Chapter 5
Hydrogen: Driving Renewable Energy

Hydrogen can be found in many organic compounds other than water. It is the most abundant element on Earth, but it does not occur naturally as a gas. It is always combined with other elements, such as with oxygen to make water. Once separated from another element, hydrogen can be burned as a fuel or converted into electricity. A fuel cell uses the chemical energy of hydrogen or another fuel to cleanly and efficiently produce electricity. If hydrogen is the fuel, electricity, water, and heat are the only products. Fuel cells are unique in terms of the variety of their potential applications; they can provide power for systems as large as a utility power station and as small as a laptop computer.

5.1 Introduction

Hydrogen can be considered the simplest element in existence. An atom of hydrogen consists of only one proton and one electron. It is also the most plentiful element in the universe and in the Earth's crust. Despite its simplicity and abundance, hydrogen does not occur naturally as a gas on Earth and must be manufactured—it is always combined with other elements in compound form such as water, coal, and petroleum. Water, for example, is a combination of hydrogen and oxygen (H_2O). This is because hydrogen gas is lighter than air and rises into the atmosphere as a result.

Hydrogen has the highest energy content of any common fuel by weight, but it has the lowest energy content by volume. It is the lightest element, and is a gas at normal temperature and pressure. Once separated from other elements, hydrogen can be burned as a fuel or converted into electricity.

Hydrogen is also found in many organic compounds, notably the *hydrocarbons* that make up many of our fuels, such as gasoline, natural gas, methanol, and propane. Two of the most common methods used for the production of hydrogen by separating it from hydrocarbons are *electrolysis* (or water splitting) and application of heat, known as *steam reforming*. Steam reforming is currently the least

B. Zohuri, *Hydrogen Energy*, https://doi.org/10.1007/978-3-319-93461-7_5

expensive method for producing hydrogen, and, currently, most hydrogen is made this way from natural gas. It is used in industries to separate hydrogen atoms from carbon atoms in methane; however, because methane is a fossil fuel, the process of steam reforming results in greenhouse gas emissions, which is linked to global warming. The other method for the production of hydrogen is electrolysis, which involves passing an electrical current through water to separate water into its basic elements: hydrogen and oxygen. Hydrogen is then collected at the negatively charged cathode and oxygen at the positive anode. Hydrogen produced by electrolysis is extremely pure, and results in no emissions since electricity from renewable energy sources can be used. Unfortunately, electrolysis is currently a very expensive process.

There are also several experimental methods of producing hydrogen such as photo-electrolysis and biomass gasification. Scientists have also discovered that some algae and bacteria produce hydrogen under certain conditions, using sunlight as their energy source.

5.2 Hydrogen as an Energy Carrier

Hydrogen can be considered a clean energy carrier similar to electricity. Hydrogen can be produced from various domestic resources such as renewable energy and nuclear energy. In the long-term, hydrogen will simultaneously reduce the United States dependence on foreign oil and the emission of greenhouse gases and other pollutants.

Hydrogen is also considered as a secondary source of energy, commonly referred to as an energy carrier. Energy carriers are used to move, store, and deliver energy in a form that can be easily used. Electricity is the most well-known example of an energy carrier.

Hydrogen as an important energy carrier in the future has a number of advantages. For example, a large volume of hydrogen can be easily stored in a number of different ways. Hydrogen is high in energy, yet an engine that burns pure hydrogen produces almost no pollution. It can be used for transportation, heating, and power generation in places where it is difficult to use electricity. In some instances, it is cheaper to ship hydrogen by pipeline than sending electricity over long distances by wire.

Currently, hydrogen is mainly used as a fuel in the United States National Aeronautics and Space Administration (NASA) space program, as illustrated in Fig. 5.1. Liquid hydrogen has been used to propel space shuttles and other rockets into orbit since the 1970s, while hydrogen fuel cells power the electrical systems of the shuttle, producing a clean byproduct—pure water, which the crew drinks [1].

In the future, hydrogen will join electricity as an important energy carrier, since it can be made safely from renewable energy sources and is virtually non-polluting. It will also be used as a fuel for “zero-emission” vehicles and to heat homes and offices, produce electricity, and fuel aircraft. Renewable energy sources, like the Sun and wind, cannot produce energy all the time but they could, for example, produce

Fig. 5.1 Shuttle launch

electric energy and hydrogen, which can be stored until needed. Hydrogen can also be transported (like electricity) to locations where it is needed.

Hydrogen has great potential as a way to reduce the United States' reliance on imported energy sources such as oil. However, before hydrogen can play a bigger energy role and become a widely used alternative to gasoline, many new facilities and systems must be built [2].

Fig. 1.20 in Chap. 1 illustrates the future hydrogen energy infrastructure required. The hydrogen is produced through a wind electrolysis system and is then compressed up to pipeline pressure and fed into a transmission pipeline. The pipeline transports the hydrogen to a compressed gas terminal where the hydrogen is loaded into compressed gas tube trailers. A truck delivers the tube trailers to a forecourt station where the hydrogen is further compressed, stored, and dispensed to fuel cell vehicles [2].

5.3 Hydrogen Fuel Cells

As stated at the beginning of this chapter, and discussed in Chap. 1, a fuel cell converts the chemical energy of hydrogen or another fuel to cleanly and efficiently produce electricity. If hydrogen is the fuel, electricity, water, and heat are the only products (see Fig. 1.19). Fuel cells are unique in terms of the variety of their potential applications; they can provide power for systems as large as a utility power station and as small as a laptop computer. Hydrogen-powered fuel cells are not only pollution-free, but a two- to three-fold increase in the efficiency can be experienced when compared to traditional combustion technologies.

Fuel cells can power almost any portable device that normally uses batteries, transportation such as vehicles, trucks, buses, and marine vessels, as well as provide auxiliary power to traditional transportation technologies. Hydrogen could play a particularly important role in the future by replacing the imported petroleum we currently use in our cars and trucks in the United States [3].

As already noted, the purpose of a fuel cell is to produce an electrical current that can be directed outside the cell to do work, such as powering an electric motor or a light bulb. Because of the way electricity behaves, this current returns to the fuel cell, completing an electrical circuit. The chemical reactions that produce this current are the key to how a fuel cell works (illustrated in Fig. 1.19). Oxygen enters the fuel cell at the cathode and, in some cell types (such as that in Fig. 1.19), combines with electrons returning from the electrical circuit and hydrogen ions that have traveled through the electrolyte from the anode. In other cell types the oxygen picks up electrons and then travels through the electrolyte to the anode, where it combines with hydrogen ions [4].

The electrolyte plays a key role: only the appropriate ions must be permitted to pass between the anode and cathode. If free electrons or other substances could travel through the electrolyte, they would disrupt the chemical reaction.

Whether they combine at anode or cathode, together hydrogen and oxygen form water, which drains from the cell. As long as a fuel cell is supplied with hydrogen and oxygen, it will generate electricity.

As fuel cells create electricity chemically, rather than by combustion, they are not subject to the thermodynamic laws that limit a conventional power plant and are thus more efficient in extracting energy from a fuel. Waste heat from some cells can also be harnessed, further boosting system efficiency [4].

Fuel cells are often compared to batteries as both convert the energy produced by a chemical reaction into usable electric power. However, the fuel cell will produce electricity as long as fuel (hydrogen) is supplied, never losing its charge. Fuel cell research aims to lower the cost and improve the performance and durability of fuel cell technologies.

Fuel cells offer a promising technology for use as a source of heat and electricity for buildings, and as an electrical power source for electric motors propelling vehicles. Fuel cells operate best on pure hydrogen. But fuels such as natural gas, methanol, or even gasoline can be reformed to produce the hydrogen required for fuel cells. Some fuel cells can even be fueled directly with methanol, without using a reformer.

Fuel cells can be used in a wide range of applications, including transportation, material handling, and stationary, portable, and emergency backup power applications. Fuel cells have several benefits over conventional combustion-based technologies currently used in many power plants and passenger vehicles. They can operate at higher efficiencies than combustion engines, and can convert the chemical energy in the fuel to electrical energy with efficiencies of up to 60%. Fuel cells have lower emissions than combustion engines. As hydrogen fuel cells emit only water, there are no carbon dioxide emissions and no air pollutants that create smog and cause health problems at the point of operation. Also, fuel cells are quiet during operation as they have fewer moving parts.

The United States Fuel Cell Technologies Office (FCTO) focuses on applied research, development, and innovation to advance hydrogen and fuel cells for transportation and diverse applications enabling energy security, resiliency, and a strong domestic economy in emerging technologies.

The United States Department of Energy's (DOE) hydrogen and fuel cell efforts are part of a broad portfolio of activities aimed at building a competitive and sustainable clean energy economy, reducing greenhouse gas emissions by 80% by 2050 [5], and eliminating dependence on imported fuel will require the use of diverse domestic energy sources and advanced fuels and technologies in all sectors of the economy. Achieving these goals requires a robust, comprehensive research and development (R&D) portfolio that balances short-term objectives with long-term needs and sustainability.

Fuel cells and hydrogen comprise key elements of the DOE portfolio. The DOE's efforts to enable the widespread commercialization of hydrogen and fuel cell technologies form an integrated program—the DOE Hydrogen and Fuel Cells Program, as reflected in the Hydrogen and Fuel Cells Program Plan [6]. This Program is coordinated across the DOE and includes activities in the offices of Energy Efficiency and Renewable Energy (EERE), Science, Nuclear Energy, and Fossil Energy.

As part of these R&D goals, the DOE works closely with its national laboratories, universities, and industry partners to overcome critical technical barriers to fuel cell development. Cost, performance, and durability are still key challenges in the fuel cell industry:

- *Cost*—Platinum represents one of the largest cost components of a fuel cell, so much of the R&D is focused on approaches that will increase activity and utilization of current platinum group metal (PGM) and PGM–alloy catalysts, as well as non-PGM catalyst approaches for long-term applications.
- *Performance*—To improve fuel cell performance, R&D is focused on developing ion-exchange membrane electrolytes with enhanced efficiency and durability at reduced cost; improving membrane electrode assemblies (MEAs) through integration of state-of-the-art MEA components; developing transport models and in situ and ex situ experiments to provide data for model validation; identifying degradation mechanisms and developing approaches to mitigate their effects; and maintaining core activities on components, subsystems, and systems specifically tailored for stationary and portable power applications.
- *Durability*—A key performance factor is durability, in terms of a fuel cell system lifetime that will meet application expectations. DOE durability targets for stationary and transportation fuel cells are 40,000 h and 5000 h, respectively, under realistic operating conditions. In the most demanding applications, realistic operating conditions include impurities in the fuel and air, starting and stopping, freezing and thawing, and humidity and load cycles that result in stresses on the

chemical and mechanical stability of the fuel cell system materials and components. R&D focuses on understanding the fuel cell degradation mechanisms and developing materials and strategies that will mitigate them.

More details of technical targets and goals can be found in the Fuel Cells section of the FCTO's *Multi-Year Research, Development, and Demonstration Plan*, where full details about technical targets, or individual target tables, can be found for the following [7]:

- Fuel cell systems, stacks, and components for light-duty transportation applications
  - Fuel cell systems and stacks
  - PEMFC components
  - Fuel cell system humidifiers and air compressions systems
- Fuel cell transit buses
- Fuel cell backup power systems
- Fuel cell systems for stationary (combined heat and power) applications
- Fuel cell systems for portable power and auxiliary power applications.

5.4 Fuel Cells

A fuel cell is a device that generates electricity by a chemical reaction. Every fuel cell has two electrodes, the anode (which is positively charged) and the cathode (which is negatively charged) [1]. The reactions that produce electricity take place at the two electrodes. Every fuel cell also has an electrolyte, which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds the reactions at the electrodes [8]. Multiple fuel cells are usually assembled into a stack and generate direct current (DC).

A single fuel cell consists of an electrolyte sandwiched between two electrodes. Bipolar plates on either side of the cell help distribute gases and serve as current collectors. Hydrogen is the basic fuel for fuel cells, but fuel cells also require oxygen. The basic chemical reaction of fuel cell is as follows:

$$\mathbf{2H_2 + O_2 \rightarrow 2H_2O + 2e^-}$$

Depending on the application, a fuel cell stack may contain from a few to hundreds of individual fuel cells layered together. This "scalability" makes fuel cells ideal for a wide variety of applications, such as stationary power stations, portable devices, and transportation.

