Chapter 2
Current Status: General

Kazunari Sasaki

Abstract This chapter describes recent progress in fuel cells and hydrogen technologies, especially in Japan where real commercialization of these technologies is underway, including fuel cell vehicles (FCVs) and buses, hydrogen fueling stations, residential and industrial fuel cell systems, as well as electrolyzers for hydrogen production from renewable power. Possible ways to realize a future carbon-neutral and carbon-free energy society are discussed in this chapter.

Keywords Fuel cell vehicles · Hydrogen fueling stations · Residential and industrial fuel cells · Types of fuel cells · Electrolyzer · Social demonstration · Transition to carbon-free society

2.1 The First Year of Hydrogen, 2015

The year 2015 will be marked in history as the year where the use of hydrogen as an energy carrier began in a full-fledged manner in our society. Fuel cell vehicles (FCVs) were released to the general market on December 15th 2014, representing a great step forward in our efforts to achieve zero-emissions from automobiles, which have generated huge quantities of harmful exhaust gases in the past [1]. Figure 2.1 shows the MIRAI FCV produced by Toyota Motor Corporation (see also Chap. 34). Other types of fuel cells are under development as shown in Fig. 2.2.

Comparing FCVs with electric vehicles (EVs), both of which emit no exhaust gas, EVs are currently superior in terms of the cost of fuel (electricity) and the convenience of being able to charge the EV at home. However, FCVs are capable of being driven much further than EVs without recharging, and FCVs require only around 3 min to refuel with hydrogen (compared with many hours of charging for EVs). Ideally, both together will contribute greatly to our escape from the dependency on

K. Sasaki (✉)
International Research Center for Hydrogen Energy,
Kyushu University, Fukuoka 819-0395, Japan
e-mail: sasaki@mech.kyushu-u.ac.jp

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Fig. 2.1 Automotive fuel cells: Toyota MIRAI FCV, handed over to Kyushu University President on March 25th 2015 as the first official commercially available university FCV in the world

petroleum-derived energy resources such as gasoline. "The-chicken-or-the-egg" discussions have been held over the establishment of the necessary hydrogen infrastructure for FCVs for many years. The volume of vehicle sales for a motor company is determined by consumers. However, it is difficult for energy suppliers to take a plunge and invest in hydrogen infrastructure (such as hydrogen filling stations) unless they know clearly how many FCVs will be sold (see Chap. 41). The impact of the launch of commercial sales of FCVs was indeed large, and businesses that had waited to see the sales numbers before acting are now beginning to enter the market. The advantages of advance entrance are also great, and future developments are expected to be led by the companies that are early adopters of this new technology. Construction of commercial hydrogen filling stations is underway in various parts of the country. Figure 2.3a shows the opening ceremony for the Kokura hydrogen filling station in Fukuoka prefecture, the second commercial hydrogen station supplying 70 MPa high-pressure hydrogen gas to open in Japan (see Chap. 40). Various attempts have been made to develop small-scale hydrogen filling stations to reduce system cost and to produce renewable hydrogen. For example, Fig. 2.3b shows a small-scale hydrogen filling stations which can produce and supply 35 MPa hydrogen gas onsite. While the hydrogen gas pressure is not sufficient to fully fill the FCV tanks, such a small system may be sufficient for small cities and local areas in an initial stage of FCV commercialization.

Research and development initiatives regarding hydrogen energy have been implemented globally for years. In Japan, improvements in the core fuel cell technology and peripheral hydrogen-related technologies were promoted actively with industry–academia–government collaborations. These collaborations led to the release of ENE-FARM, a fuel cell for residential purposes. Much of this success

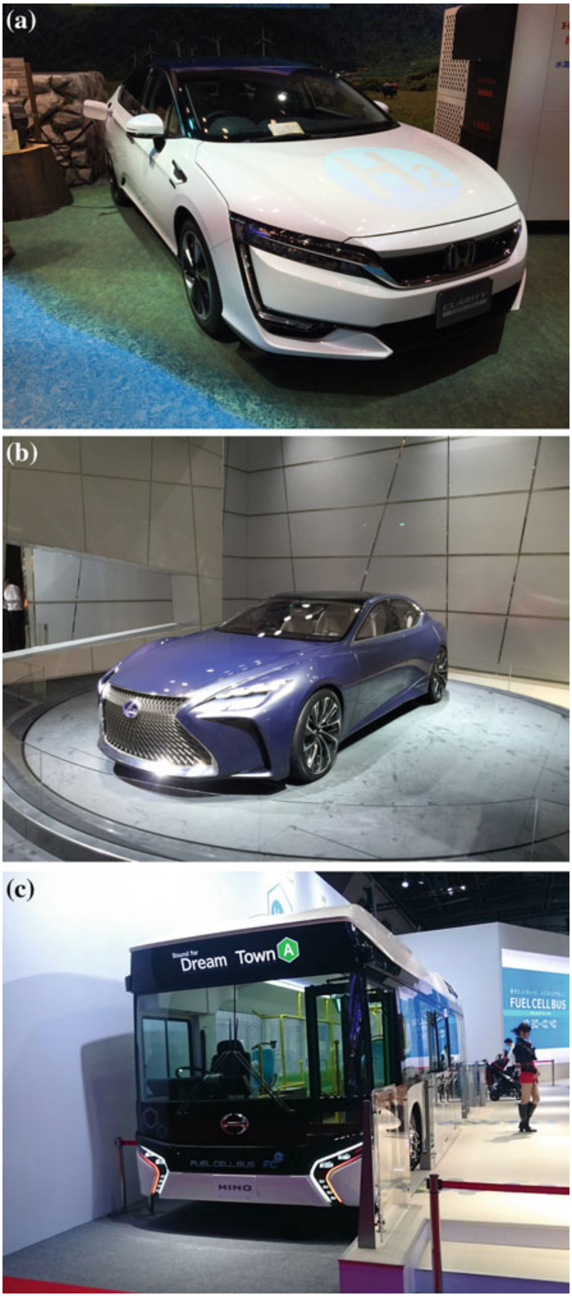

Fig. 2.2 Automotive fuel cells: **a** the Honda "CLARITY Fuel Cell" vehicle to be commercialized from March 2016, **b** the Toyota Lexus FCV, and **c** the Hino fuel cell bus, all exhibited in Tokyo Motor Show 2015

