CHAPTER 1

INTRODUCTION

Global environmental concerns and the ever-increasing need for electrical power generation, steady progress in power deregulation, and tight constraints over the construction of new transmission lines for long distance power transmission have created increased interest in distributed generation (DG). Of particular interest are renewable DGs with free energy resources, such as wind and solar photovoltaic (PV), and alternative energy DG sources with low emission of pollutant gases, such as fuel cell (FC) and microturbine (MT) power generation devices.

In this chapter, some background about the restructured utility that lead to increased interest in DG is given first. Then, an overview of distributed generation and its different types is addressed. Distributed generation applications of fuel cells will be covered next. Finally, since all viable types of fuel cells use hydrogen (H_2) as fuel, the last part of this chapter covers the hydrogen economy, a need for a fuel-cell-powered society.

1.1 BACKGROUND: A BRIEF HISTORY OF U.S. ELECTRIC UTILITY FORMATION AND RESTRUCTURING [1–4]

Electric utilities were initially formed in the United States in late nineteenth century and established as isolated electric systems without

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Modeling and Control of Fuel Cells, By M. Hashem Nehrir and Caisheng Wang

connection to one another. In 1920s, the isolated electric systems were interconnected to help each other in load sharing and backup power. In 1934, the U.S. Congress passed the *Public Utility Holding Company Act* (*PUHCA*), where it increased the jurisdiction of the Securities Exchange Commission as well as the jurisdiction of the Federal Power Commission. This act created incentives for the isolated utilities to expand and create regional utilities, where several state utilities joined under a regional utility company. Each entity operated in its region under an investor-owned monopoly, owning generation, transmission, and distribution. However, each utility was subject to state regulation, where the utilities' rates had to be approved by the Public Utilities Commissions.

In 1977, the U.S. Department of Energy (DOE) was created to oversee the nation's energy-related activities, and under it, the Federal Energy Regulatory Commission (FERC) was formed to establish rules for generation, transport, and quality of power, among others.

The U.S. Congress passed the *Public Utilities Policy Act* (*PURPA*) in 1978. This act encouraged the construction and integration of nonutility-owned power generation technologies, including conventional and nonconventional (renewable/alternative) energy sources, to the utility grid. Under the above act, FERC sets rules for the interconnection of these power generation sources to the utility grid. Until near the end of the twentieth century, the utilities were still operating under the vertical (monopoly) structure; each utility owned generation, transmission, and distribution in a given region.

The major *Energy Policy Act*, enacted by the Congress in 1992, drove the U.S. power industry into complete restructuring; now, more than 15 years later, it is still ongoing. As a result of this act, "Exempt Wholesale Generator (EWG)" entities were created with the restriction that EWGs can only sell the power they generate on the wholesale market and not on the retail market. On the contrary, electric utilities are not required to purchase power from EWGs, but they are required to purchase power from qualified power generating facilities that include renewable/alternative energy power generation facilities. This energy policy act created a major shift in regulatory power from the regional level to the federal level with FERC continuing to be its rule making body. According to the policy act, the power generating entities had transmission access for the power they generated. In 1996, FERC issued the "Mega Rule," which spelled out how open access transmission of power is to be handled. It requires the transmission system owners to treat all transmission users on a nondiscriminatory basis and file tariffs for their transmission services.

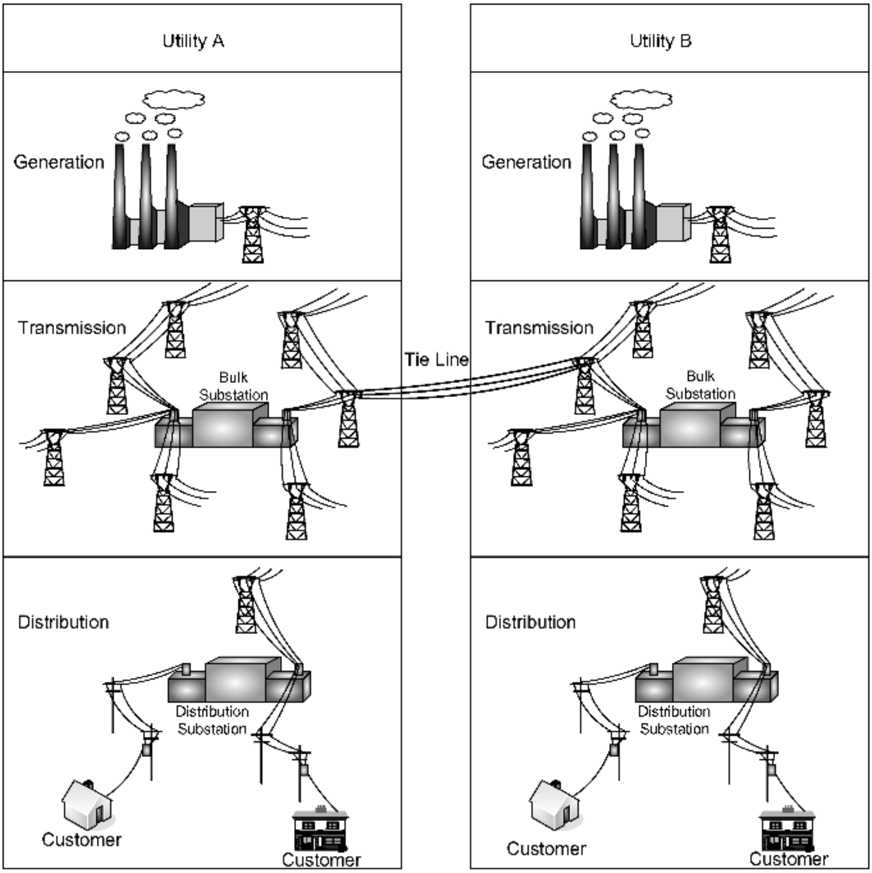
Gradually, the vertical electric utility, where one company owned generation, transmission and distribution facilities, changed to a horizontal structure. In this new paradigm, generation, transmission and distribution companies became separate and independent, namely GENCO, TRANSCO, and DISCO. Generation being the only one of the three entities that is truly deregulated, numerous independent power producers (IPPs) were formed and found an opportunity to market their power. This change also created the opportunity for large and small power marketers to be formed to begin marketing the power produced by IPPs (GENCOs). Since the start of power deregulation in 1996, FERC has promoted the formation of regional transmission organizations (RTOs).