There are several kinds of fuel cells, and each operates a bit differently. But, in general terms, hydrogen atoms enter a fuel cell at the anode where a chemical reaction strips them of their electrons. The hydrogen atoms are now "ionized," and carry a positive electrical charge. The negatively charged electrons provide the current through wires to do work. If alternating current (AC) is needed, the DC output of the fuel cell must be routed through a conversion device called an inverter.

Oxygen enters the fuel cell at the cathode and in some cell types it combines with electrons returning from the electrical circuit and hydrogen ions that have traveled through the electrolyte from the anode. In other cell types the oxygen picks up electrons and then travels through the electrolyte to the anode, where it combines with hydrogen ions.

The type of fuel also depends on the electrolyte. Some cells need pure hydrogen, and therefore demand extra equipment such as a "reformer" to purify the fuel. Other cells can tolerate some impurities but might need higher temperatures to run efficiently. Liquid electrolytes circulate in some cells, which require pumps. The type of electrolyte also dictates a cell's operating temperature—"molten" carbonate cells run hot, just as the name implies.

Fuel cells are employed in stationary power generation, portable power supply and transportation. Small, stationary power generators provide 0.5–10 kW uninterrupted power supply to households, shopping malls, and data centers. Grid-scale fuel cell generation is also in development. Portable fuel cells are best suited for auxiliary power units (APUs), portable devices, personal computers, smartphones, and so on.

The application of fuel cells in transportation represents the future for the automotive and computation industries. Buses, light vehicles (cars), unmanned aerial vehicles (UAVs), and trains will soon be running on fuel cells.

Another great appeal of fuel cells is that they generate electricity with very little pollution—much of the hydrogen and oxygen used in generating electricity ultimately combines to form a harmless by-product, namely water. However, obtaining hydrogen is a challenge and can be energy intensive.

Despite its many advantages, the commercialization of fuel cell technology faces many technical and economic challenges. The durability and cost of fuel cell systems represent the biggest barriers. Fuel cells are still in the "technology development phase." Efforts are being made to reduce the cost and improve durability of fuel cells.

5.4.1 Different Types of Fuel Cells

Each type of fuel cell has advantages and drawbacks compared to the others, and none is cheap and efficient enough yet to widely replace traditional ways of generating power, such as coal-fired, hydroelectric, or even nuclear power plants.

While there are dozens of types of fuel cells, there are six principle kinds in various stages of commercial availability, or undergoing research, development, and demonstration (RD&D). These six fuel cell types are significantly different from each other in many respects; however, the key distinguishing feature is the electrolyte material.

The following sections and associated images describe the six main types of fuel cells. More detailed information can be found on the website provided by the

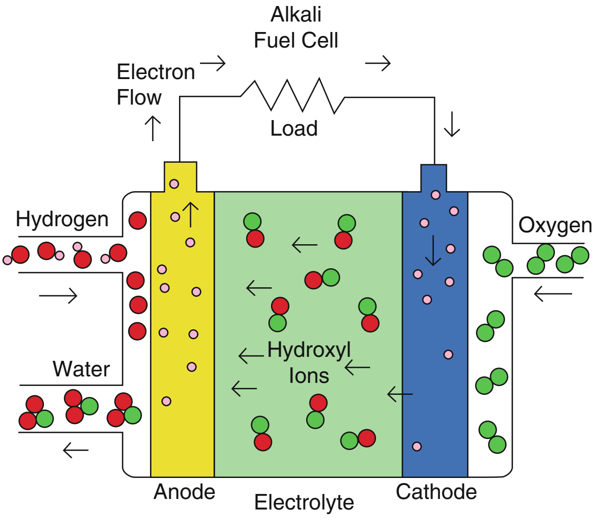

Fig. 5.2 Alkali fuel cell. (Courtesy of the Smithsonian Institution)

National Museum of American History, Smithsonian Institution at http://americanhistory.si.edu/fuelcells/basics.htm. Information and description of these fuel cells is courtesy of the Smithsonian Institution's website.

Alkali Fuel Cell

Alkali fuel cells (see Fig. 5.2) operate on compressed hydrogen and oxygen. They generally use a solution of potassium hydroxide (chemically, KOH) in water as their electrolyte. Efficiency is about 70%, and operating temperature is 150–200 °C (about 300–400 °F). Cell output ranges from 300 W to 5 kW. Alkali cells were used in Apollo spacecraft to provide both electricity and drinking water. However, they require pure hydrogen fuel, and their platinum electrode catalysts are expensive. And, like, any container filled with liquid, they can leak.

Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cells (PAFCs) (see Fig. 5.3) use phosphoric acid as the electrolyte. Efficiency ranges from 40% to 80%, and operating temperature is between 150 and 200 °C (about 300–400 °F). Existing phosphoric acid cells have outputs up to 200 kW, and 11 MW units have been tested. PAFCs tolerate a carbon monoxide concentration of about 1.5%, which broadens the choice of fuels they can use. If gasoline is used, the sulfur must be removed. Platinum electrode-catalysts are needed, and internal parts must be able to withstand the corrosive acid.

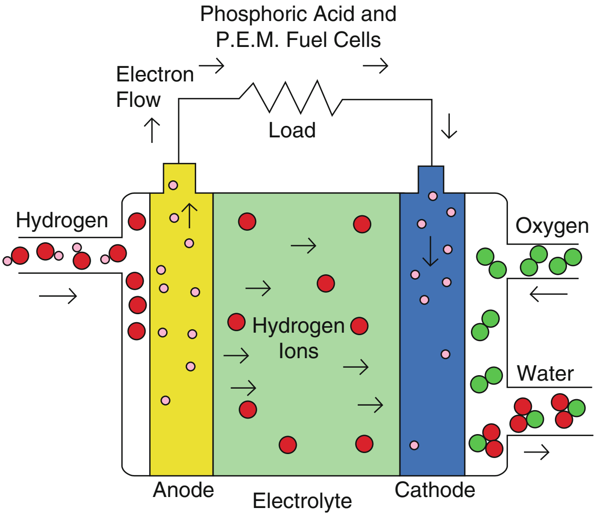

Fig. 5.3 Phosphoric acid fuel cell. (Courtesy of the Smithsonian Institution)

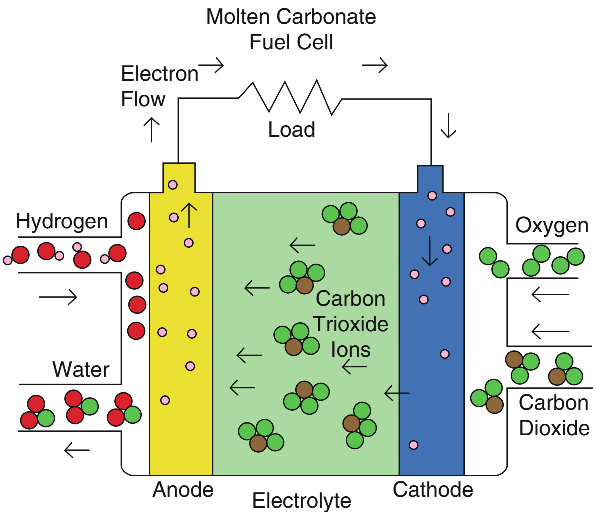

Fig. 5.4 Molten carbonate fuel cell. (Courtesy of the Smithsonian Institution)

Molten Carbonate Fuel Cell (MCFC)

The molten carbonate fuel cells (MCFCs) (see Fig. 5.4) use high-temperature compounds of salt (such as sodium or magnesium) carbonates (chemically, CO_3) as the electrolyte. Efficiency ranges from 60% to 80%, and operating temperature is about 650 °C (1200 °F). Units with output up to 2 MW have been constructed, and designs exist for units up to 100 MW. The high temperature limits damage from carbon monoxide "poisoning" of the cell and waste heat can be recycled to make additional electricity. Their nickel electrode-catalysts are inexpensive compared to the platinum used in other cells. But the high temperature also limits the materials and safe uses of MCFCs—they would probably be too hot for home use. Also, carbonate ions from the electrolyte are used up in the reactions, making it necessary to inject carbon dioxide to compensate for this.

Full-scale demonstration plants are now testing MCFCs. The electrolyte in an MCFC is an alkali carbonate (sodium, potassium, or lithium salts, i.e., Na_2CO_3, K_2CO_2, or Li_2CO_3) or a combination of alkali carbonates that is retained in a ceramic matrix of lithium aluminum oxide ($LiAlO_2$). An MCFC operates at 600–700 °C where the alkali carbonates form a highly conductive molten salt with carbonate ions (CO_3=) providing ionic conduction through the electrolyte matrix. Relatively inexpensive nickel (Ni) and nickel oxide (NiO) are adequate to promote reaction on the anode and cathode, respectively, at the high operating temperatures of an MCFC.

MCFCs offer greater fuel flexibility and higher fuel-to-electricity efficiencies than lower-temperature fuel cells, approaching 60%. The higher operating temperatures of MCFCs make them candidates for combined-cycle applications, in which the exhaust heat is used to generate additional electricity. When the waste heat is used for co-generation, total thermal efficiencies can approach 85%.

Proton Exchange Membrane (PEM)

Proton exchange membrane (PEM) fuel cells (see Fig. 5.5) work with a polymer electrolyte in the form of a thin, permeable sheet. Efficiency is about 40–50%, and operating temperature is about 80 °C (about 175 °F). Cell outputs generally range from 50 to 250 kW. The solid, flexible electrolyte will not leak or crack, and these cells operate at a low enough temperature to make them suitable for homes and cars. However, their fuels must be purified, and a platinum catalyst is used on both sides of the membrane, raising costs.

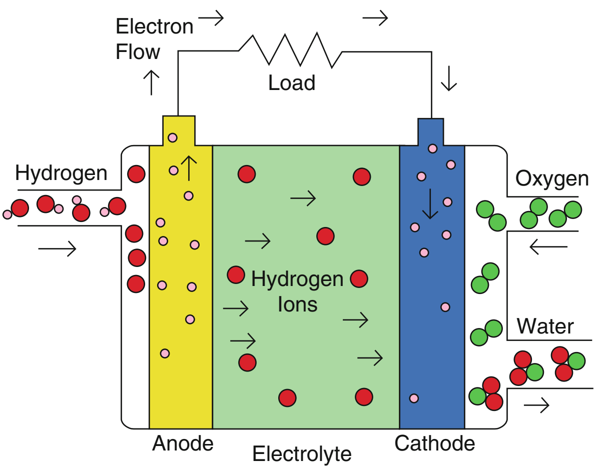

Fig. 5.5 Proton exchange membrane fuel cell. (Courtesy of the Smithsonian Institution)

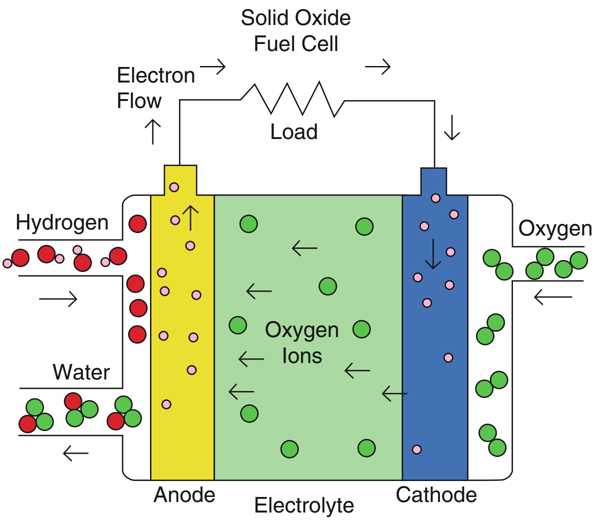

Fig. 5.6 Solid oxide fuel cell. (Courtesy of the Smithsonian Institution)

