops, for example, South American sugar cane, are already being used successfully as fuel sources, mainly for transport. Bioelectricity can be an important option in supporting electricity needs, particularly of rural populations in lower-income countries. The production of electricity using biomass has some health consequences, but these are much less than those from coal, oil, and natural gas. Wood sawdust and sugar cane bagasse are some general forms of biomass that can be used to produce electricity and hydrogen. Abudala et al. [29] analyzed exergetically a hydrogen production system based on biomass that uses wood sawdust and found the hydrogen yield reaches 80–130 g H_2/kg biomass. The biomass is introduced to a gasifier at an operating temperature range of 1,000–1,500 K. Also, a 4.5 kg/s steam at 500 K is used as the gasification medium.

-Wind. Wind mills and horizontal-axis and vertical-axis turbines are used to convert the kinetic energy of the wind into electricity. It is one of the more cost-effective forms of renewable energy with today's technology. The electricity produced by wind energy can be supplied to the grid. The technology is beneficial for locations where wind velocity is high, for example, the coastal and sub-coastal areas. For better functioning of a wind energy system, knowledge of the natural geographic variation in wind speed is important to smooth out fluctuations. Similar to the limitations of solar energy, wind energy generation is also affected by the intermittent nature of wind speed. Similar to hydro energy, wind energy also essentially used to produce electricity first and then the electricity can be used for hydrogen production.

-Tidal, Wave, and Ocean Thermal. Some other renewable sources are tidal, wave, and ocean thermal technologies that can produce electricity or can help reduce the electrical load of a power plant. Tidal energy utilizes the power of tide to produce electricity whereas wave energy systems use the waves formed in an ocean or sea. Oscillators are placed in the sea, and their oscillatory motion when waves come in contact with them is utilized to generate electricity. The ocean thermal technology uses the temperature difference between the upper and the deep lower layers of ocean water to generate electricity. The electricity produced by this technology may be utilized to produce hydrogen by electrolysis of seawater.

-Hybrid Renewable Systems. Hydrogen can also be produced by combining two or more renewable systems, for example, photovoltaic and wind [30, 31]. The two technologies are not competing with each other; rather, they are complementing and supporting each other. On one hand, the wind technology can be beneficial for off-sunshine periods; on the other hand, the solar photovoltaic technology can compensate for conditions of no wind during the daytime. This symbiotic behavior of the two technologies ensures a better and continuous supply of electricity to the electrolyzer to produce hydrogen. The excess power produced by the system can be stored in batteries and used in adverse conditions. Another example of the coupling of two technologies can be solar thermal and geothermal. The hot water from the geothermal sources can be further heated to a desirable temperature (approximately 550 °C) by using solar concentrating collectors; then, by using a high-temperature electrolyzer, hydrogen can be produced. One of the advantages of the hybrid renewable technology is to ensure a continuous supply of input energy, which when using these technologies individually sometimes can be challenging. The performance of such hybrid systems can be better than the systems that use the two technologies separately.

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