In 1999, FERC Order 2000 required the transmission system owners to put their transmission system under the control of RTOs. Today, several regions have established independent system operators (ISOs), or are in the planning stage to establish ISOs, to operate their transmission systems and provide transmission services. In 2005, the U.S. government passed the *Energy Policy Act of 2005*. This act authorizes the creation of an electric reliability organization (ERO), giving it the authority to enforce compliance of all market participants with the reliability standards of the National Electric Reliability Council (NERC), which was voluntary prior to 2005. In 2006, FERC certified NERC to be the U.S. ERO. Given the close interconnection of the U.S. and Canadian electric system, NERC is also seeking recognition as the ERO from the Canadian government.

Figure 1.1a shows the structure of the vertical utility of the past, where generation, transmission, and distribution systems in one region were owned by the utility in that region and sale of power within the region took place by that utility. Figure 1.1b shows the restructured horizontal utility, where different GENCOs market their power and TRANSCOs and DISCOs arrange the transport of power to customers. Figure 1.2 shows the role of ISO in the restructured utility and the deregulated power market. ISOs oversee the transport of power from generation to transmission to distribution including the marketing (buy/sell) of electric power. The structure and different entities of ISO in a region depends on the market structure in that region. At the time of writing this book, power deregulation and utility restructuring are being actively pursued worldwide.

1.2 POWER DEREGULATION AND DISTRIBUTED GENERATION [1,4]

As explained in the previous section, numerous IPPs were formed as a result of power deregulation, which also spurred the consideration of DG sources. The main reason behind this consideration was, and still is,



(a) Utilities of past.

FIGURE 1.1 Utility structure of past and present.

economics and the driving market forces. The fast growth in demand for electricity along with the slow growth in generation capacity in the last quarter of the twentieth century resulted in shrinking spinning reserve margins, which as a result, made power systems vulnerable and brought about the need for additional power generation. The economic constraints behind building large central power generating stations and expanding the transmission infrastructure encouraged the consideration of DGs. DGs are modular in structure and less costly to build, normally placed at the distribution level at or near load centers, and are small in size (relative to the power capacity of the system in which they are placed). When possible, DGs can be strategically (optimally) placed in distribution systems for grid

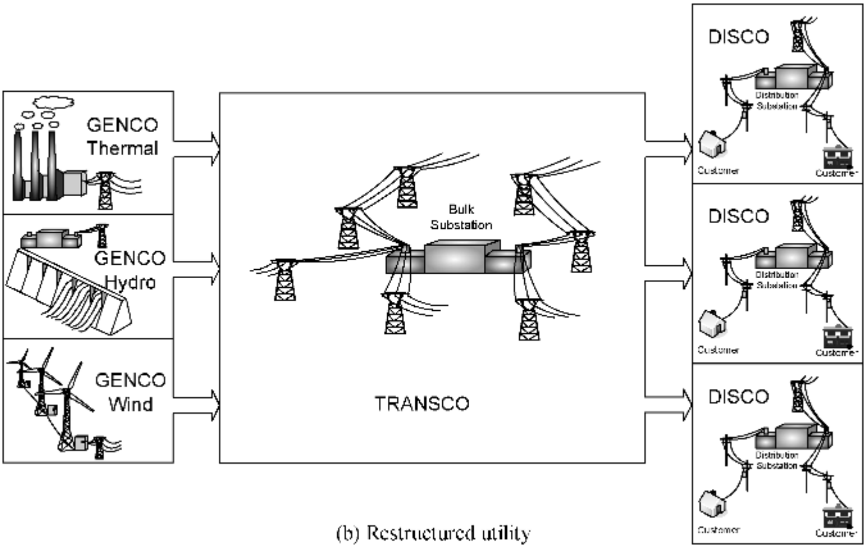


FIGURE 1.1 (*Continued*)

reinforcement, reducing power losses, on-peak operating costs, and improving voltage profiles and load factors. As a result, their installation can defer or eliminate the need for system upgrades, and can improve system integrity, reliability and efficiency. Because of these benefits, DG became, and still is, a priority.