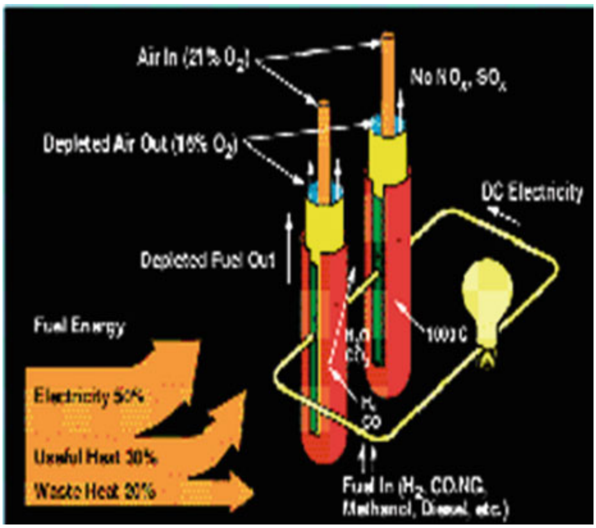

Fig. 5.7 Tubular solid oxide fuel cell. (Courtesy of Siemens Westinghouse Power Corporation)

Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cells (SOFCs) (see Figs. 5.6, 5.7, and 5.8) use a hard, ceramic compound of metal (such as calcium, zirconium, or Yttria-stabilized zirconia [Y_2O_3-stabilized ZrO_2]) oxides (chemically, O_2) as electrolyte. SOFCs approach 60% electrical efficiency in the simple cycle system, and 85% total thermal efficiency in co-generation applications (Singhal 1997). Operating temperatures are between 600 and 1000 °C (about 1100–1800 °F), and ionic conduction is accomplished by oxygen ions (O=). Cell output is generally up to 100 kW, but can range from 1 kW to 250 kW plants, with plans to reach the multi-megawatt range. Typically, the anode

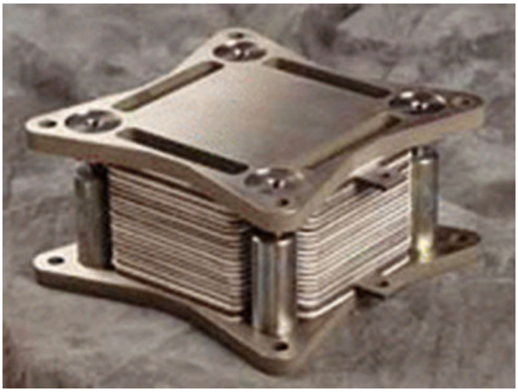

Fig. 5.8 Planar solid oxide fuel cell. (Courtesy of Siemens Westinghouse Power Corporation)

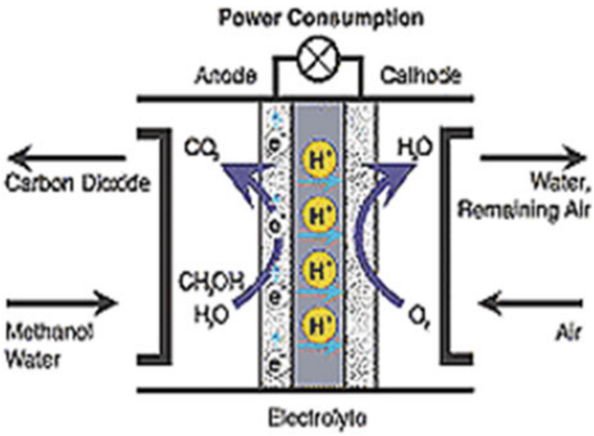

Fig. 5.9 Direct methanol fuel cell

of an SOFC is cobalt or nickel zirconia (Co-ZrO_2 or Ni-ZrO_2) and the cathode is strontium-doped lanthanum manganite (Sr-doped $LaMnO_3$). At such high temperatures, a reformer is not required to extract hydrogen from the fuel, and waste heat can be recycled to make additional electricity. High-temperature operation, up to 1000 °C, also allows more flexibility in the choice of fuels and can produce very good performance in combined-cycle applications. However, the high temperature limits applications of SOFC units and they tend to be rather large. While solid electrolytes cannot leak, they can crack.

The flat plate and monolithic designs are at a much earlier stage of development typified by sub-scale, single cell, and short stack development (kW scale). At this juncture, tubular SOFC designs are closer to commercialization.

Direct Methanol Fuel Cell (DMFC)

The direct methanol fuel cell (DMFC) (see Fig. 5.9) is similar to the PEM fuel cell in that it uses a polymer membrane as an electrolyte. However, a catalyst on the DMFC anode draws hydrogen from liquid methanol, eliminating the need for a fuel reformer. While potentially a very attractive solution to the issues of hydrogen storage and transportation (particularly for portable applications), the principal problem facing the commercial application of the DMFC today stems from its relatively low performance in comparison to hydrogen.

5.5 Fuel Cell Technologies

The Fuel Cell Technologies Program (FCT Program), situated within EERE, addresses key technical challenges for fuel cells and hydrogen production, delivery, and storage and the institutional barriers, such as hydrogen codes and standards, training, and public awareness that inhibit the widespread commercialization of hydrogen and fuel cell technologies. The FCT Program conducts applied research, technology development, and learning demonstrations, as well as safety research, systems analysis, early market deployments, and public outreach and education activities. These activities include cost-shared, public–private partnerships to address the high-risk, critical technology barriers preventing extensive use of hydrogen as an energy carrier. Public and private partners include automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, standards development organizations, other federal agencies, state government agencies, universities, national laboratories, and other national and international stakeholder organizations. The FCT Program encourages the formation of collaborative partnerships to conduct RD&D and other activities, such as deployment, that support program goals.

The FCT Program addresses the development of hydrogen energy systems for transportation, stationary power, and portable power applications. Transportation applications include fuel cell vehicles (such as buses, automobiles, and heavy-duty vehicles), niche markets (such as lift trucks), and hydrogen refueling infrastructure. Stationary power applications include hydrogen used for backup emergency power, commercial/industrial power and heat generation, and residential electric power generation. Consumer electronics such as mobile phones, laptop computers, and recharging systems are among the portable power applications. The DOE funds RD&D efforts that will provide the basis for the near-, mid-, and long-term production, delivery, storage, and use of hydrogen derived from diverse energy sources, including renewable, fossil fuels, and nuclear energy as coordinated within the Program.

As stated earlier, fuel cell research aims to lower the cost and improve the performance and durability of fuel cell technologies. Research is performed on a variety of fuel cell types—PEMFCs, alkaline membrane fuel cells (AMFCs), and DMFCs—which are generally differentiated by the fuel used, as listed here:

1. *Catalysts:* Work in this area involves developing and optimizing advanced electrocatalysts and novel synthesis methods. Related projects concentrate on

extended-surface catalysts with reduced precious-metal loading and improved performance, durability, and activity compared with standard catalytic materials. Researchers are investigating fuel cells and electrolyzer catalysts under acidic and alkaline conditions, with the goal of "thrifting" platinum, iridium, and their alloys (in acidic-based systems) and silver, cobalt, nickel, and their oxides/alloys (in alkaline-based systems). Also under study are support materials for catalyst dispersion, with a focus on nitrogen-doped carbon supports and corrosion-resistant, non-carbon supports.

2. *Polymer Electrolytes:* AMFCs enable the use of non-precious-metal catalysts, but they are vulnerable to ambient carbon dioxide conditions. This vulnerability decreases, however, at higher operating temperatures. Researchers are developing novel chemistries to enable higher-temperature and higher-current-density operation via the use of perfluorinated alkaline membranes. Researchers are also exploring traditional PEMs with tethered heteropolyacid functionality to allow higher-temperature, lower-humidity operation and are investigating the stability of covalently tetherable captions.
3. *Electrode Design/High-Current-Density Operation:* This cross-cutting research area is focused on incorporating novel catalysts into high-performance devices and investigating the impact of low-precious-metal loading on high-current-density performance.
4. *Contaminants:* As fuel cell systems become more commercially competitive, and as automotive fuel cell R&D trends toward decreased catalyst loadings and thinner membranes, fuel cell operation becomes even more susceptible to contaminants. The National Renewable Energy Laboratory (NREL) also participates in the DOE's Fuel Cell Durability Working Group. Contaminants derived from fuel cell system component/structural materials, lubricants, greases, adhesives, sealants, and hoses have been shown to affect the performance and durability of fuel cell systems. Companies are currently performing research to identify and quantify these system-derived contaminants and to understand the effects of system contaminants on fuel cell performance and durability. The goal is to increase the understanding of fuel cell system contaminants and to help guide the implementation and, where necessary, development of system materials that will help enable fuel cell commercialization.

Again, more details can be found in official site of DOE office at Energy Efficiency & Renewable Energy as well as that of the NREL [9, 10].

5.6 Fuel Cell Backup Power Systems

The DOE technical targets for fuel cell backup power systems are given in Table 5.1. More information on these targets can be found in the Fuel Cells section of the FCTO's *Multi-Year Research, Development, and Demonstration Plan* [11].

Table 5.1 Technical targets: fuel cell backup power systems (1–10 kW) operating on direct hydrogen [10]

Characteristic	Units	2015 status[a]	2020 targets
Lifetime	Years	10	15
Durability[b]	Hours	8000	10,000
Energy efficiency[c]	%	50	60
Mean time between failures	Years	5	5
Ambient temperature range	°C	−10 to 40	−50 to 50
Noise	dB at 1 m	65	60
Start-up time[d]	Seconds	80	15
Availability	%	99.7	96.3
Equipment cost[e]	$/kW	6100[f]	1000
Annual maintenance cost[e]	$/kW	30	20
Annualized total cost of ownership[g]	$/kW	500	200

[a]Unless otherwise stated, status based on input from DE-FOA-0000738
[b]Time until 10% voltage degradation when operated on a backup power duty cycle
[c]Ratio of direct current (DC) output energy from the power plant to the lower heating value of the input fuel (hydrogen, averaged over cycle
[d]Time indicated is start-up time for the fuel cell. The backup power system, including hybridized batteries, is expected to provide uninterruptible power
[e]Excludes tax credits and subsidies
[f]National Renewable Energy Laboratory (NREL), "Current Fuel Cell System Low Volume Price by Application"
[g]Annualized cost of ownership including cost of capital equipment, installation, operation and maintenance, fuel, and fuel storage. Based on a 5 kW system with 10-year lifetime

5.7 Fuel Cell Systems for Stationary Combined Heat and Power Applications

Tables 5.2 and 5.3 list the DOE technical targets for stationary fuel cell applications [12]. These targets have been developed with input from developers of stationary fuel cell power systems.

More information on these targets can be found in the Fuel Cells section of the FCTO's *Multi-Year Research, Development, and Demonstration Plan* [11].

5.8 Fuel Cell Systems for Portable Power and Auxiliary Power Applications

Tables 5.4 and 5.5 list the DOE technical targets for fuel cell systems for portable power and auxiliary power applications [12].

More information on these targets can be found in the Fuel Cells section of the FCTO's *Multi-Year Research, Development, and Demonstration Plan* [13].

Table 5.2 Technical targets: 1–25 kW residential and light commercial combined heat and power and distributed generation fuel cell systems operating on natural gas[a]

Characteristic	Units	2015 status	2020 targets
Electrical efficiency at rated power[b]	% (LHV)	34–40	>45[c]
CHP energy efficiency[d]	% (LHV)	80–90	90
Equipment cost[e], 5-kW_{avg} system[f]	$/kW	2300–2800[g]	1500
Transient response (10–90% rated power)	Min	5	2
Start-up time from 20 °C ambient temperature	Min	10	20
Degradation with cycling[h]	%/1000 h	<2%	0.3%
Operating lifetime[i]	h	12,000–70,000	60,000
System availability[j]	%	97	99

AC alternating current, *CHP* combined heat and power, *LHV* lower heating value, *SOFC* solid oxide fuel cell

[a]Pipeline natural gas delivered at typical residential distribution line pressures

[b]Regulated AC net/LHV of fuel

[c]Higher electrical efficiencies (e.g., 60% using SOFC) are preferred for non-CHP applications

[d]Ratio of regulated AC net output energy plus recovered thermal energy to the LHV of the input fuel. For inclusion in CHP energy-efficiency calculation, heat must be available at a temperature sufficiently high to be useful in space and water heating applications. Provision of heat at 80 °C or higher is recommended

[e]Complete system, including all necessary components to convert natural gas to electricity suitable for grid connection, and heat exchangers and other equipment for heat rejection to conventional water heater, and/or hydronic or forced air heating system. Includes all applicable taxes, and markups, based on projection to high-volume production (50,000 units per year)

[f]kW_{avg} is the average output (AC) electric power delivered over the life of system while unit is running

[g]Battelle preliminary 2015 cost assessment of stationary CHP systems, range represents different technologies (SOFC vs PEMFC) at manufacturing volumes of 50,000 units per year

[h]Durability testing should include effects of transient operation, startup, and shutdown

[i]Time until >20% net power degradation

[j]Percentage of time the system is available for operation under realistic operating conditions and load profile. Unavailable time includes time for scheduled maintenance

5.9 Hydrogen Storage

The FCTO is developing onboard automotive hydrogen storage systems that allow for a driving range of more than 300 miles while meeting cost, safety, and performance requirements.