Fig. 2.3 Hydrogen filling stations: **a** the Kokura hydrogen filling station (stationary, 70 MPa), which was the second such station to open to the general public in Japan, on October 22, 2014; **b** the Fukuoka Prefecture hydrogen filling station (mobile, 70 MPa); and **c** a small-scale hydrogen filling station “Smart Hydrogen Station (SHS)” (35 MPa) developed by Honda and Iwatani exhibited in Tokyo Motor Show 2015

can be attributed to strategic measures that had continuity and prospects for commercialization, large-scale demonstrations of new technology developments followed by subsidy support. More recently, hydrogen has been given a clear position in Japan’s national energy policy as a secondary energy carrier next to electricity and heat within the Basic Energy Plan that was revised on April 11, 2014. The "Strategic Road Map for Hydrogen and Fuel Cells" was drawn up based on this new policy [2]. The document includes a future roadmap starting with the commercial release of ENE-FARM in 2009 and that of FCVs in 2015. Acceleration in commercialization and full popularization is expected as outlined in Japan's roadmap. Such roadmaps are still lacking in many other countries. Although the distributed quantity of hydrogen remains small, hydrogen is already being used in much larger quantities in industrial processes and so forth. If popularization of FCVs advances, it is expected that even the current hydrogen production level will be too low. Japan's roadmap, however, clearly describes medium- to long-term strategies to obtain CO_2-free hydrogen including mass quantity imports. Hydrogen, which is used in fuel cells that can directly convert the chemical energy of fuel into electricity unlike thermal engines, has the potential to bring about innovative and fundamental changes in the ways that society is powered by energy.

2.2 Electrochemical Energy Conversion: Fuel Cells

Fuel cells are central components of hydrogen energy systems (see Part IV). They are similar to conventional batteries and rechargeable batteries such as lithium ion batteries that supply electricity. All of these electrochemical devices are centered around electrolyte layers through which only specific ions are able to pass. However, while batteries contain the chemicals that serve as the energy source inside the electrochemical devices, fuel cells do not contain this chemical energy inside the device. Therefore, the substance that functions as the energy source needs to be supplied to fuel cells in order to generate electricity. They will keep generating electricity as long as the fuel is supplied. In terms of functionality, they are actually more closely related to power generators than batteries.

There are many materials through which only specific ions can pass, and fuel cells operate at temperatures at which these ions can diffuse easily. Known mobile ions include hydrogen ions or protons (H^+), oxygen ions (O^{2-}), carbonate ions (CO_3^{2-}), and hydroxyl ions (OH^-). Different types of fuel cells are categorized in Fig. 2.4, according to the type of mobile ions that are utilized [3–5]. What is common among these different types of fuel cell is that there are electrodes on both sides of the electrolyte, fuel oxidation reactions occur at the anode, and oxygen reduction reactions occur at the cathode.

Polymer electrolyte fuel cells (PEFCs) and solid oxide fuel cells (SOFCs) are representative fuel cells for which technological development is being advanced for practical applications and full popularization. The principle of fuel cells was demonstrated in 1839 by Sir William Grove in Britain [6], whilst Baur et al. demonstrated fuel cell technology using a solid electrolyte at the Swiss Federal Institute of Technology (ETH) in 1937 [7]. Figure 2.5 shows the operational principle for both of these types of fuel cells. In PEFCs (widely used in FCVs and residential fuel cell units), hydrogen gas is supplied to the anode (fuel electrode)

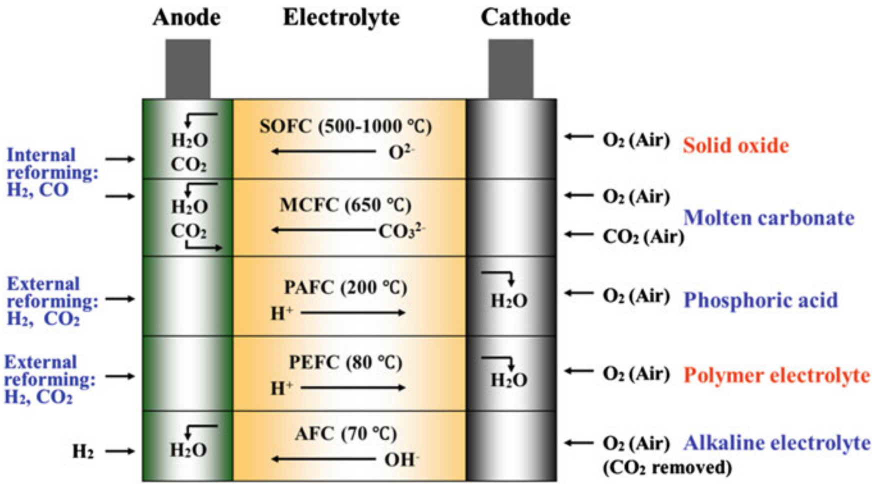

Fig. 2.4 Different types of fuel cell [3]

side as fuel (Fig. 2.5a). The hydrogen molecule is dissociated into protons and electrons at the electrode surface, which contains catalysts such as platinum. Since the electrolyte allows only the protons to pass, the protons diffuse through the electrolyte membrane. However, electrons cannot pass through the electrolyte and therefore flow through the external circuit via the electronically conductive electrode. Air is supplied to the other electrode, where the oxygen molecule, protons that have passed through the electrolyte membrane, and electrons that have arrived via the external circuit react together to form water (H_2O). Although the same reaction occurs when hydrogen gas and oxygen gas are mixed and ignited, water is formed in fuel cells only for the amount of electrons that have run through the external circuit of the fuel cell. That is, current flows from the air electrode (cathode) to the fuel electrode (anode). As a consequence, electricity can be generated by supplying hydrogen.