DGs also have barriers and obstacles, which must be overcome before they can become a mainstream service. These barriers include technical, economic, and regulatory issues. Some of the proposed technologies have not yet entered the market; they need to meet some pricing and performance targets before entry. In addition to this, the most important

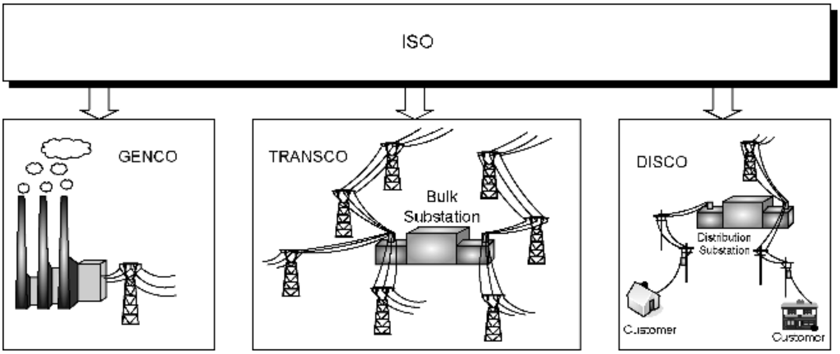


FIGURE 1.2 Role of ISO in the restructured utility.

issues facing DGs are *safety issues*, *operation issues, power quality issues, and accountability issues*. These issues are briefly discussed below:

Safety issues are very important. Grid-connected DGs can keep the power lines live after a grid power outage (thus making it unsafe for maintenance crews to work on the power lines) if appropriate measures are not taken to disconnect the DGs from the grid shortly after the outage. The IEEE Power Engineering Society has taken a leading role in developing standards (e.g., IEEE Standard 1547 [26]) for detection of *power islands*, that is, when the grid power goes out and DGs are still connected to the grid. According to the above standard, the islanded DGs must be disconnected from the grid within two seconds. Research is under way to develop reliable islanding detection and autonomous operation of DGs so that they can operate as isolated DGs to provide power to some critical loads, which they may be feeding. In spite of the technical and socio-economic issues, DGs, conventional and modern, are expected to become wide-spread around the globe.

Operation and reliability issues of DGs could have positive or negative impacts on the distribution systems to which they are connected. DGs are normally connected to the utility grid at the distribution level and can bring voltage support to the grid by providing reactive power support. This condition could be helpful for reliable operation of distribution systems provided that the distribution system is properly configured for inclusion of DGs. On the contrary, DGs could have negative impact on distribution systems operation. For example, DGs with variable output power (i.e., wind and solar) may not be able to provide the required power at the right time, or, DGs that use induction generators (e.g., wind), receive reactive power from the grid and could actually worsen reactive coordination and operational reliability.

Power quality issues are becoming more pronounced as the more modern DG technologies (e.g., wind, photovoltaic, fuel cells) utilize power electronic devices (i.e., dc/dc and dc/ac converters) to interface with the utility grid. These devices inject nonsinusoidal (or at least imperfect sinusoidal) current to the grid. If the harmonics generated by these devices are not properly filtered, they can cause operational problems and possible malfunction of loads connected to distribution system to which the DGs are connected. IEEE standards 519-1992 and 1547-2003 recommend that the total current harmonic distortion injected by a DG source should be less than 5% [25,26].

Accountability issues related to DGs can be very complex. The end-users may not know or care about the nature of the restructured power industry.

However, they want reliable power. In a distribution system enhanced with one or more DGs, if the DGs trip out or are not able to provide the desired amount of power to the grid, the quality of power provided to the end-users may diminish. Who is accountable to the customers for such problems, the DG owners or the end-use service provider? This is a serious problem facing the restructured power industry, which will increase in magnitude as DGs penetrate the power grid. Therefore, carefully written policies, regulations, and buy–sell agreements are needed to address such problems—thus making the role of FERC in the deregulated power market more important than ever.