Small amounts of hydrogen (up to a few MWh) can be stored in pressurized vessels at 100–300 bar or liquefied at 20.3 K (−423 F). Alternatively, solid metal hydrides or nano-tubes can store hydrogen with a very high density. Very large amounts of hydrogen can be stored in manmade underground salt caverns of up to 500,000 m^3 at 200 bar (2900 psi), corresponding to a storage capacity of 167 GWh hydrogen (100 GWh electricity). In this way, longer periods of flaws or of excess wind/photovoltaic energy production can be leveled. Even balancing seasonal variations might be possible.

Table 5.3 Technical targets[a]: 100 kW–3 MW combined heat and power and distributed generation fuel cell systems operating on natural gas[b]

Characteristic	Units	2015 status[c]	2020 targets
Electrical efficiency at rated power[d]	% (LHV)	42–47	> 50[e]
CHP energy efficiency[f]	% (LHV)	70–90	90
Equipment cost, natural gas	$/kW	1200[g]–4500[h]	1000[i]
Installed cost, natural gas	$/kW	2400[g]–5500[h]	1500[i]
Equipment cost, biogas	$/kW	3200–6500[j]	1400[i]
Installed cost, biogas	$/kW	4900–8000[j]	2100[i]
Number of planned/forced outages over lifetime	–	50	40
Operating lifetime[k]	h	40,000–80,000	80,000
System availability[l]	%	95	99

AC alternating current, *CHP* combined heat and power, *DOE* Department of Energy, *LHV* lower heating value, *SOFC* solid oxide fuel cell, *LT-PEMFC* Low Temperature-Proton-exchange membrane fuel cells

[a]Includes fuel processor, stack, and ancillaries

[b]Pipeline natural gas delivered at typical residential distribution line pressures

[c]Status varies by technology

[d]Ratio of regulated AC net output energy to the LHV of the input fuel

[e]Higher electrical efficiencies (e.g., 60% using SOFC) are preferred for non-CHP applications

[f]Ratio of regulated AC net output energy plus recovered thermal energy to the LHV of the input fuel. For inclusion in CHP energy-efficiency calculation, heat must be available at a temperature sufficiently high to be useful in space and water heating applications. Provision of heat at 80 °C or higher is recommended

[g]M. Wei, 100 kW LLT-PEMFC, projection at volume of 1000 systems/year

[h]DOE Hydrogen and Fuel Cells Program Record 11,014, "Medium-scale CHP Fuel Cell System Targets,"

[i]Includes projected cost advantage of high-volume production (totaling 100 MW per year)

[j]Assumed $2500/kW higher cost to operate on biogas than on hydrogen (DOE Hydrogen and Fuel Cells Program Record 11014, "Medium-scale CHP Fuel Cell System Targets")

[k]Time until > 10% net power degradation

[l]Percentage of time the system is available for operation under realistic operating conditions and load profile. Unavailable time includes time for scheduled maintenance

5.9.1 Why Study Hydrogen Storage?

Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell technologies in applications including stationary power, portable power, and transportation. Hydrogen has the highest energy per mass of any fuel; however, its low ambient temperature density results in a low energy per unit volume, requiring the development of advanced storage methods that have potential for higher energy density.

5.9.2 How Hydrogen Storage Works

Hydrogen can be stored physically as either a gas or a liquid (see Fig. 5.10). Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar

Table 5.4 Technical targets: portable power fuel cell systems (5–50 W/100–200 W)[a]

Characteristic	Units	2015 status	Ultimate targets
Specific power[b]	W/kg	23[h]/25[i]	45/50
Power density[b]	W/L	24[h]/30[i]	55/70
Specific energy[b,c]	Wh/kg	121[j]/450[j]	650/640
Energy density[b,c]	Wh/L	200[i]/300[i,j]	650/900
Cost[d]	$/W	15[i]/15[i]	7/5
Durability[e,f]	Hours	1500[i]/2000[i]	5000/5000
Mean time between failures[f,g]	Hours	500[i]/500[i]	5000/5000

[a]These targets are technology neutral and make no assumption about the type of fuel cell technology or type of fuel used. In addition to meeting these targets, portable power fuel cells are expected to operate safely, providing power without exposing users to hazardous or unpleasant emissions, high temperatures, or objectionable levels of noise. Portable power fuel cells are also expected to be compatible with the requirements of portable electronic devices, including operation under a range of ambient temperature, humidity, and pressure conditions, and exposure to freezing conditions, vibration, and dust. They should be capable of repeatedly turning off and on and should have turndown capabilities required to match the dynamic power needs of the device. For widespread adoption, portable power fuel cell systems should minimize life-cycle environmental impact through the use of reusable fuel cartridges, recyclable components, and low-impact manufacturing techniques

[b]This is based on rated net power of the total fuel cell system, including fuel tank, fuel, and any hybridization batteries. In the case of fuel cells embedded in other devices, only device components required for power generation, power conditioning, and energy storage are included. Fuel capacity is not specified, but the same quantity of fuel must be used in calculation of specific power, power density, specific energy, and energy density

[c]Efficiency of 35% is recommended to enable high specific energy and energy density

[d]Cost includes material and labor costs required to manufacture the fuel cell system and any required auxiliaries (e.g., refueling devices). Cost is defined at production rates of 25,000 and 10,000 units per year for 5–50 W and 100–200 W units, respectively

[e]Durability is defined as the time until the system rated power degrades by 20%, though for some applications higher or lower levels of power degradation may be acceptable

[f]Testing should be performed using an operating cycle that is realistic and appropriate for the target application, including effects from transient operation, startup and shutdown, and off-line degradation

[g]Mean time between failures (MTBF) includes failures of any system components that render the system inoperable without maintenance

[h]Status calculated based on commercial products from myFC (myfcpower.com/pages/jaq)

[i]Department of Energy Hydrogen and Fuel Cells Program Record 11009

[j]Status calculated based on commercial products from ultra-cell (ultracell-llc.com)

[5000–10,000 psi] tank pressure). Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at 1 atmosphere pressure is −252.8 °C. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption).

Table 5.5 Technical targets: fuel cell auxiliary power units (1–10 kW) operating on ultra-low-sulfur diesel fuel

Characteristic	Units	2015 status	2020 targets
Electrical efficiency at rated power[a]	% (LHV)	29[b]	40
Power density	W/L	16[b]	40
Specific power	W/kg	18[b]	45
Factory cost, system[c]	$/kWe	2100[d]	1000
Transient response (10–90% rated power)	Min	5[e]	2
Start-up time from 20 °C	Min	70[b]	30
Start-up time from standby conditions[f]	Min	–	5
Degradation with cycling[g]	%/1000 h	2.6[e]	1
Operating lifetime[g,h]	h	3000[e]	20,000
System availability[i]	%	97[e]	99

APU auxiliary power unit, *DOE* Department of Energy, *SOFC* solid oxide fuel cell
[a]Regulated DC net/LHV of fuel
[b]DESTA-Demonstration of 1st European SOFC Truck APU, Programmed Review Days 2015
[c]Cost includes materials and labor costs to produce system. Cost defined at 50,000 unit/year production of a 5-kW system. Today's low-volume cost is expected to be higher than quoted status. Allowable cost is expected to be higher than the target for systems with rated power below 5 kW, and lower than the target for systems with rated power above 5 kW
[d]Modeled cost of a 5 kW SOFC APU system produced at 50,000 units/year. F. Eubanks et al., "Stationary and Emerging Market Fuel Cell System Cost Analysis-Auxiliary Power Units," 2015 Annual Merit Review, slide 20
[e]DOE Hydrogen Program Record 11001, "Revised APU Targets"
[f]Standby conditions may be at or above ambient temperature depending on operating protocol
[g]Durability testing should include, at minimum, daily cycles to stand-by condition, and weekly cycles to full off condition (ambient temperature). The system should be able to meet durability criteria during and after exposure to vibration associated with transportation and highway operation, and during operation in a range of ambient temperature from −40 °C to 50 °C, a range of ambient relative humidity from 5% to 100%, and in dust levels up to 2 mg/m^3
[h]Time until > 20% net power degradation
[i]Percentage of time the system is available for operation under realistic operating conditions and load profile. Scheduled maintenance does not count against system availability

5.9.3 Research and Development Goals

The FCTO conducts R&D activities to advance hydrogen storage systems technology and develop novel hydrogen storage materials. The goal is to provide adequate hydrogen storage to meet the DOE hydrogen storage targets for onboard light-duty vehicle, material-handling equipment, and portable power applications. By 2020, the FCTO aims to develop and verify onboard automotive hydrogen storage systems achieving targets that will allow hydrogen-fueled vehicle platforms to meet customer performance expectations for range, passenger and cargo space, refueling time, and overall vehicle performance. Specific system targets include the following:

- 1.5 kWh/kg system (4.5 wt.% hydrogen)
- 1.0 kWh/L system (0.030 kg hydrogen/L)
- US$10/kWh (US$333/kg stored hydrogen capacity).

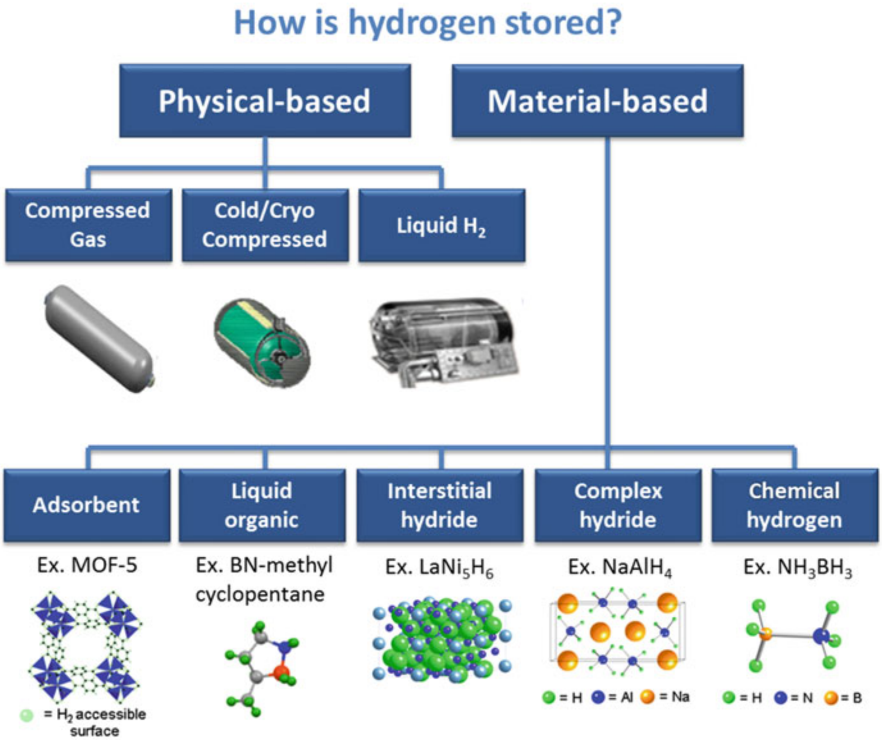

Fig. 5.10 Hydrogen storage. (Courtesy of the US Department of Energy)

The collaborative Hydrogen Storage Engineering Center of Excellence (HSECoE) conducts analysis activities to determine the current status of materials-based storage system technologies. The Hydrogen Materials—Advanced Research Consortium (HyMARC) conducts foundational research to understand the interaction of hydrogen with materials in relation to the formation and release of hydrogen from hydrogen storage materials.

5.9.4 Hydrogen Storage Challenges

High-density hydrogen storage is a challenge for stationary and portable applications and remains a significant challenge for transportation applications. Presently available storage options typically require large-volume systems that store hydrogen in gaseous form. This is less of an issue for stationary applications, where the footprint of compressed gas tanks may be less critical.