Using electrolyte materials in which oxygen ions act as charge carriers instead of protons is also possible. In the SOFC, as shown in Fig. 2.5b, air is supplied to the cathode in the same fashion as the PEFC. Since the SOFC uses an oxygen ion conductor, oxygen molecules in the air gain electrons from the cathode surface and dissociates into oxygen ions. The oxygen ions formed here diffuse through the electrolyte layer. At the anode, these oxygen ions and hydrogen molecules react to form water (steam), generating electrons. These electrons pass through the external circuit and are used in the reactions that take place at the air electrode. The overall SOFC reaction in which electricity is generated by supplying hydrogen is therefore identical to that of the PEFC.

Furthermore, water (steam) is formed on the cathode in PEFCs, while it is formed on the anode in SOFCs. In PEFCs, the oxygen gas, which is initially present in the air at a concentration of only 20 %, is further diluted by the steam that is

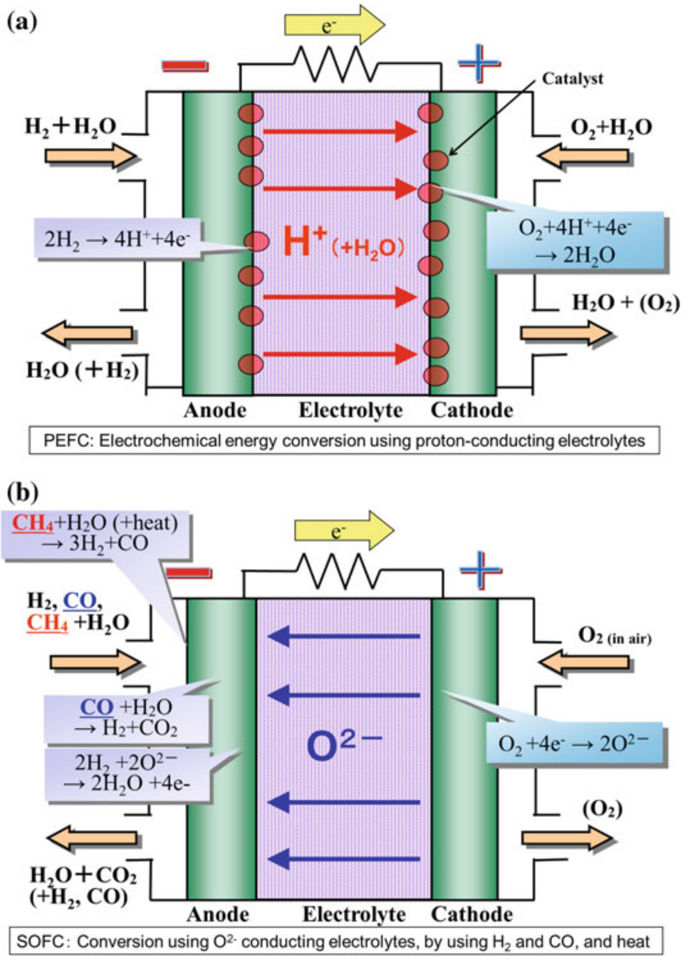

Fig. 2.5 Operational principles of **a** polymer electrolyte fuel cells (PEFCs) and **b** solid oxide fuel cells (SOFCs)

formed. In SOFCs, the steam formed on the fuel electrode is used in the steam reforming reactions ($CH_4 + H_2O \rightarrow 3H_2 + CO - 206$ kJ/mol) with hydrocarbon fuels such as methane and in the water shift reactions ($CO + H_2O \rightarrow H_2 + CO_2 + 41$ kJ/mol). These reactions generate more hydrogen gas. The steam reforming reaction is an endothermic reaction, and thus it is possible to form hydrogen by using the heat generated inside the fuel cell and extract more electricity. In addition, the electrochemical reactions at the electrodes occur more quickly with small voltage losses as the operating temperature is higher. These are the reasons why SOFCs have better electricity generation efficiencies than PEFCs.

As shown in the operational principles for fuel cells, there is no process that "burns" the fuel during fuel cell power generation. In thermal engines, the chemical energy of the fuel is converted to thermal energy through combustion, and then the thermal energy is converted into electrical energy via kinetic energy in turbines as the generators rotate. In comparison, fuel cells convert chemical energy directly into electrical energy. Fuel cells therefore are capable of *direct conversion of energy from the source*, and the fuel to drive the electrochemical reactions is hydrogen. Such technology represents an innovative energy conversion method to extract electricity with high efficiency *without burning*. This is a huge accomplishment for humans, who have addressed economic development needs in the past by burning considerable quantities of fossil energy resources.

The operational temperatures for various types of fuel cell are shown in Fig. 2.4. These data reflect the temperatures at which the electrolytes show sufficient ionic conductivity. High ionic conductivity leads to higher cell voltage, which is the driving force for moving ions against the electrical resistance, and low conductivity leads to voltage losses in fuel cells. Electrochemical reactions will become slower if the temperature is too low, and this will also cause voltage losses in fuel cells. Conversely, problems such as performance decreases and cell degradation start to appear if the operational temperature is too high. The optimal operational temperature is therefore determined by the balance between both of these considerations.