1.3 DG TYPES

In this book distributed generation is referred to small generators, starting from a few kWs up to 10 MW, whether connected to the utility grid or used as stand-alone at an isolated site. Normally small DGs, in the 5–250 kW range serve households to large buildings (either in isolated or grid-connected configuration). In grid-connected configuration, DGs with larger capacities are managed by a utility or an IPP. They are located at strategic points, normally at the distribution level, near load centers, and used for such purposes as capacity support, voltage support and regulation, and line loss reduction. DG technologies can be categorized to renewable and nonrenewable DGs.

Renewable energy technologies are in general sustainable (i.e., their energy source will not run out) and cause little or no environmental damage; they include the following:

- Solar photovoltaic
- Solar thermal
- Wind
- Geothermal
- Tidal
- Low-head (small) hydro
- Biomass and biogas
- Hydrogen fuel cells (hydrogen generated from renewable resources).

Nonrenewable energy technologies are referred to those that use some type of fossil fuel such as gasoline, diesel, oil, propane, methane, natural gas, or coal as their energy source. Fossil fuel-based DGs are not considered sustainable power generation sources as their energy source will not renew. They include the following:

- Internal combustion engine (ICE)
- Combustion turbine
- Gas turbine
- Microturbine
- Fuel cells (using some type of fossil fuel, e.g., natural gas, to generate hydrogen).

Both types of DGs (renewable and nonrenewable) discussed above are popular and widely used around the world. The downside of renewable resource DGs is the intermittent nature of their renewable energy source; and the disadvantage of fossil fuel-based DGs is that they generate environmentally polluting, and in some cases poisonous exhaust gases, such as SO_2 and NO_x, which are similar to the pollutants from conventional centralized power plants. However, considering the increasing need for electricity, the benefits of the nonrenewable DG technologies with low emission of polluting gasses exceed their disadvantages and are expected to be used in the foreseeable future.

Fuel cell technology can belong to either of the above categories. If the hydrogen fuel needed to power the fuel cell is generated from a renewable source, the fuel cell power-generating unit is considered a renewable energy technology. An example of this case (i.e., wind and solar energy used to generate hydrogen to fuel a fuel cell stack) will be covered in Chapter 9. On the contrary, if hydrogen is produced from a fossil fuel source (e.g., natural gas or methane), the fuel cell is considered a nonrenewable energy technology.

Through careful design, selected fossil fuel driven DGs can be built to oxidize some of the fossil fuel (by combining with oxygen) to produce heat. Such operation modes, whether in electromechanical (rotational) or electrochemical (fuel cell) systems, are referred to as combined heat and power (CHP) operation mode.

Table 1.1 shows some existing and potential DG technologies, nonrenewable and renewable, and their capacity and efficiency ranges.

Most of the new DG technologies include power electronic devices to provide usable output power. These DGs are often referred to as *power electronically interfaced DGs*. Enormously improved power control of these generation sources has become possible by controlling their power electronic interfacing units. In a common approach the output voltage of these generation devices, whether dc or ac, is converted to a controlled

TABLE 1.1 Dispatchability, Capacity Range, and Efficiency Range of Existing and Potential DG Technologies [2,5,27,28]

DG Types	Capacity Range	Efficiency Range (%)	Dispatchable
ICE	50 kW–5 MW	25–40	Yes
Gas turbine	1–100 MW	30–40	Yes
Microturbine	10–500 kW	20–30	Yes
Wind	150 kW–5 MW	<40	No
Solar PV	200 W–10 MW	10–20	No
Biomass	20–50 MW	10–20	Yes
Fuel cells	0.5 kW–3 MW	40–65	Yes
PAFC	50 kW–1 MW	~40	
PEMFC	0.5 kW–1 MW	35–40	
SOFC[a]	5 kW–2 MW	45–65	
MCFC[a]	5 kW–3 MW	50	

[a] Efficiency of these fuel cells could reach or exceed 80% in CHP operation mode.

dc voltage and then converted to usable ac, which can be connected to a utility grid or used stand-alone.

Distributed generation devices can pose both positive and negative impacts on existing power systems. These new issues, such as islanding detection and operation (discussed earlier) and optimal size and placement of DGs in power systems, have made DG operation an important research area, which can help obtain maximum potential benefits from DGs.

Since this book's focus is on Fuel cell DGs (FCDGs), this topic will be covered in the next section.

1.4 FUEL CELL DG

Fuel cells are static energy conversion devices that convert the chemical energy of fuel directly into dc electrical energy. Fuel cells have a wide variety of potential applications including micropower, auxiliary power, transportation, stationary power for buildings, and cogeneration applications.