However, fuel cell-powered vehicles require enough hydrogen to provide a driving range of more than 300 miles with the ability to quickly and easily refuel

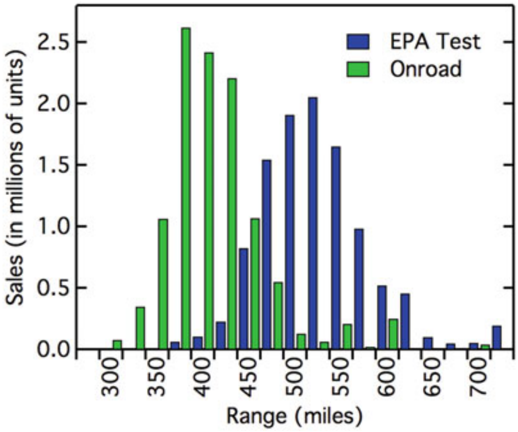

Fig. 5.11 2010 US light-duty vehicle sales distribution by driving range. (Courtesy of the US Department of Energy)

the vehicle. While some light-duty hydrogen fuel cell electric vehicles (FCEVs) that are capable of this range have entered the market, these vehicles will rely on compressed gas onboard storage using large-volume, high-pressure composite vessels (see Fig. 5.11).

The large storage volumes required may have less impact for larger vehicles, but providing sufficient hydrogen storage across all light-duty platforms remains a challenge. The importance of the 300-mile range goal can be appreciated by looking at the sales distribution by range chart (Fig. 5.11), which shows that most vehicles sold today are capable of exceeding this minimum.

On a mass basis, hydrogen has nearly three times the energy content of gasoline—120 MJ/kg for hydrogen versus 44 MJ/kg for gasoline. On a volume basis, however, this is reversed; liquid hydrogen has a density of 8 MJ/L, whereas gasoline has a density of 32 MJ/L, as shown in Fig. 5.12, which compares specific energy (i.e., energy per mass or gravimetric density) and energy density (i.e., energy per volume or volumetric density) for several fuels based on lower heating values. Onboard hydrogen storage capacities of 5–13 kg hydrogen will be required to meet the driving range for the full range of light-duty vehicle platforms.

To overcome these challenges, the FCTO is pursuing two strategic pathways, targeting both near-term and long-term solutions. The near-term pathway focuses on compressed gas storage, using advanced pressure vessels made of fiber reinforced composites that are capable of reaching 700 bar pressure, with a major emphasis on system cost reduction. The long-term pathway focuses on both:

1. Cold or cryo-compressed hydrogen storage, where increased hydrogen density and insulated pressure vessels may allow for DOE targets to be met; and
2. Materials-based hydrogen storage technologies, including sorbents, chemical hydrogen storage materials, and metal hydrides, with properties having potential to meet DOE hydrogen storage targets.

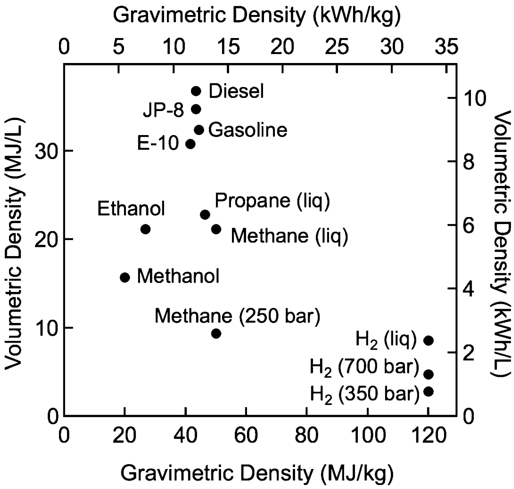

Fig. 5.12 Comparison of specific energy versus volumetric density. (Courtesy of the US Department of Energy)

5.10 Hydrogen Energy Storage

Hydrogen is the most versatile means of energy storage—it can be produced and stored in all scales and used as a fuel, chemical material, or natural gas substitute.

Electricity can be converted into hydrogen by electrolysis and the hydrogen can be then stored and eventually re-electrified. Currently, round-trip efficiency is as low as 30–40% but could increase up to 50% if more efficient technologies are developed. Despite this low efficiency, the interest in hydrogen energy storage (HES) is growing due to the much higher storage capacity than batteries (small scale) or pumped hydro and compressed air energy storage (CAES) (large scale).

Hydrogen is an energy-rich gas, which is one of the reasons that it is used as a rocket fuel. It can be produced from a variety of feedstock—and from electricity—and stored in many different ways, from a few grams in handheld cartridges to thousands of tons in an underground cavern. This gives hydrogen a unique potential to store renewable energy on both a small and very large scale. Especially for longer-term storage (weeks to months), hydrogen is the only viable alternative in sight currently. It is also versatile to use: it can be converted back to power, used as fuel for cars, used as a material for many industrial products (such as hardened fats), or even be converted to synthetic natural gas. Hydrogen makes all these markets accessible for renewable power.

HES systems have been the topic of numerous studies and analyses. These systems typically involve the production of hydrogen from electricity by electrolysis. Most electrolysis units involve alkaline or PEMFC conversion processes [14, 15]. As early as 1999, Ogden provided an overview of hydrogen infrastructure components, which included storage systems [16], and Yang reviewed general similarities and differences between hydrogen and electricity as energy carriers [17]. Many studies of future hydrogen scenarios have been developed [18, 19], and this complementarily between hydrogen and electricity has been the focus of high-renewable scenarios developed by Barton and Gammon for the United Kingdom [20], and more recently by Jacobson et al. [21] for California (2014). Several studies have compared hydrogen storage systems with other storage systems on the basis of cost, performance, and other attributes relevant to market viability and policy development [22–25].

In addition to numerous analytical studies, multiple grid-connected and remote demonstration projects have been executed during the past decade with approximately 80 hydrogen fueling stations currently based on electrolysis, 35 of which are located in North America [28]. Recently, interest has focused on power-to-gas applications, with several projects, especially in Germany, converting electrolytic hydrogen to synthetic methane (CH_4) by methanation. Methanation involves combining electrolytic hydrogen with carbon dioxide (CO_2) by a thermo-catalytic or biologic process. The concept of power-to-gas (a phrase derived from the German "*Strom zu Gas*") is to produce "green gas" with hydrogen from renewables and carbon dioxide from bioenergy or other sources, which allows for a significant increase in the overall utilization of renewable energy assets [26]. Power-to-gas and biogas projects in Austria, the Netherlands, Denmark, Sweden, Germany, and elsewhere were reviewed by Iskov and Rasmussen [27]. In 2013, Gahleitner [28] reviewed 41 international power-to-gas projects and concluded with recommendations to improve overall system performance, develop codes and standards, and determine optimum system configurations. Also in 2013, Grond et al. [29] reviewed technologies for power-to-gas systems and concluded that these systems can provide community energy storage, time shifting/load leveling, and transmission and distribution management services.

HES units can not only increase the utilization of renewable energy resources but also have the potential to provide services to the grid. These services can be on the transmission or distribution level and enable access to additional revenue streams for HES systems. Several studies have been performed to assess the ability and value for electrolyzers, acting as demand response devices, to provide grid services [40–42]. In this respect, electrolytic hydrogen can play a role within the larger architecture of a smart grid and/or "smart gas" system by providing increased flexibility and resiliency. As is the case with other energy storage options, there are challenges to characterizing the value of these grid services to equipment owners, utilities, and electricity market operators.

HES, is more than "electricity in, electricity out." To understand this topic better, the reader is referred to the report "Hydrogen Energy Storage, Grid and Transportation Services" published by the NREL in February 2015.

5.10.1 Hydrogen Production

Alkaline electrolysis is a mature technology for large systems, whereas PEM electrolyzers are more flexible and can be used for small decentralized solutions. The conversion efficiency for both technologies is about 65–70% (lower heating

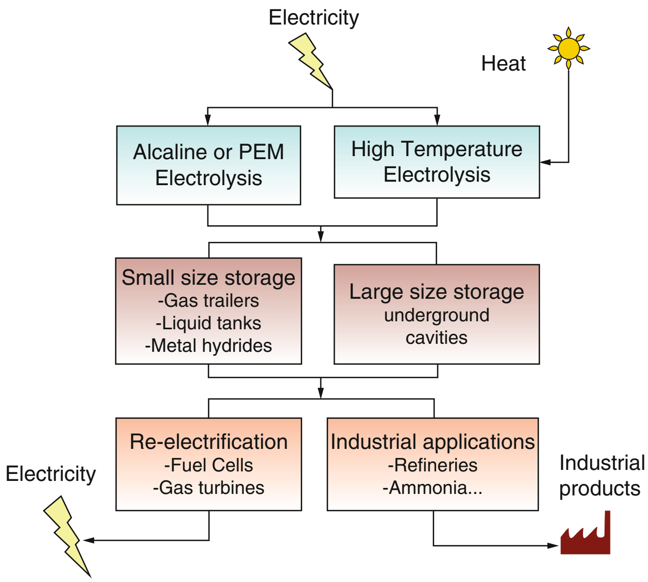

Fig. 5.13 Hydrogen production process. (Courtesy of European Institute for Energy Research (EIFER))

value). High-temperature electrolyzers are currently under development and could represent a very efficient alternative to PEM and alkaline systems, with efficiencies up to 90% (see Fig. 5.13).

5.10.2 Hydrogen Re-Electrification

Hydrogen can be re-electrified in fuel cells with efficiencies up to 50%, or alternatively burned in combined cycle gas power plants (efficiencies as high as 60%).

Because of the limited round-trip efficiency, direct uses of green hydrogen are under development, for example as feedstock for the chemical and the petrochemical industry, as fuel for future fuel cell cars, or blended with natural gas of up to 5–15% in natural gas pipelines. Electrolytic hydrogen can also be used for the production of synthetic liquid fuels from biomass, thereby significantly increasing the efficiency of the biomass utilization.

Deployment of hydrogen as an integrated solution by several European and American companies to supply electric power to small isolated sites or islands is via pipes. Demonstration projects have been performed since 2000 in Europe and the USA and commercial products are available. Large-scale hydrogen storage in salt caverns is the standard technology. To date, there are two full-sized hydrogen caverns in operation in Texas, USA, and a third is under construction; three older caverns are operating at Teesside in the UK.

5.11 Pipelines and Underground Hydrogen Storage

As part of the application of hydrogen as a source of renewable energy source during peak demand for electricity, one approach for power-to-gas applications is to inject hydrogen directly into natural gas pipelines rather than to undertake the additional step of methanation. This pathway was researched thoroughly in the European Union's NaturalHy project [30] and is discussed by Melaina et al. [31] in the context of the United States' natural gas pipeline systems. In general, few changes to existing natural gas transmission or distribution pipeline networks are required if the hydrogen blend level is very low. Although industry codes and standards have become more stringent and society's tolerance for risk has decreased, hydrogen was a major constituent of town gas used for heating and lighting in homes, commercial buildings, and industry for nearly a century until 1950 [32–34]. Dodds and Hawkes [35] reviewed issues related to hydrogen blending potential in the United Kingdom's natural gas system and advised that early blend levels be limited to 2–3% hydrogen by volume (2014). Standards in Germany suggest up to 5%, with potential to increase to 6–20% [36]. As is evidenced by these studies, there is continued interest in pipeline material research for enabling power-to-gas applications. Power-to-gas projects today have a bias toward methanation, partly because of the lack of standards and pipeline-specific analysis required to approve direct injection of hydrogen. However, if suitable gas quality standards exist to facilitate direct hydrogen blending, it will likely lower the development cost for these systems. Furthermore, methanation processes are not expected to achieve 100% conversion of the input hydrogen feedstock, so the development of gas quality standards for lower levels of direct hydrogen blending is also expected to facilitate the growth of the methanation technologies.

In addition to injection into the natural gas system, underground geologic formations can be used to store large amounts of natural gas or hydrogen. This concept has several successful demonstrations and continues to attract interest in North America and Europe [37]. Salt caverns, which are currently used to store natural gas seasonally, are perhaps the best example of very large-scale hydrogen storage [38]. For example, Ozarslan [39] recently evaluated a large-scale solar hydrogen storage system that used salt caverns (2012).