Typical materials used in fuel cells are summarized in Table 2.1. In general, the issue is to activate the electrochemical reactions in fuel cells that operate at low

Table 2.1 Typical materials used in fuel cells

	Polymer electrolyte fuel cells (PEFC)	Alkaline fuel cells (AFC)	Phosphoric acid fuel cells (PAFC)	Molten carbonate fuel cells (MCFC)	Solid oxide fuel cells (SOFC)
Operational temperature (°C)	20–80	20–90	160–210	600–700	600–1000
Fuel gas	H_2, alcohol	H_2	H_2	H_2, CO	H_2, CO, C_xH_y
Oxidant	Air, O_2	Air, O_2 (without CO_2)	Air, O_2	Air (+CO_2)	Air
Electrolyte materials	Cation exchange membrane	KOH solution	Concentrated H_3PO_4 solution	$(Li,K)_2CO_3$	$ZrO_2(Y_2O_3)$ $ZrO_2(Sc_2O_3)$ $CeO_2(Gd_2O_3)$ La(Sr)Ga(Mg) O_3
Electrode materials, electrocatalyst	Pt/C Pt–Ru/C Pt–Co/C	Pt-based catalyst, Ni–Al, transition metal catalyst	Pt-based catalyst	Ni-based porous plate	La(Sr)MnO_3 La(Sr)Co(Fe)O_3, Ni–$ZrO_2(Y_2O_3)$
Stack component materials	Carbon paper, corrosion-resistive alloy	Ni	Carbon plate, Teflon, SiC	Ni alloy, stainless steel, $LiAlO_2$	Cr-based alloy, stainless steel, La(Sr)CrO_3

temperatures, and thus, e.g., platinum-based catalysts are inevitably used. In fuel cells that operate at higher temperatures, nonprecious catalysts such as Ni can be used. Since the electrolytes exhibit high ionic conductivity, they contain the conductive ions in large quantities. The proton conductor usually used in PEFCs is strongly acidic, whereas alkaline electrolyte fuel cells use strongly basic electrolyte materials. Thus, corrosion resistance is a challenge that needs to be solved by the deployment of peripheral materials. Ti-based materials are often used as separators in PEFCs. However, the materials that can be used for fuel cells that operate at high temperatures are limited because of limitations in regards to, e.g., oxidation and high-temperature tolerance, especially near the air electrode.

2.3 Hydrogen Utilization Technologies

As is clear from the operational principles, fuel cells comprise technology that can generate electricity with high efficiency and the reactions involve hydrogen. Hydrogen itself is the most abundant element in nature and is contained in various fuels in the form of chemically coupled hydrogen atoms. Therefore, if a society utilizing hydrogen can be cultivated, it will be possible to use various energy sources containing hydrogen. Energy diversification would be very helpful in countries like Japan, which depend on imports for most energy resources, and it would be of value to many countries at the national level in terms of energy security [8, 9].

The fundamental social values of deploying hydrogen energy technology with fuel cells at the core can be summarized as follows:

- Fuel cells can generate electricity efficiently without burning fuel (via electrochemical reactions involving hydrogen).
- When hydrogen gas is used as the fuel, only water is formed as the byproduct (however, CO_2 is generally emitted when hydrogen gas is produced).
- If vehicles can be run on hydrogen, the automotive industry and motorized communities will no longer depend on crude oil and will become sustainable (key industries and our daily transportation requirements will no longer depend on politically sensitive specific natural resources).
- Electricity obtained from fluctuating natural energy sources can be stored in the form of hydrogen (the capacity to accept electricity from renewable energy increases as it is stored as hydrogen).

As shown in Fig. 2.6, this technology has the potential to change how energy is supplied. When seen from the perspective of energy supplying businesses, this would mean that gas companies and petroleum companies will be indirectly supplying and selling electricity, as it can be supplied from city gas or LP gas when ENE-FARM technology is used, for example. If hydrogen is used as the fuel for vehicles, several businesses such as petroleum companies, which manufacture and

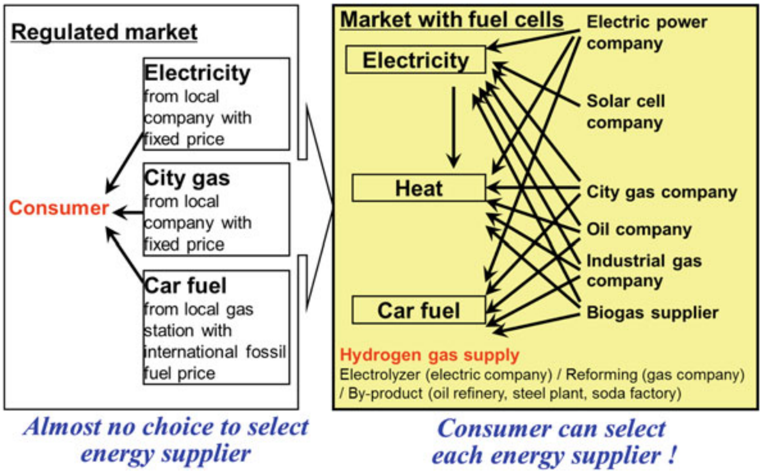

Fig. 2.6 Fuel cells and hydrogen energy as seen from the viewpoint of consumers

sell hydrogen, city gas companies, which can produce hydrogen from city gas, and industrial gas companies, which deal in hydrogen, will be selling fuel for vehicles. If hydrogen can be formed through electrolysis of water, power companies can also sell this fuel for automobiles. When seen from the perspective of consumers, there will come a time when they have more options available when purchasing energy for their residential and transportation needs. In the future, when liberalization helps to eliminate monopolies or oligopolies, new forms of energy technology will likely open "Pandora's box" by facilitating the removal of barriers among industries and business categories. Since hydrogen can be formed by anyone, it is a technology with the potential for use in any industry.