Since entering the twenty-first century, fuel cell technologies have experienced exponential growth; the number of installed FC units worldwide is increasing rapidly. As shown in Fig. 1.3, Government policies, public opinion, and technology advances in fuel cells all contributed to this phenomenal growth. It is expected that FC (and FCDG) technology will advance in the first half of the twenty-first century as the computer technology did in the second half of the twentieth century. However, a

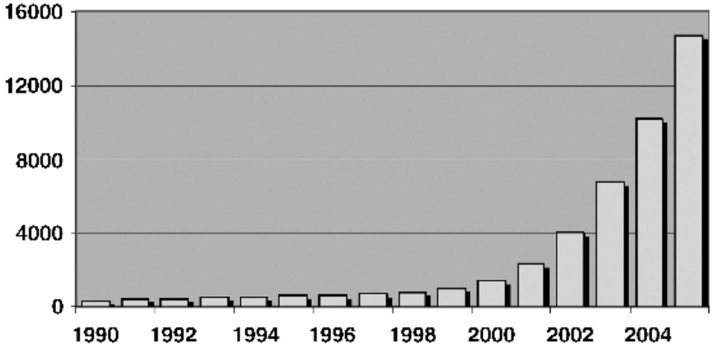


FIGURE 1.3 Cumulative installed FC units worldwide, 1990–2005. *Source*: 2005 Worldwide survey of fuel cells, www.fuelcelltoday.com [29].

number of barriers must be overcome before FCDG can be a reliable energy source. The main barriers are technical and economic issues.

In 2005, The U.S. DOE updated its "Hydrogen, Fuel Cells and Infrastructure Technologies Program's Multi-Year Research, Development and Demonstration Plan." In this plan, it lays out industry targets for key fuel cell performance indices such as cost, durability, and power density. In 1999, the Solid State Energy Conversion Alliance (SECA) was founded for bringing together government, industry, and the scientific community to promote the development of SOFC, which shows great potential for residential, auxiliary power, and DG applications. Through these years, collaborative work among the government (through the national laboratories), industry, and universities, have brought great advances in fuel cell technologies. Such supports give FCs a potential bright future, although extensive work is still needed to be done before they can play an important role in the energy market.

Among different types of fuel cells, polymer electrolyte membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC), and molten carbonate fuel cells (MCFC) show great potential in DG applications. PEMFC and SOFC also show great potential in transportation applications. Compared with conventional power plants, these FCDG systems have many advantages such as high efficiency, zero, or low emission (of pollutant gases) and flexible modular structure. FCDGs can be strategically placed at any site in a power system (normally at the distribution level) for grid reinforcement, deferring or eliminating the need for system upgrades, and improving system integrity, reliability, and efficiency.

Table 1.2 gives the current status and the DOE goals for PEMFC [17,18], and Table 1.3 summarizes the current development stage of SOFC and

TABLE 1.2 Current Status and the DOE Targets for PEMFC Stack[a] in Stationary Applications[b]

Characteristics	Units	Current Status	2010 Goal
Stack power density	W/L	1330	2000
Stack specific power	W/kg	1260	2000
Stack efficiency @ 25% of rated power	%	65	65
Stack efficiency @ rated power	%	55	55
Precious metal loading	g/kW	1.3	0.3
Cost	$/kWe	75	30
Durability with cycling	h	2200[c]	5000
Transient response (time to go from 10% to 90% of rated power)	s	1	1
Cold startup time to 90% of rated power @ −20°C ambient temperature	s	100[c]	30
Survivability (lowest ambient temperature)	°C	−40	−40

[a] Based on the technical targets reported in [17] for 80 kWe (net) transportation fuel cell stacks operating on direct hydrogen.

[b] Excludes hydrogen storage and fuel cell ancillaries: thermal, water, air management systems.

[c] Based on the performance data reported by Ballard Power Systems, 2005 [18].

SECA targets [19–21]. Considering the emphasis put on FC research, the potential for reaching the DOE and SECA goals is high.

Fuel cell energy systems include power electronic interfacing devices to provide controllable dc and ac power. Voltage and power control is normally achieved by controlling the power electronic devices. Figure 1.4 shows the major processes of a fuel cell energy system. Fuel (e.g., natural gas) containing hydrocarbons is fed to the fuel processor to be cleaned and converted into a hydrogen-rich gas. The principle of gas reforming will be briefly discussed in Section 1.5.3. Through electrochemical energy conversion (explained in Chapter 2), in each fuel cell, the energy of hydrogen is converted to dc electricity. The cells are bundled together in series and parallel combinations (called a fuel cell stack) to produce the desired power and voltage for a particular application. The power-conditioning unit converts the electric power from dc into regulated dc or ac for consumer use. An energy storage device may also be a part of the fuel cell system for energy management and/or load transient mitigation purposes, where energy flow can be bi-directional between the fuel cell and the storage system, as shown in the figure. The FC by-products include heat and clean exhaust, which can be used for water or space heating, or to produce additional electricity.