5.12 Materials-Based Hydrogen Storage

The FCTO's applied materials-based hydrogen storage technology RD&D activities focus on developing materials and systems that have the potential to meet DOE 2020 light-duty vehicle system targets with an overarching goal of meeting ultimate full-fleet, light-duty vehicle system targets.

Materials-based research is currently being pursued on metal hydride, chemical hydrogen storage, and sorbent materials:

- Metal hydride materials research focuses on improving the volumetric and gravimetric capacities, hydrogen adsorption/desorption kinetics, cycle life, and reaction thermodynamics of potential material candidates.
- Chemical hydrogen storage materials research focuses on improving volumetric and gravimetric capacity, improving transient performance, reducing release of volatile impurities, and developing efficient regeneration processes for the spent storage material.
- Sorbent materials research focuses on increasing effective adsorption temperature through increase of the dihydrogen binding energies and improving volumetric and gravimetric storage capacities through optimizing the material's pore size, increasing pore volume and surface area, and investigating effects of material densification.

A key component for advancing storage materials is the use of reliable material property measurement techniques. It is imperative to understand how the hydrogen storage properties of a material can be significantly influenced by not only individual sample characteristics—including chemical composition and distribution and microscopic and macroscopic material structure—but also pressure, temperature, and sample size. To help researchers better understand the proper measurement techniques, the FCTO commissioned a best practices manual that gives a detailed overview of the recommended best practices in measuring the hydrogen storage properties of materials.

5.12.1 Technical Targets and Status

Materials-based research offers a long-term solution to the challenge of onboard automotive storage, as well as opportunities for stationary and portable power applications, with the potential to significantly reduce the required storage pressure, increase gravimetric and volumetric capacity, and reduce cost. From 2005 through 2010, the DOE Hydrogen Storage program supported three collaborative efforts—the Metal Hydride Center of Excellence, the Hydrogen Sorption Center of Excellence, and the Chemical Hydrogen Storage Center of Excellence—as well as independent projects that investigated more than 400 materials for potential use in hydrogen storage applications. Analysis activities in the HSECoE have determined the current status of systems using these materials. The HSECoE has also developed spider charts showing three modeled systems for each material class and how they compare against all of DOE's 2020 targets.

Table 5.6 presents the projected performance and cost of materials-based automotive systems compared with the 2020 and ultimate DOE targets.

Figure 5.14 shows hydrogen gravimetric capacity as a function of hydrogen release temperature for many of the unique hydrogen storage materials investigated by the FCTO.

Table 5.6 Projected performance and cost of materials-based automotive hydrogen storage systems[a]

Storage system targets	Gravimetric density [kWh/kg system (kg H_2/kg system)]	Volumetric density [kWh/L system (kg H_2/L system)]	Cost [US $/kWh (US $/kg H_2)]
2020	1.5 (0.045)	1.0 (0.030)	10 (333)
Ultimate	2.2 (0.065)	1.7 (0.050)	8 (266)
Current status (from HSECoE)			
MH: $NaAlH_4$	0.4 (0.012)	0.4 (0.012)	43 (1430)
Sorbent: MOF-5, 100 bar, 80 K	1.3 (0.038)	0.7 (0.021)	15 (490)
CH storage: off-board regenerable[a, b]	1.5 (0.046)	1.3 (0.040)	17 (550)

CH chemical hydrogen, *HSECoE* Hydrogen Storage Engineering Center of Excellence, *MH* metal hydride, *MOF* Metal-Organic Framework
[a]Assumes a storage capacity of 5.6 kg of usable hydrogen
[b]MH reflects status at the end of phase I; CH and sorbent reflect status at the end of phase II

5.13 Industrial Application of Hydrogen Energy

When it comes to industrial applications, hydrogen (H_2) is everywhere. Hydrogen has been deployed as an industrial gas for over 100 years and large volumes are used across the widest range of applications every day. Hydrogen is also set to play a defining role in the much-publicized third, “green” industrial revolution. It is the most commonly occurring element in nature and—unlike fossil fuels such as crude oil or natural gas—will never run out. Like electricity, hydrogen is an energy carrier, not a source of energy. It must therefore be produced. Yet hydrogen offers several key benefits that increase its potential to replace fossil fuels. Stored hydrogen, for example, can be used directly as a fuel or to generate electricity.

Hydrogen will open up regenerative, sustainable mobility choices in our everyday lives. Hydrogen-powered vehicles have a long-distance range and can be rapidly fueled. Decades of research, development, and testing have shown that hydrogen technology is a workable, economically viable alternative suited to mass deployment. A series of illustrations presented here shows different applications of hydrogen in industry: a fuel cell bus at a hydrogen station (Fig. 5.15), hydrogen drive vehicles in an urban city (Fig. 5.16), a conceptual application of hydrogen driving a bicycle (Fig. 5.17), and different applications of hydrogen in various industries (Fig. 5.18).

The compressor unit is the key component of a hydrogen fueling station because fueling is carried out using compressed gaseous H_2 at pressures from 35 to 70 MPa. Apart from the initial state—gaseous or liquid—the technology used for fueling also depends on a range of other factors, such as, for example, the throughput and the type of vehicle to be fueled.

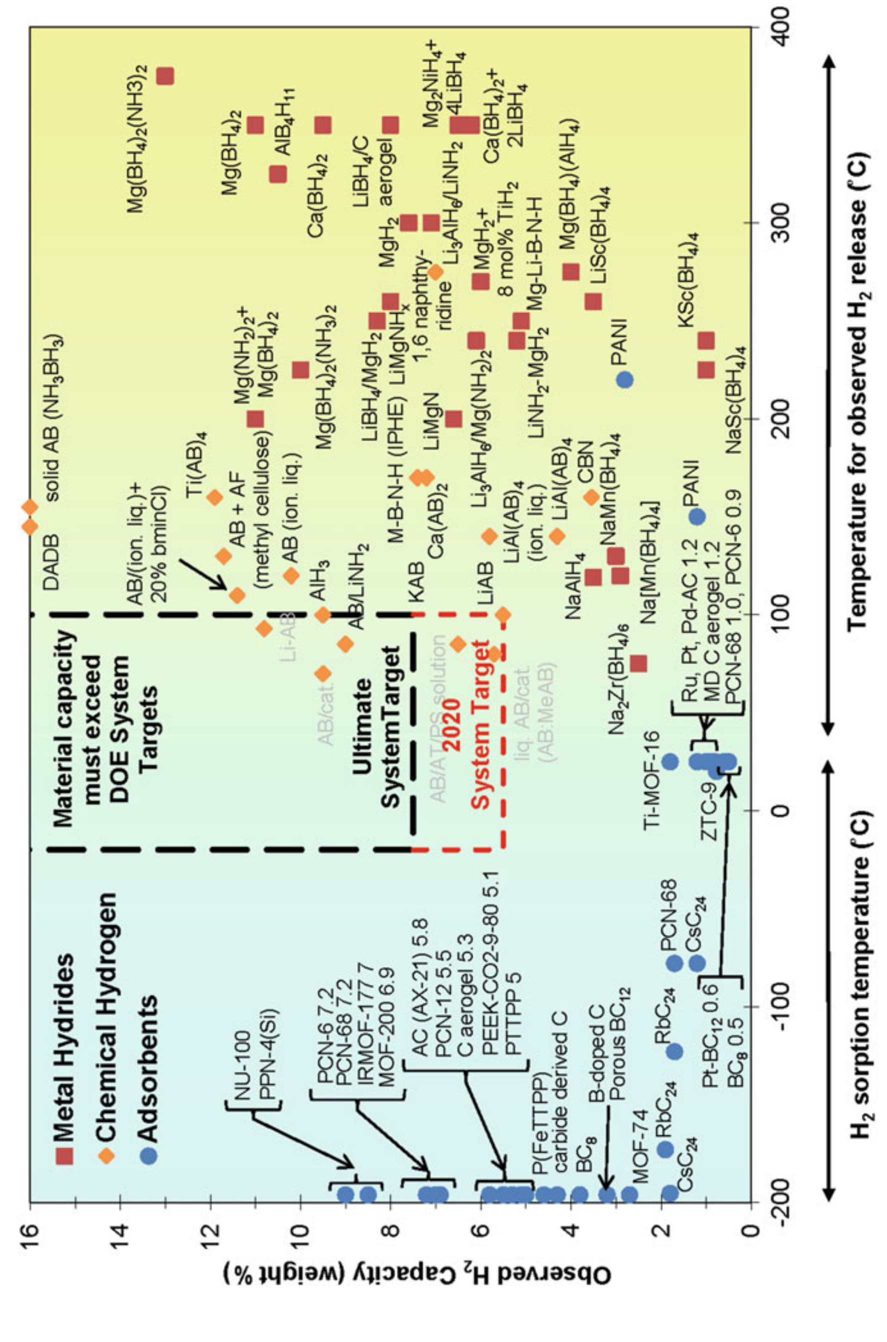

Fig. 5.14 Hydrogen gravimetric capacity as a function of hydrogen release temperature for many of the unique hydrogen storage materials. (Courtesy of the US Department of Energy)

Fig. 5.15 Bus with fuel cell drive functionality at a hydrogen fuel station. (Courtesy of Linde Group)

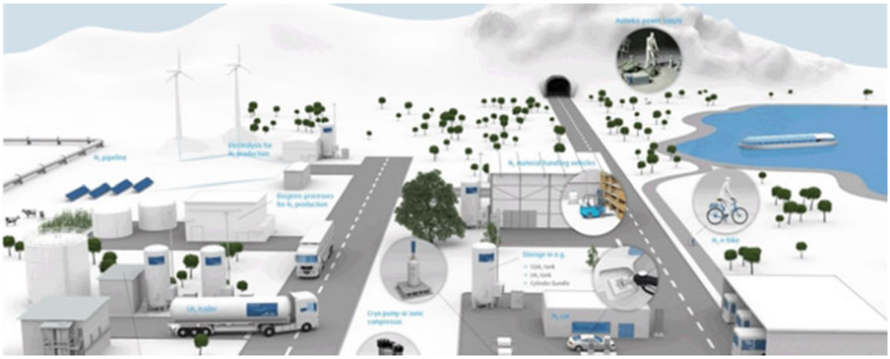

Fig. 5.16 Vehicle driven by hydrogen in a metropolitan area. (Courtesy of Linde Group)

Fig. 5.17 Bicycle driven by hydrogen. (Courtesy of Linde Group)

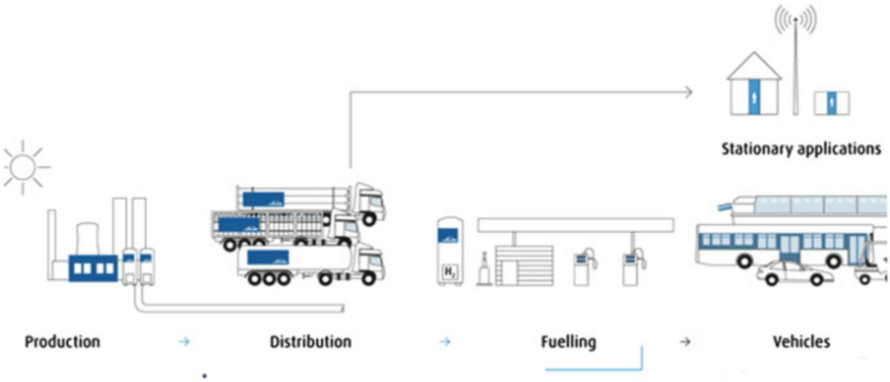

Fig. 5.18 Various industry applications of hydrogen. (Courtesy of Linde Group)

With the ionic compressor and the cryo pump, Linde has two cutting-edge, self-developed and patented technologies in its portfolio which are reliable, require little maintenance, and have high energy efficiency. Both systems can be tailored to meet individual requirements. Linde is also the first company worldwide that can produce small series of hydrogen fueling technologies.

5.14 Electrical Energy Storage

Electrical energy storage (EES) is one of the key technologies in the areas covered by the International Electrotechnical Commission (IEC). EES techniques have shown unique capabilities in coping with some critical characteristics of electricity, for example hourly variations in demand and price. In the near future EES will become indispensable in emerging IEC-relevant markets in the use of more renewable energy, to achieve CO_2 reduction, and for smart grids [43].