There are various different possible applications for fuel cells. Applications that have already been commercialized in Japan include residential fuel cells (see Fig. 2.7, which shows various types of ENE-FARM units) and FCVs. The former was released in 2009, and the cumulative number of units sold exceeded 150,000 in December 2015 with the support of governmental subsidy measures (see Chap. 35). This high level of adoption was also fostered by cost reduction measures on the part of concerned businesses as well as increased concern among residents who experienced planned outages that occurred immediately after the 2011 Tohoku Earthquake Disaster. The national Japan Revitalization Strategy has specified measures to achieve popularization of 5.3 million ENE-FARM units by around 2030. This number corresponds to 10 % of all the households in Japan, and it is expected that this would result in reductions of CO_2 emissions from Japan by several percent [2]. Such technology is becoming popularized widely as "a hot-water supply system that can also generate electricity" in place of the hot water supply systems that are widely installed now. Although installation of ENE-FARM units is limited to detached residences for the time being, measures to install them in

Fig. 2.7 Various types of ENE-FARM fuel cell units for residential use. The ones shown here are installed on Ito Campus at Kyushu University

housing complexes such as apartment blocks are being launched. In this case, they need to be installed within the maintenance space or on the balcony, and thus, further miniaturization of such systems is inevitable. The PEFC ENE-FARM type represents more advanced technology, whereas miniaturization of hot water tanks for SOFC systems is likely possible given that the outlet hot water temperature is high. The SOFC ENE-FARM type whose system can be simplified also has a high potential for miniaturization, and technological developments in these areas are being conducted in parallel.

Regarding FCVs, commercially released in December 2014, three major domestic motor companies in Japan have plans for additional releases, and joint development projects have been launched with major motor manufacturers overseas. These FCVs are global products, and popularization in the state of California, U.S., and Europe, where there are strong demands for zero-emission vehicles, can be expected. Development of fuel cell buses (see Fig. 2.8) is also underway in addition to the development of smaller FCVs. A target release date of 2016 has been set for fuel cell buses. In Europe, social demonstrations, and so forth have been conducted on buses with strong public benefits, and product development is being accelerated in Japan for the Tokyo Olympics and Paralympics to be held in 2020. While fuel cell buses are thought to represent a fuel cell system equivalent to a few FCVs, they are also expected to function positively in terms of hydrogen filling station business as operational patterns can be easily determined for buses and the hydrogen charging quantities per vehicle will be large. Such buses may also play a critical role as “safe stations” to support the life lines of local residents and information bases that can offer transportation services, electricity, heat, water, and

Fig. 2.8 Fuel cell bus (FC bus)

communication access. They may even be able to provide electricity for shelters and assist in evacuations.

Importantly, future applications of fuel cells will not just be limited to ENE-FARM or FCVs. With commercial releases planned in 2017, as specified by Japan's national roadmap, industrial-scale fuel cells are expected to deliver environmentally friendly benefits in industrial fields, which account for more than half the demand for city gas. However, in this field, they will compete with existing thermal engines such as gas engines, diesel power generators, and microgas turbines. Therefore, requirements for low system costs and durability will be high. Commercialization at the level of several kilowatts to several hundreds of kilowatts, which is advantageous for high efficiency, should also be expected. For example, an 250 kW-class industrial fuel cell system shown in Fig. 2.9a with an electric efficiency approaching 55 %-LHV under demonstration in Kyushu University will be commercialized from 2017 (see Chap. 36). Commercialization of industrial fuel cells has progressed relatively rapidly in the U.S., where power outages often occur. Popularization began in data centers and information and communications technology (ICT)-related facilities where even a momentary outage is unacceptable. In Japan, where liberalization of the energy industry is continuing, commercialization of SOFC-based systems is being accelerated. If they continue to grow in size, commercialized power generation units will be able to serve as replacements for existing thermal power generators.

A "triple combined cycle," which combines fuel cells with gas turbines and steam turbines, is expected to become the sole technology that can exceed the power generation efficiency of the "(double) combined cycle" that is currently utilized in the latest current thermal power generation technologies. The extreme power generation capabilities of the new technology may even be able to achieve power generation efficiencies higher than 70 % (see Chap. 37). It is also important

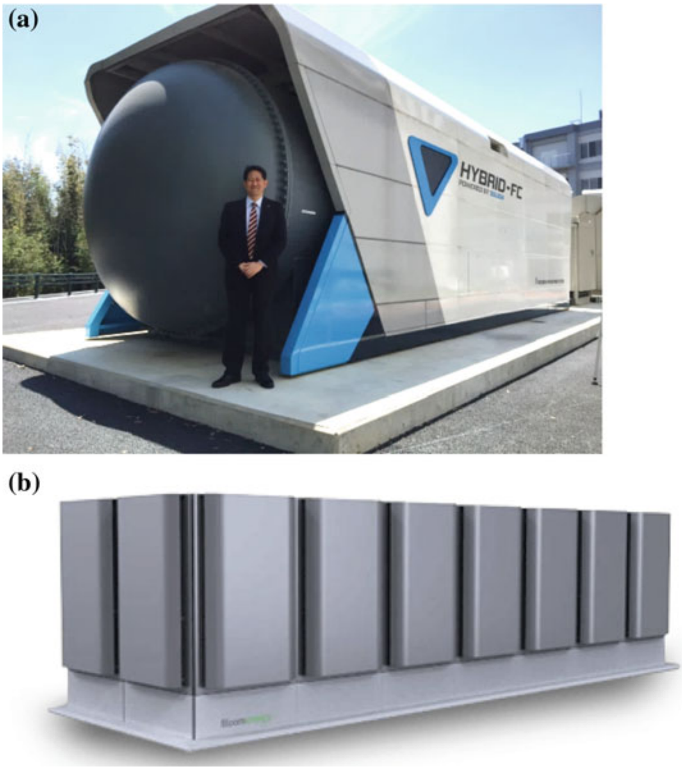

Fig. 2.9 Industrial-scale fuel cells **a** manufactured by Mitsubishi Hitachi Power Systems in Japan and **b** by Bloom Energy in the U.S

to note that coal, which exists in rich deposits, could be used as a power generation fuel in addition to natural gas. There already are some efforts in place to develop power generation systems that combine fuel cells driven by gasified coal with gas turbine and steam turbine systems. Further efforts should be made to increase the energy conversion efficiency of fuel cell systems [10].

The use of various types of fuels could be another important challenge. In particular, the application of renewable-sourced biogas and biofuels can realize carbon-neutral power generation (see Chap. 38).