TABLE 1.3 Current Status and the SECA Targets for 3–10 kW SOFC Module in Stationary Applications

	Phase			
	I[a]	Current Status	II	III (By 2010)
Cost	800$/kW	724$/kW[b]	[c]	$400/kW
Efficiency	35–55%	41%[b]	40–60%	40–60%
Steady state test hours	1,500	1,500	1,500	1,500
Availability	80%	90%[b]	85%	95%
Power degradation per 500 h	≤2%	1.3%[d]	≤1%	≤0.1%
Transient test cycles	10	n/a	50	100
Power degradation after cycle test	≤1%	n/a	≤0.5%	≤0.1%
Power density	0.3 W/cm^2	0.575 W/cm^2[e]	0.6 W/cm^2	0.6 W/cm^2
Operating temperature	800°C	700–750°C[d]	700°C	700°C

[a] The goals of Phase I have been achieved. GE is the first of six SECA industry teams to complete Phase I of the program [20].

[b] Based on the data reported by GE.

[c] Evaluate the potential to achieve $400/kW [19].

[d] Based on the data reported by FuelCell Energy [21].

[e] Based on the data reported by Delphi [20].

Voltage and power control of a FC system can be achieved through proper control of the power-conditioning unit. Therefore, accurate models of FC power plants and the power electronic devices are necessary to evaluate the coordination between the two, and for controller design. The

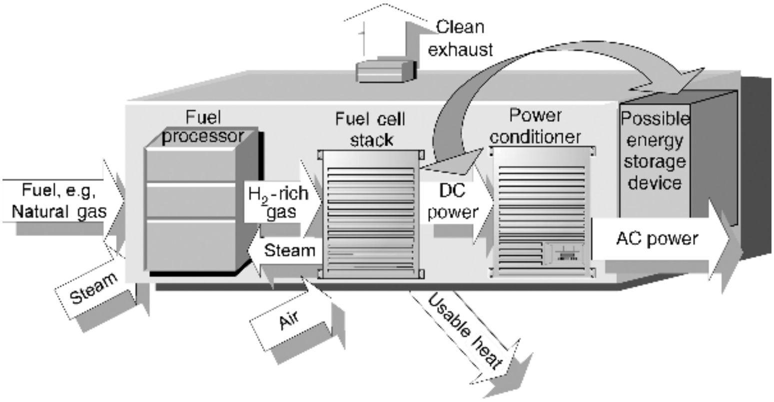


FIGURE 1.4 Major processes in a generic FC energy system.

modeling of FCDG systems and controller design for the components of the power-conditioning unit (i.e., dc/dc converter and dc/ac converter) will be discussed in detail in Chapters 3, 4, 6, 8, and 9.

1.5 THE HYDROGEN ECONOMY

1.5.1 Introduction

The concept of hydrogen energy, hydrogen production and use, and the hydrogen economy is not new. Since William Grove, a British scientist, first demonstrated the basic principle of fuel cell operation in 1839 utilizing hydrogen and oxygen (see Chapter 2), many researchers around the world have looked into different ways of hydrogen production and use. Investigations on different methods of energy production, in general, and hydrogen production, in particular, increased in the 1950s and accelerated significantly after the oil embargo, by oil producing countries, in 1973. Since then, energy production from renewable resources such as wind and solar, hydrogen production using the generated energy, and fuel cells have caught worldwide attention, for example [6–10]. Such research activities are currently ongoing and at their peak.

In 1990, the U.S. Congress passed a Hydrogen Research and Development Act, which required the Department of Energy to develop critical hardware for hydrogen technology, as an important step toward the H_2-based economy. Based on this act, a Hydrogen Technical Advisory Panel, composed of experts from industry and academia, was formed to advise the Secretary of Energy on the status and recommended direction of hydrogen energy development. In 1996, Congress passed the Hydrogen Future Act, further promoting research for the development and demonstration of hydrogen production, storage, transport, and use.

In 2001, DOE announced its National Vision for transition to a hydrogen-based economy to 2030 and beyond [22]. In response to a request from the DOE, the National Academies' National Research Council (NRC) appointed the Committee on Alternatives and Strategies for Future Hydrogen Production and Use in 2002 to address the complex subject of an H_2 economy. This committee was formed by the NRC's Board on Energy and Environmental Systems and the National Academy of Engineering (NAE) Program Office [11]. It evaluated the cost and status of technologies for H_2 production, transportation, storage, and end use. The committee also reviewed DOE's hydrogen research, development, and demonstration strategies. The visions held by this committee are still believed to be true.

The hydrogen economy is referred to an economy that relies on hydrogen as the commercial fuel that would deliver a substantial fraction of a nation's energy-based goods and services. This vision is based on two expectations: (1) that H_2 can be produced from domestic energy sources in a manner that is affordable and environmentally friendly, and (2) that applications using H_2-based FCs and FC vehicles (FCVs) can gain market share in competition with conventional power generation sources and transportation vehicles. To the extent that these expectations can be met, the entire world would benefit from reduced vulnerability to energy disruptions and improved environmental quality, especially through lower carbon emissions. However, before this vision can become a reality and the transition to such an economy can take place, many technical, social, and policy challenges must be overcome to make the use of H_2-based FCs and FCVs widespread [11–15].