Historically, EES has played three main roles. First, EES reduces electricity costs by storing electricity obtained at off-peak times, when its price is lower, for use at peak times instead of electricity bought then at higher prices. Secondly, in order to improve the reliability of the power supply, EES systems support users when power network failures occur due to natural disasters, for example. Their third role is to maintain and improve power quality, frequency, and voltage [43].

Regarding emerging market needs, in on-grid areas, EES is expected to solve problems—such as excessive power fluctuation and undependable power supply—associated with the use of large amounts of renewable energy. In the off-grid domain, electric vehicles with batteries are the most promising technology to replace fossil fuels by electricity from mostly renewable sources.

The smart grid has no universally accepted definition, but in general it refers to modernizing the electricity grid. It comprises everything related to the electrical system between any point of electricity production and any point of consumption.

Through the addition of smart grid technologies the grid becomes more flexible and interactive and can provide real-time feedback. For instance, in a smart grid, information regarding the price of electricity and the situation of the power system can be exchanged between electricity production and consumption to realize a more efficient and reliable power supply. EES is one of the key elements in developing a smart grid [43].

5.14.1 Characteristics of Electricity

Two characteristics of electricity lead to issues in its use, and at the same time generate the market needs for EES. First, electricity is consumed at the same time as it is generated. The proper amount of electricity must always be provided to meet the varying demand. An imbalance between supply and demand will damage the stability and quality (voltage and frequency) of the power supply even when it does not lead to totally unsatisfied demand [43].

The second characteristic is that the places where electricity is generated are usually located far from the locations where it is consumed. Generators and consumers are connected through power grids and form a power system. Due to the locations and quantities of power supply and demand, much power flow may happen to be concentrated into a specific transmission line and this may cause congestion. Since power lines are always needed, if a failure on a line occurs (because of congestion or any other reason) the supply of electricity will be interrupted; also, because lines are always needed, supplying electricity to mobile applications is difficult. The following sections outline the issues caused by these characteristics and the consequent roles of EES.

5.14.2 Electricity and the Roles of Electrical Energy Storage

The high generation cost of electricity during the peak-demand period is a fundamental concern. Power demand varies from time to time (see Fig. 5.19), and the price of electricity changes accordingly. The price for electricity at peak-demand periods is higher and at off-peak periods lower. This is caused by differences in the cost of generation in each period.

During peak periods, when electricity consumption is higher than average, power suppliers must complement the base-load power plants (such as coal-fired and nuclear) with less cost-effective but more flexible forms of generation, such as oil and gas-fired generators. During the off-peak period, when less electricity is consumed, costly types of generation can be stopped. This is a chance for owners of EES systems to benefit financially. From the utilities' viewpoint there is a huge potential to reduce total generation costs by eliminating the costlier methods through storage

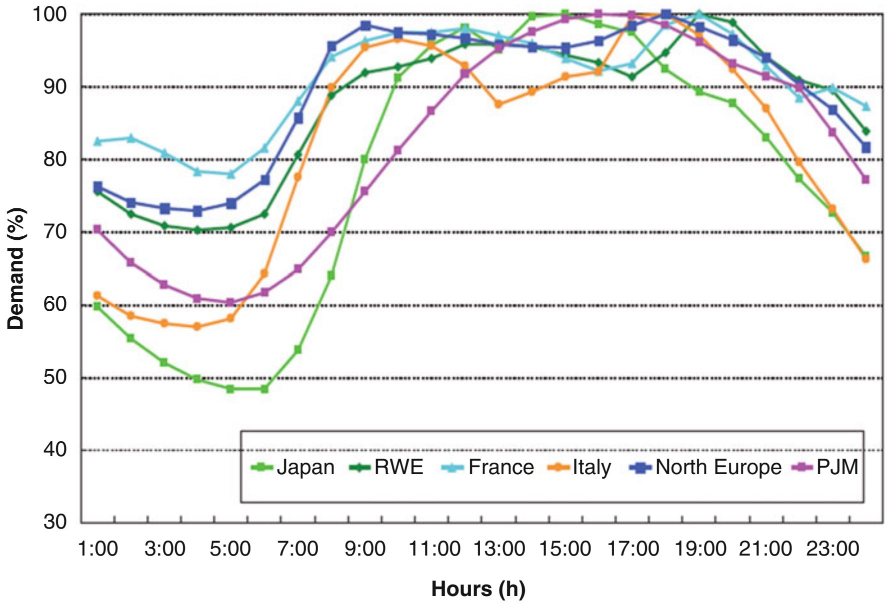

Fig. 5.19 Comparison of daily load curves. (Courtesy of IEEJ—The Institute of Energy Economics, Japan, 2005)

of electricity generated by low-cost power plants during the night being reinserted into the power grid during peak periods.

With high photovoltaic and wind penetration in some regions, cost-free surplus energy is sometimes available. This surplus can be stored in EES and used to reduce generation costs. Conversely, from the consumers' point of view, EES can lower electricity costs as it can store electricity bought at low off-peak prices and they can use it during peak periods in the place of expensive power. Consumers who charge batteries during off-peak hours may also sell the electricity to utilities or to other consumers during peak hours.

A fundamental characteristic of electricity leads to the utilities' second issue: maintaining a continuous and flexible power supply for consumers. If the proper amount of electricity cannot be provided when consumers need it, the power quality will deteriorate and, at worst, may lead to service interruption. To meet changing power consumption levels, appropriate amounts of electricity should be generated continuously, relying on an accurate forecast of the variations in demand.

Power generators therefore need two essential functions in addition to the basic generating function. First, generating plants are required to be equipped with a "kilowatt function," to generate sufficient power (kW) when necessary. Secondly, some generating facilities must possess a frequency control function, fine-tuning the output so as to follow minute-by-minute and second-by-second fluctuations in demand, using the extra power from the kilowatt function if necessary. Renewable energy facilities such as solar and wind do not possess both a kilowatt function and a

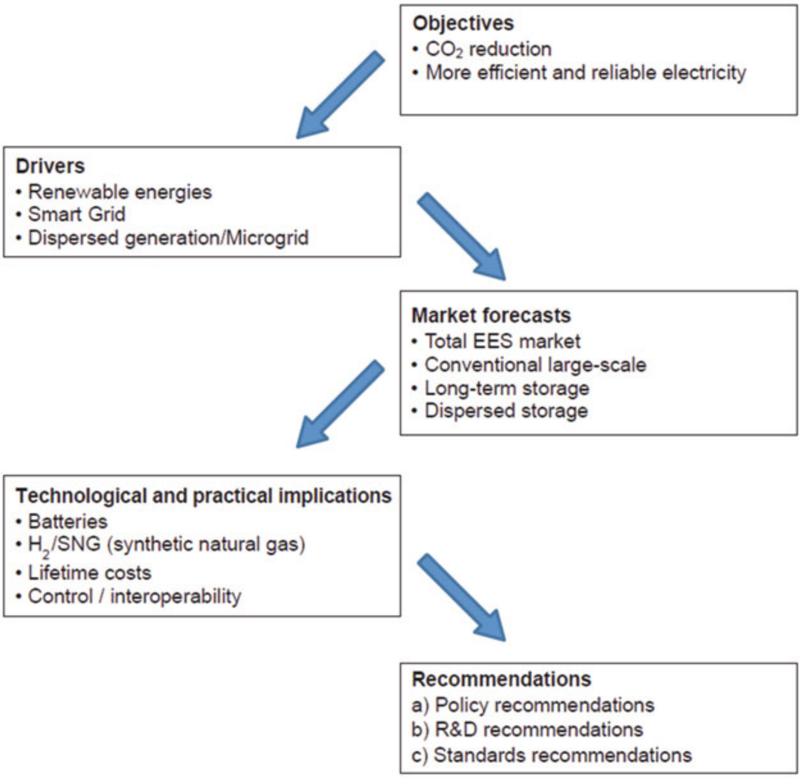

Fig. 5.20 Flowchart of the logical progression of electrical energy storage (EES) objectives. R&D research and development. (Courtesy of the International Electrotechnical Commission)

frequency control function unless they are suitably modified. Such a modification may be a negative power margin (i.e., decreasing power) or a phase-shift inverter.

EES is expected to be able to compensate for such difficulties with a kilowatt function and a frequency control function. Pumped hydro has been widely used to provide a large amount of power when generated electricity is in short supply. Stationary batteries have also been utilized to support renewable energy output with their quick response capability.

Figure 5.20 provides an overall illustration of ESS to given an overall perspective. Note that in the electricity market, global and continuing goals are carbon dioxide reduction and more efficient and reliable electricity supply and use.

Corresponding to these goals, three major drivers determining the future of EES have been identified: the foreseeable increase in renewable energy generation, the design and rollout of smart grids, and the future spread of dispersed generation and dispersed management of electrical energy—referred to here for simplicity as "microgrids." These drivers are only partly independent of each other: renewables clearly encourage, and simultaneously need, microgrids, and the increase in both renewables and dispersed sources demands a smarter grid. However, these three drivers illuminate different aspects of what will affect the future of EES systems.

The results of these drivers on future demand for EES may be divided into four market segments: the total EES market, conventional large-scale systems (e.g., pumped hydro storage [PHS]), long-term storage (e.g., H_2), and dispersed storage. How these markets are expected to develop has direct implications for which technologies will be most needed, which technology will need what type of further development, what considerations will influence rollout and penetration, and what implementation problems may be expected.

For further information refer to IEC white paper on EES [43].

5.15 Strategic Asset Management of Power Networks

Electricity networks around the world are facing a once-in-a-lifetime level of profound challenges, ranging from the massive uptake of distributed generation devices, such as rooftop solar generation, through to significant changes in the control and communications equipment used in the network itself. Power networks in developed nations are struggling with an equipment base nearing the end of its lifetime, whilst those in developing nations wrestle with trying to identify best-practice examples on which to model their operations. Compounding these challenges, there is ever-increasing regulatory and funding pressure being placed on electricity network businesses to justify their management actions and expenditure decisions [44].

There is great variation around the world on how electricity network companies approach what are arguably their number one challenge—the design, maintenance, and operation of a large network of electrical equipment. Network companies often take quite different approaches in testing equipment, calculating the lifetime and financial costs of various equipment maintenance options, and even reporting on the performance of their system. The variety here is hardly intentional—it stems from a lack of internationally accepted global standards or guidelines on how to practice asset management in the electricity network sector.

This current lack of international standards or guidelines on asset management for electrical networks will have a significant impact on the reliability and future viability of the electricity sector.

Whilst standards such as the ISO 55000 series provide general guidance on best-practice asset management procedures, they do not provide the industry-specific guidance that is needed given the operational methods and challenges of the electricity transmission and distribution industry.

The current situation means that:

- Network businesses around the world use different metrics to measure and report on the performance of their network. Without a commonly accepted definition of ways to calculate, for example, failure rates, it is very difficult to benchmark across organizations or jurisdictions.

- There is a lack of consensus on what are best practice methods for everything from testing the health of a particular item of equipment to prioritizing various asset management options. This makes stakeholder communication difficult, and means many electricity network businesses waste time and resources developing their own methods to address a particular problem. This situation is particularly exacerbated in developing nations or in the context of relatively small organizations, who could benefit greatly by simply adopting best practice methods developed by others.
- Without worldwide standards on measuring and reporting on electricity network asset management procedures and performance, broader stakeholder engagement is very difficult. When a network business cannot benchmark its performance against peers, or demonstrate that it is following industry recognized best practice, stakeholders such as regulators or funding bodies can struggle to trust the network business's management decisions or appreciate the full depth of challenges ahead.

Electricity networks in many developed nations face the very significant challenge of an aging asset base. In many nations, electricity network rollout proceeded apace throughout the 1940s to 1980s but has slowed in recent years. Many significant items of equipment are now operating close to, or even beyond, their expected retirement age.

In many developed nations, the age of the asset base and the current slow rate of replacement mean it would take hundreds of years to renew all assets. This has significant reliability implications.

The aging equipment problem is not just one of equipment wear—it also constitutes a human resources issue, as in many cases the people with the skills and expertise to complete maintenance, or the experience needed to make asset management decisions regarding this older equipment, have retired from the industry. With an equipment fleet nearing the end of its life and a shortage of parts or people to maintain it, there are very significant implications for the reliability of electricity networks in many developed nations.

Whilst aging equipment may not represent such a challenge in developing nations, or in others with more recently installed networks, simply understanding the optimal path forward amidst a plethora of technologies, management options, and an often challenging regulatory or funding environment can be very difficult.