Besides these applications, fuel cells are beginning to be used in forklift trucks in the U.S. Compared to the storage battery-type forklifts, which require a long time for charging, the hydrogen charging time for the fuel cell forklifts is much shorter. While expectations are high for hydrogen PEFCs, they will require hydrogen filling stations. If high output development becomes possible, there will be an opportunity to deploy direct alcohol-type fuel cells whose fuel is alcohol, which is easier to handle. Power supplies for mobile devices and portable power generators are also potential applications with high expectations. While direct alcohol-type fuel cells may reach the commercial market faster than other technologies, development of SOFC-type devices that can use various different fuels are also being developed (see Chap. 39).

Demands for decarbonization measures are not limited to vehicles and buses. Low carbonization is also desired in ships; hence, there is a chance that such technology could soon be deployed on ocean going vessels. Research and development activities aimed at utilizing hydrogen fuel cells in aircrafts are also being conducted. In aerospace applications, where such technologies have been deployed in space shuttles and the space station, the acquisition of energy supplies during the periods when photovoltaic cells (e.g., in the shadow of the earth) cannot be used has been a challenge. Compared to storage batteries, which become heavier in proportion to the capacitance, hydrogen energy storage, which uses the electricity generated by the photovoltaic cells for electrolyzing water to store hydrogen, can lead to weight reductions, and this may be an option that can meet the high expectations for performance in aerospace applications. Even among the general public, hydrogen energy technology will become more important as an energy storage technology if measures to store the electricity generated by fluctuating renewable energy sources as hydrogen can be fully adopted (see Part II).

2.4 Hydrogen Production and Storage Technologies

In a society that utilizes hydrogen, how hydrogen is produced, stored, and transported to the place of use will be key points. Hydrogen gas is essential for FCVs, and it is already widely produced in industrial fields. Specifically, oil refineries handle large volumes of hydrogen gas, which is an essential substance used for example during the desulfurization processes. FCVs require hydrogen gas with high purity to prevent catalyst deterioration, thus the gas has to be supplied to FCVs after purification, according to international standards. Steelworks use large quantities of coal in blast furnaces, and the trace content of hydrogen contained in the coal comes out as hydrogen gas in large volumes when the coal is steamed. Therefore, it should be possible to sell this byproduct gas as fuel for FCVs if it is purified, thereby adding value to such industries. Furthermore, soda electrolysis generates large volumes of hydrogen gas as byproducts during caustic soda production, and this too is a potential source for FCV fuel. However, hydrogen gas from these processes is already used widely in other industrial processes. Another potential source for fuel is through the production of hydrogen gas by having city gas and steam react at a high temperature of about 700 °C (i.e., steam reforming, see Chap. 8). In this case, the city gas infrastructure can be utilized as it is. This could enable hydrogen gas production at a relatively low cost, but it will also require maintaining the reformers at high temperatures in order to produce the hydrogen.

Hydrogen can also be formed through water electrolysis using alkaline electrolytes or solid polymer electrolytes (see Chaps. 9 and 10). In these cases, the existing electricity supply network can be utilized as energy transportation

Fig. 2.10 Water electrolysis-type hydrogen filling station (Ito Campus, Kyushu University)

infrastructure (see Fig. 2.10, which shows a water electrolysis-type hydrogen filling station). Efficiency levels for water electrolysis are approximately 70 % with alkaline water electrolysis and 80 % with PEFC-type water electrolysis (see Fig. 2.11, which shows a PEFC-type water electrolysis system installed inside the hydrogen filling station). While the price for mass production of hydrogen will be high, there is the operational flexibility to produce only the amount of hydrogen that is necessary at the time when it is needed. This requires no shipments and this technology is suited to local small-scale hydrogen production and supply.

Fig. 2.11 Polymer electrolyte fuel cell (PEFC)-type water electrolysis system (inside the hydrogen filling station at Kyushu University)

In the medium- to long-term outlooks, establishment of more efficient, CO_2-free hydrogen production methods with lower costs are highly desirable. Reverse operation of SOFC power generation (via solid oxide electrolyzer cells; SOECs) is expected to deliver even higher conversion efficiencies than can be currently achieved with the PEFC-type (see Chap. 11). In addition, it is also expected that mass imports of hydrogen gas produced from unused resources overseas will be available when producing CO_2-free hydrogen. For example, hydrogen production by electricity using inexpensive electricity from hydroelectric power plants overseas, production of hydrogen gas from brown coal or natural gas taken from small-scale gas fields, and so forth are all expected to allow for the import of CO_2-free hydrogen (carbon offsets via underground carbon capture and storage technologies may be needed in some situations). In addition, if direct production of hydrogen via photocatalysis and other technologies becomes possible in the far future, we will be able to create a renewable hydrogen circulation society, although challenges still remain regarding conversion efficiencies, durability, and scale increases (Chap. 12).

The technologies to store and transport the hydrogen gas acquired in such ways will be the key to the successful realization of a hydrogen-fueled society (see Part III). During the development processes for FCVs, researchers tried various technologies for hydrogen production and hydrogen storage for automobiles. Trials using on-vehicle gasoline reforming, alcohol reforming, hydrogen storage as liquid hydrogen or in hydrogen storage materials, and incorporation of the hydrogen storage system inside the tank were all considered. Eventually, it was decided to store high-pressure hydrogen gas for the fuel cells of FCVs. This fuel is usually

Fig. 2.12 Hydrogen tanks for high-pressure hydrogen storage (inside the hydrogen filling station at Kyushu University)

stored in high-pressure tanks at hydrogen filling stations (see Fig. 2.12, which shows a high-pressure hydrogen storage tank at the hydrogen filling station). However, it is important to note that liquid hydrogen or liquefied hydrogen may be more advantageous to use when hydrogen is stored or transported in large quantities. There are examples of such use in rocket fuels. In regards to hydrogen transport in liquid form, existing fuel transportation vehicles and infrastructure can be used for liquid hydrogen as well as for the storage of chemical substances that are rich in hydrogen atoms such as organic hydrides. Further advancements are expected in hydrogen storage technologies that employ alloy-type or complex-type materials with a high capability for hydrogen storage. Carbon-based materials with large surface areas to adsorb hydrogen may also be applicable. At the same time as the development of hydrogen storage materials, technological developments regarding hydrogen carriers appropriate for mass hydrogen storage are being implemented. The expectations are high for substances that contain many hydrogen atoms and have high energy densities such as ammonia and methylcyclohexane. In this case, measures to ensure safety and security including social acceptance will be inevitable for societies that deploy such substances as part of the overall energy system.