H_2 is a versatile energy carrier (an energy storage medium, not a primary energy source) with the potential for use in a variety of applications, including stationary electrical power generation and transportation. H_2 is combustible and can be used as fuel in conventional internal combustion engines to produce mechanical or electrical power. It can also be combined with oxygen within FCs to produce electricity. In both cases, the overall energy efficiency of using H_2 is higher than ICEs operating with conventional fuels such as coal, diesel, or gasoline. In particular, H_2-powered FC vehicles are expected to be two to three times more efficient than gasoline-fueled ICE vehicles. Further, unlike conventional ICEs, which emit pollutant gasses as a result of combustion, H_2-powered FCs and FCVs emit only water vapor. For these reasons H_2 production has been receiving considerable attention worldwide, and FCs and FCVs are often promoted as a means to reduce dependence on oil.

1.5.2 Challenges of Transition to a Hydrogen Economy [11,24]

Expanded use of hydrogen as an energy carrier would address many of today's concerns about the use of conventional fossil fuel, including energy security and environmental quality. Despite its compelling benefits, transition to a hydrogen economy faces multiple challenges. Unlike gasoline and natural gas, hydrogen has no existing large-scale supporting infrastructure, and building one will require major investment. Although hydrogen production, storage, and delivery technologies are currently in commercial use by the chemical and refining industries, existing hydrogen storage and conversion technologies are too costly and far from widespread use in energy applications.

The transition to a hydrogen economy will likely be a lengthy period, during which FCVs and hydrogen-based FC power generation units will not be competitive (at least in cost) with conventional ICE vehicles and power generation units. Therefore, it is expected that the need for hydrogen fuel will be limited during the transition period, and hydrogen can be produced through distributed production technologies for limited use. However, many challenges related to the safe and cost-effective hydrogen production, storage and delivery must be resolved before it can be produced at small-scale, for example through steam methane reforming (SMR) of natural gas or electrolysis.

Natural gas is not renewable; greenhouse (CO_2) gas emission is also associated with its use. Therefore, it cannot be relied on as a long-term energy source for hydrogen production, especially for those countries that lack natural gas reserves. However, it is considered as a potential energy source for hydrogen production during the transition period.

Wind and solar energy are environmentally friendly options to provide some of the electricity needed for distributed hydrogen production via water electrolysis. Such production approaches will allow time for the market to develop before significant investment is set in place for centralized hydrogen production and delivery. Centralized hydrogen generation faces a multitude of challenges, including the need for hydrogen transmission pipelines, storage, and distribution infrastructure.

In the remainder of this section, key factors essential for the development of hydrogen economy, namely production, utilization, storage and distribution of hydrogen, and the U.S. DOE's hydrogen research programs to promote hydrogen economy are discussed.

1.5.3 Hydrogen Production

The various technologies that can be used to produce hydrogen include

- H_2 production by reforming natural gas.
- Conversion of coal to H_2.
- Use of nuclear energy (NE) to produce H_2.
- Electrolysis of water using electricity from the grid, or electricity produced from solar and/or wind energy.
- H_2 production from biomass.

A brief description of the above technologies and their associated technical challenges are discussed as follows.

1.5.3.1 Hydrogen Production by Reforming Natural Gas Natural gas is the most cost effective fossil fuel used for H_2 production. Currently, over 90% of the H_2 produced in the U.S. is through steam methane reforming of natural gas. The main reason for this is that the supply of natural gas is abundant. Moreover, natural gas has a high percentage of H_2 content, and the price is still affordable. Its downside is that it is a fossil fuel gas, and its increased use would eventually increase its cost. SMR can also be applied to other H_2-rich (hydrocarbn) fuels, such as methanol and gasoline. Figure 1.5 shows the block diagram of a typical SMR process. The corresponding chemical reactions are also given in the figure. The hydrocarbon fuel will first go through the purification process, where its poisonous materials, such as sulfur and chloride, are removed. The purification will not only improve the quality of product (H_2), but also increase the life of the downstream reforming and other catalysts used in the system. Then the purified hydrocarbons react with steam at high temperature (750–800°C) to produce a synthesis gas (syngas), a mixture mainly of CO and H_2. The CO produced in the previous step will be further converted into hydrogen through the water shift reaction with the aid of a catalyst. A liquid absorption system can be used to remove CO_2 from the product gas. To further remove residual traces of carbon oxides, a methanation process can be applied to produce high purity product hydrogen.