We need to consider the elaboration of detailed international standards or guidelines to introduce a common language across the electricity network business industry regarding current system performance. Metrics such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are vital to the benchmarking of electricity network performance, yet such metrics are calculated differently around the world.

5.16 Orchestrating Infrastructure for Sustainable Smart Cities

Cities are facing unprecedented challenges. The pace of urbanization is increasing exponentially. Every day, urban areas in the United States grow by almost 150,000 people, either due to migration or births. Between 2011 and 2050, the world's urban population is projected to rise by 72% (i.e., from 3.6 billion to 6.3 billion) and the population share in urban areas from 52% in 2011 to 67% in 2050. In addition, due to climate change and other environmental pressures, cities are increasingly required to become "smart" and take substantial measures to meet stringent targets imposed by commitments and legal obligations [45].

Furthermore, the increased mobility of our societies has created intense competition between cities to attract skilled residents, companies, and organizations. To promote a thriving culture, cities must achieve economic, social, and environmental sustainability. This will only be made possible by improving a city's efficiency, and this requires the integration of infrastructure and services. While the availability of smart solutions for cities has risen rapidly, the transformations will require radical changes in the way cities are run today.

Thus, developing smart cities is not only a process whereby technology providers offer technical solutions and city authorities procure them. Building up smart cities also requires the development of the right environment for smart solutions to be effectively adopted and used.

The development of a smart city requires participation, input, ideas, and expertise from a wide range of stakeholders. Public governance is naturally critical, but participation from the private sector and citizens of the community are equally important. It also requires a proper balance of interests to achieve the objectives of both the city and the community at large.

The IEC [45] proposes a number of answers on the *what, who*, and *how* of smart city development in their executive summary. It calls for a wider collaboration between international standardization bodies that will ultimately lead to more integrated, efficient, cheaper, and environmentally friendly solutions.

> "*Needs of cities differ strongly but… the main three pillars of development remain the same*." [45]

There is no single trend, solution, or specific approach for smart cities. Regional trends illustrate that there are divergent urban growth patterns among major regions with different levels of economic development. Still, significant disparities in the level of urbanization can also be observed across different countries within the same region. Nevertheless, all cities aiming to develop into smart cities have to be built on three sustainability pillars:

- *Economic Sustainability*

  Cities need to provide citizens with the capacity to develop their economic potential and attract business and capital. With the global financial crisis, the economic sustainability of cities has taken center stage. The crisis has unearthed considerable weaknesses in the financial models and planning strategies of public authorities in the provision of services and in their infrastructure investments. Their financial sustainability now depends also on new financial models, as well as more efficient and better-integrated services and infrastructures.

- *Social Sustainability*

  A city's attractiveness for people, business, and capital is closely related to the quality of life, business opportunities, and security and stability, which are guaranteed by social inclusiveness.
- *Environmental Sustainability*

  Cities face a number of environmental sustainability challenges, generated by the city itself or caused by weather or geological events. To reduce the impact of the city on the environment resource it is important to promote the efficient and intelligent deployment of technology and to integrate infrastructures. This process can also be developed in such a manner as to increase the resilience of the city to environmental shocks. These three pillars have one common denominator, namely the need to achieve more and better with less: efficiency. Efficiency must also be achieved in a manner that brings benefits and opportunities to citizens, making the city more dynamic and participatory.

5.16.1 Smart Technology Solutions Create Value

Rather than being an expense, smart technology integration can create considerable opportunities for added value in any city. Technology integration helps cities to improve efficiency, enhance their economic potential, reduce costs, open the door to new business and services, and improve the living conditions of its citizens. A key condition for value creation through integration is the compatibility of technologies; which is best achieved through common and consensus-based standards that ensure interoperability [45].

Presently, however, smart city projects concentrate mainly on vertical integration within existing independent infrastructure and services silos, for example, energy, transport, water, or health. A truly "smart" city requires horizontal integration as well as creating a system of systems capable of achieving considerable increases in efficiency and generating new opportunities for the city and its citizens.

5.16.2 New Approaches Needed to Smart City Solution

Cities are faced with a complex challenge, as the traditional processes of planning, procuring, and financing are not adequate for their needs. Smart cities can only exist if fundamental reforms are undertaken. Thus, there is a need for new approach and it is necessary to design, implement, and finance smart city solutions [45].

5.16.3 Stakeholders are Key Drivers to Smart City Solution

A smart city cannot be imposed by decree, as the city is shaped by a large number of individual decisions and social and technological changes cannot be fully accounted for [45]. The present advances in telecommunications, information and communication technologies (ICT), and affordable energy efficiency and energy production tools are changing the relationship between citizens and city services. Citizens are increasingly becoming providers of city services and not only users. A good plan requires participation, input, and ideas from a wide range of stakeholders within the city. This means that city planning needs to allow for bottom-up processes of modernization. The stakeholders are:

- Political leaders, managers, and operators of the local government (city).
- The service operators—public or private: water, electricity, gas, communication, transport, waste, education, and so on.
- End users and producers: inhabitants and local business representatives.
- Investors: private banks, venture capitalists, pension funds, international banks.
- Solution providers: technology providers, financiers, and investors.

Giving each of these groups a true stake in smart city development is important to achieve the necessary consensus for the changes. Their concerns need to be carefully considered and acknowledged, and ultimately the direction and next steps have to be collectively approved. In the absence of proper consultation, the authorities will sooner or later face considerable additional obstacles to make their vision a reality.

5.16.4 Without Integration Rising to the Level of Systems There Cannot be a Smart City

The transformation of a city into a smart form presents its stakeholders a wide range of challenges, including benefits and consequences when such a transformation is undertaken. A promising approach to support city planners, but also standards developing organizations (SDOs), is to model a city as a collection of activity domains in an integrated virtual organization (the city), where various groups of stakeholders (local governments, public and private corporations, academia, healthcare institutions, cultural associations, religious congregations, and financial firms) participate in operating and sustaining the city as a whole. Modeling the interrelations allows identification of pain points, gaps, and overlaps in standardization and clarification of the technical needs for integration [45].

While the technologies to develop smart cities are mostly already readily available and improving, their deployment is hampered by technical, social, and administrative challenges. Horizontal integration of infrastructures through technology is essential to reap the benefits of innovation and the potential and necessary efficiency.

Thus, interoperability is essential; without it, city planning is marred by unexpected inefficiencies leading to suboptimal outcomes and higher costs. The planning requirements for city authorities are very complex, as there are thousands of organizations and companies working in parallel to bring on the tools, systems, and products that offer potentially affordable/sustainable solutions.

To ensure that smart integrated systems are put in place in practice, internationally agreed standards that include technical specifications and classifications in order to support interoperability (i.e., devices and systems working together) are essential conditions. These include technical specifications and classifications in order to support interoperability. These are metrics against which benefits can be assessed as well as best practice documents that detail controls.

5.16.5 Horizontal and Vertical Integration a Key to Interoperability

Electric grids, gas/heat/water distribution systems, public and private transportation systems, and commercial buildings/hospitals/homes play a key role in shaping a city's livability and sustainability. To increase their performance and efficiency, these critical city systems need to be integrated [45].

The successful development of a smart city will require the combining of a bottom-up systems approach with a top-down service development and a data-centric approach. Technology integration includes everything from vertical integration from sensors, to low-cost communication, real-time analysis and control, and horizontal integration of historically isolated systems up to citizen-based services. Combined, this creates a system of systems.

Today's smart city projects are mainly focused on improving the integration of historical verticals, that is, parts of existing utilities, for example, improving energy efficiency or reducing water leakage. The next step is horizontal integration. Data from the different sectors can be combined to better manage the city and reduce risks. Thus, horizontal as well as vertical integration is key to creating value and interoperability.

5.16.6 Interoperability is the Key to Open Markets and to Competitive Solutions

Interoperability is the key to managing systems of systems and opening markets to competitive solutions. While we are now experiencing the Internet of Things (IoT) revolution (driven by the appearance of smart devices, such as wireless sensors, radio-frequency identification [RFID] tags and internet protocol [IP]-enabled devices), different producers are generating technologies using their own communication specifications and data protocols [45].

IoT market forecasts show that IoT is already making an impact on the global economy. While estimates of the economic impact during the next 5–10 years vary slightly (the International Data Corporation [IDC] estimates US$1.7 trillion in 2020 [46], Gartner sees a benefit of US$2 trillion by that time [47], and McKinsey predicts growth of US$4–11 trillion by 2025 [48]), there seems to be a consensus that the impact of IoT technologies is substantial and growing.

Future interoperability can only be guaranteed through the existence of international standards ensuring that components from different suppliers and technologies can interact seamlessly. Continued best practice sharing and development of common standards to ensure that data can flow freely between systems is essential, while maintaining the need to protect confidentiality and individual privacy.

Common terminology and procedures have to be developed in order to also ensure that organizations and businesses can efficiently communicate and collaborate, which can also be guaranteed through standards.

In addition, the multiplicity of technologies within a city now demands a top-down approach to standardization. This requires new coordination approaches between SDOs, in which all the parts of the city are jointly considered by the several technical committees involved by the different organizations. This methodology is essential as systems-level standards will enable the implementation and interoperability of smart city solutions.

5.16.7 Guiding Principles and Strategic Orientation for the International Electrotechnical Commission and Messages to Other Standards Developing Organizations

Electricity is core to any urban infrastructure system and the key enabler of cities development. As a result, the IEC has a specific role to play in the development of a smart city's set of standards. The IEC will call for, take initiative, invite, and strongly contribute to a more global and collaborative approach including not only international standardization organizations, but also all stakeholders of the smart city landscape (city planners, city operators, etc.) and specifically the citizens [45].

Technology and system integration are critical to ensure interoperability and the IEC will support active collaboration between the relevant actors as described in the following guiding principles:

- The IEC will continue to foster technology integration (electrotechnical, electronics, digital and information technology [IT]), and make sure that digital technology is fully integrated in all IEC products in a connect and share data perspective.

- The IEC shall make sure digital and IT technology suppliers are actively contributing in its work. Data aspects shall become a key issue in IEC, including IoT, data analytics, data utilization, data privacy, and cyber security.
- The system approach shall be accelerated as a top IEC priority, taking into account flexibility, interoperability, and scalability. Value creation for users (citizens and city infrastructure and service planners and operators) will remain the main driver of standardization work.
- Smart development requires solutions to be adapted to the specific needs of the city and its citizens, and standards have to be developed with this purpose in mind, removing technology barriers that prevent technology integration.

In conclusion, smart cities are necessary not only to reduce emissions, but to handle the rapid urbanization growth that the world is experiencing. Inefficiencies in urban areas bring large negative environmental and social impacts. City infrastructure is the backbone of the cities, delivering the necessary services to the population and creating the conditions for citizens to develop their professional, social, and cultural activities. Infrastructure is also essential in guaranteeing the city's resilience to environmental risks.

Until now city infrastructures have been built independently and operated separately in parallel silos (water supply, electricity, transport). Furthermore, the citizen has mainly been a consumer of services with little direct influence on the system. In a smart city, this needs to change. First of all, efficiency requires that infrastructures are appropriately interlinked horizontally. Secondly, citizens are becoming producers and service providers. In the area of energy, individuals are starting to produce energy from renewables and, thanks to the data revolution, also to deliver information and services in a number of areas. With smart systems, goods owned by citizens can be active in improving efficiency. For example, smart meters and electric cars can interact with the grid, data produced by the smart applications of the citizens can contribute to traffic control, improve emergency response, and so on. Citizens can also use the technologies to sell new services.

This change in cities needs to be accompanied by enabling conditions, which means reforming the ways cities are governed and financed—administrative reforms and new financial systems.

However, the glue allowing infrastructures to link and operate efficiently are standards. Standards are necessary to ensure interoperability of technologies and the transfer of best practices. But standards are not yet adapted to the level of technology integration we are requiring. Standard bodies still operate in sectorial parallel silos, developing standards which are not easy to understand by non-specialists, particularly city managers. Standards are facilitators for city planners, and they need to incorporate standards in planning and procurement. There is thus a need to reform the way standards are produced, ensuring those are adapted to the needs of the city planners and other service operators within the city.

Close collaboration is needed between standard bodies themselves and collaboration with outside organizations, in particular the city planners.

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