2.5 Prospects of a Hydrogen Society

The fundamental values that are derived from using fuel cells and hydrogen energy are unequivocally tied to efficient energy conversion without combustion. Particularly for Japan, where fossil fuel imports amounted to 27 trillion yen in 2013 [11], the deployment of fuel cells that can efficiently use various hydrogen-atom-containing energy resources is expected to result in significant energy savings. If we can reduce the large sums of financial capital that are expended in Japan on energy, the impact will be immeasurable. At present, approximately 88 % of electricity is provided by thermal power generation, and anticipation is high for the role of fuel cells as alternatives to thermal power plants for both residential and industrial purposes including power generation.

If plans are to continue to use thermal power generation systems to provide most of the country's electricity for a while, then the use of hydrogen in the power generation field will be important. In terms of power generation efficiency, electrochemical energy conversion processes (fuel cells) that directly convert fuel into electricity are intrinsically better than the thermal energy conversion process that burns the fuel. However, it will still take some time to develop larger fuel cell systems. In the meantime, the potential of hydrogen to reduce CO_2 emissions can be fully exploited if hydrogen energy sources can contribute to the quantity aspect of power generation in addition to the quality aspect (power generation efficiency). For example, hydrogen can sometimes be mixed into fuel sources at thermal power plants, and this could have benefits of CO_2 emission reductions corresponding to the amount of added hydrogen. However, hydrogen gas also has high ignitability and too much of an increase in combustion temperature will lead to increased emissions of NO_x, which can then result in deteriorated efficiencies if steam needs to be added to take care of these emissions (see Chap. 25). In the medium- to long-term view, a hydrogen-fueled society in which hydrogen gas is used in quantity will involve the utilization of CO_2-free hydrogen sources for power generation.

Furthermore, as specified in the basic energy plans of not only Japan but also many other countries, there are set goals to expand the use of renewable energy. However, imbalances between the demand and supply for electricity can lead to large-scale outages in the worst-case scenario owing to frequency fluctuations or other reasons. Therefore, it is difficult to accept highly fluctuating electricity originating from natural energy unless energy storage functions are provided, even if the power grid is made more robust. In regions where more renewable energy power generation systems have been installed, power generation levels could exceed power usage levels as more, e.g., photovoltaic cells come into full operation during periods with less power demand. To ensure stable supplies of electricity, energy storage technology that can function as a buffer during energy fluctuations will be necessary in addition to a thicker power grid. Although pumping-up power plants can store energy at a large scale, it takes a long time, often more than a decade, for such plants to proceed through the planning phase to the installation and operation phases. Alternatively, lithium ion batteries and NaS batteries can be used to store energy with high efficiency, but these technologies are associated with high costs when storing energy in large quantities over long periods of time.

A promising technology, shown in Fig. 2.13, is water hydrolysis-type hydrogen filling stations for FCVs that can serve as "energy storage stations." These stations store electricity by converting it into hydrogen through water electrolysis reactions during times when there is too much electricity being generated by renewable energy infrastructure. It is also possible to sell the hydrogen gas made from the excess electricity as fuel for FCVs thereby generating additional value for the product. By converting the stored hydrogen gas back into electricity and releasing it into the power grid, it would be possible to store the electrical energy in mass. In this case, the total efficiency of this energy storage system would be determined by the product of the efficiency of the water electrolysis system and the efficiency of the fuel cell system, and therefore, efforts to further improve the efficiency of both systems will be inevitable. However, the costs will start to change if hydrogen gas is produced from excess electricity that cannot be released into the power grid. If electricity can be converted not only to hydrogen but also to methane for mass energy storage, the entire existing city gas infrastructure can become an energy storage network. It would be desirable to have hydrogen energy contribute more to the power system as a part of a comprehensive energy storage network that works in combination with energy storage technology that employs hydrogen-rich energy carriers.

As discussed above, while technical innovation is steadily being advanced to facilitate a society in which hydrogen is widely used, one barrier that remains is social acceptance (see Chap. 42). While awareness of hydrogen and fuel cell

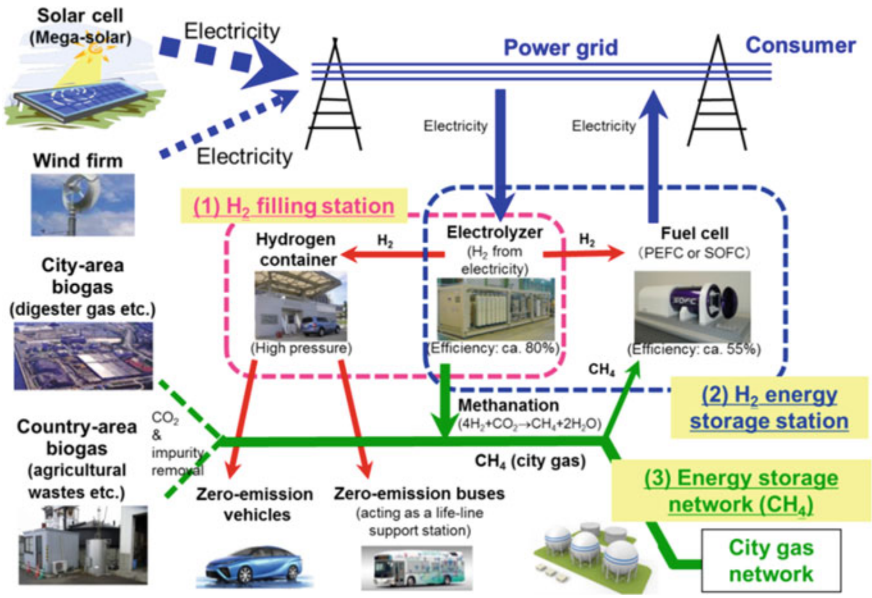

Fig. 2.13 Hydrogen energy technologies for renewable energy storage

technology has improved dramatically because of the commercialization and popularization of FCVs and ENE-FARM residential units, high-pressure hydrogen gas up to 70 MPa is still a fuel that is difficult to handle from the viewpoint of the general public. Safety measures and their technological principles in using high-pressure hydrogen gas are essential in designing and operating hydrogen energy systems such as FCVs and hydrogen filling stations (see Chap. 43).

The public's understanding of the benefits of hydrogen technology will greatly affect how well hydrogen and fuel cells are utilized within society. Ideally, efforts to improve such awareness should address the benefits to the environment as well as to social systems. In doing so, we will be able to realize the hydrogen society sooner and accelerate measures for practical applications. The "Smart Fuel Cell Demonstration Project" is part of an international strategic zone program being implemented at Kyushu University in order to demonstrate hydrogen technologies to the public. As shown in Fig. 2.14, an attempt is being made to simulate the type of "hydrogen society" that will actually be realized around 2030 using hydrogen and fuel cells on the entire Ito Campus at Kyushu University by 2015. This "society" uses approximately 1/30,000 of the annual electricity consumption for the whole nation. During the actual introduction and operation of FCVs, hydrogen filling stations, large-scale fuel cells, residential fuel cells, and so forth, we plan to examine the technical issues that are encountered when building a hydrogen society. Furthermore, best practices will be developed for control systems and social systems, whilst visions surrounding the use of hydrogen energy will be studied. Coordination with other related technologies will be inevitable as hydrogen

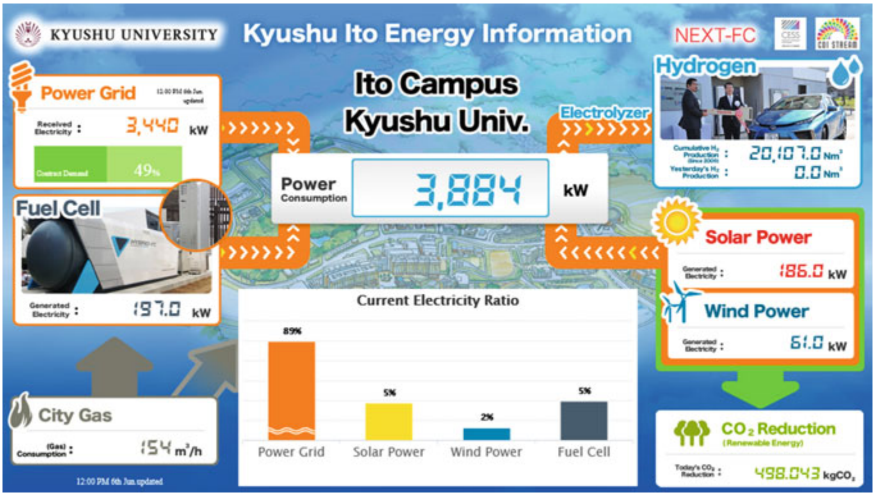

Fig. 2.14 "Hydrogen Campus" where fuel cells and hydrogen energy technologies are fully adopted

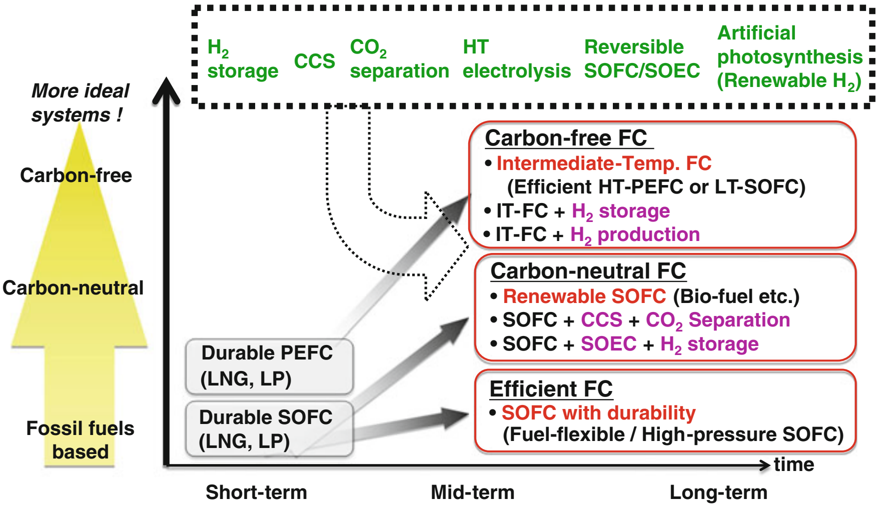

Fig. 2.15 Energy technologies related to fuel cells

energy technologies are not isolated systems (see Fig. 2.15; coordination with peripheral technologies; CCS: Carbon Capture and Storage), but we hope that the system will eventually be able to evolve to a total energy system that is centered on fuel cell technology.

Hydrogen energy technology has the potential to start a revolution that will affect the foundations of the current energy society. As the era of widespread coal and petroleum use lasted for more than a century, it will be necessary to think of hydrogen energy in units of 100 years. As the "first year of hydrogen" has come in 2015, further technological innovations for the next generation as well as the following generation that are based on technological developments over the past several decades will most definitely be forthcoming. Because energy technology development takes place over the long term, training of the next generation human resources to support it will be strategically important. In the future, it will also be necessary to foster skilled human resources that are capable of leading the world and implementing new energy policies as international development and standardization continue (see Chap. 44).

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