Distributed generation of H_2 from natural gas could be the lowest-cost option during the transition period. For example, when hydrogen-consuming devices, i.e., FCs and FCVs enter the market, H_2-generation

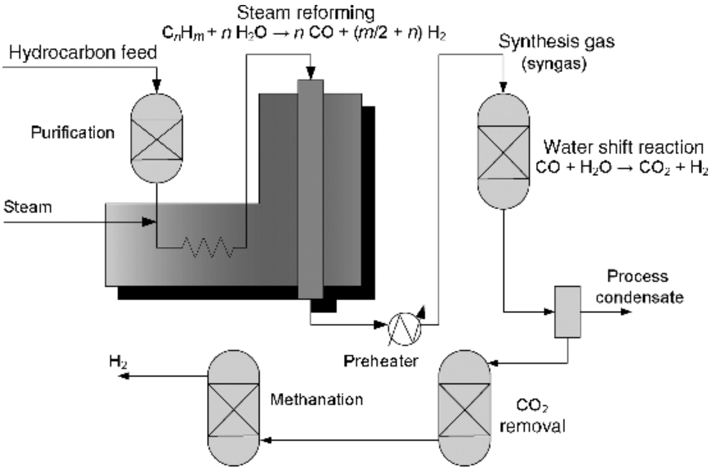


FIGURE 1.5 Steam methane reforming for H_2 generation.

appliances can be deployed in the service stations for fueling FCVs. The main challenge is to develop a reliable H_2-generation appliance that can be mass-produced and operated in the service stations. Natural gas should not be considered as a long-range fuel for centralized H_2-producing plants [11].

1.5.3.2 Hydrogen Production from Coal Coal has excellent potential for hydrogen production in large centralized plants. However, its use can be justified in the long-range, when the demand for hydrogen becomes large enough to support a large hydrogen distribution system. It has been predicted that the U.S. has enough coal to make all of the hydrogen needs of the H_2 economy for over two centuries [11], and a substantial coal infrastructure already exists to support this technology. In addition, most of the issues and technologies associated with making hydrogen from coal are similar to those associated with coal-fired electric power plants. This is particularly the case for coal gasification technology, which is the key to efficient and clean hydrogen production from coal for different hydrogen based applications. As shown in Fig. 1.6, coal gasification technology involves partial oxidation of coal with oxygen and steam in a high-temperature and elevated-pressure process as opposed to the combustion process used in conventional coal-fired power plants. Coal gasification for hydrogen production offers excellent opportunity for low-cost, high efficiency, and low emission electric power generation through a combined cycle process. Some commercial technologies for converting coal to hydrogen are already available, and the cost of hydrogen from coal is among the lowest available.

In 2003, the *FutureGen* initiative was announced by the DOE to build the world's first integrated carbon sequestration and H_2 production research power plant with zero-emissions. Research activities have been

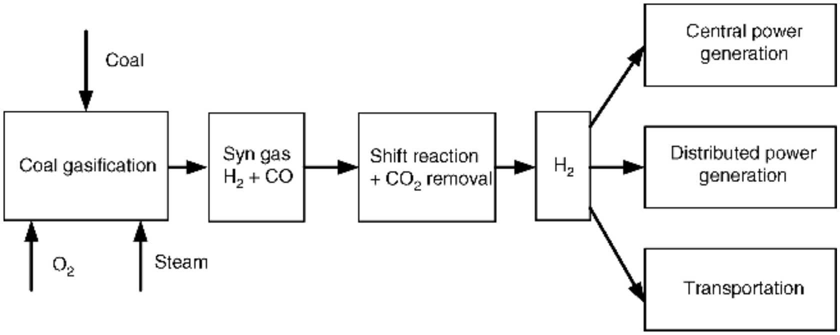


FIGURE 1.6 Schematic diagram of H_2 generation from coal.

ongoing nationwide (and in many other countries) on all aspects of carbon sequestration, and H_2 production and use.

The major drawback for making hydrogen from coal is the CO_2 emissions, which are larger than those from any other way of making hydrogen. This puts an added emphasis on the need to develop a safe and permanent storage for large amounts of CO_2 emissions (i.e., carbon sequestration techniques) before the widespread use of coal for hydrogen production [11].

In 2008, DOE announced its reconstructed approach for the FutureGen program putting more emphasis on carbon capture and storage technology compared to its 2003 plan. Coal gasification and clean coal technology stil remain the fundamental components of the future coal-based electricity production. And, high-temperature SOFCs capable of running on coal gas and developing combined cycle SPFC-gas turbine systems to generate electricity in cleaner and more efficient way is a part of the program. SECA SOFCs are one of the R&D technologies that will be tested within the FutureGen Program [30].

1.5.3.3 Hydrogen Production from Nuclear Energy

Nuclear energy is a long-term energy resource that (when used safely and its waste handled safely) can serve the world for many generations for hydrogen and power production. Further, nuclear power reactors do not emit CO_2 and toxic gasses to the atmosphere as are emitted by fossil-fueled power plants. Current U.S. plants use water as the coolant and are often called light-water reactors (LWRs). They rely on the steam Rankine cycle for thermal-to-electrical power conversion. Other countries use different technologies; in the United Kingdom, CO_2-cooled reactors are used, and heavy-water-cooled reactors (HWRs) are used in Canada and India [11].

Nuclear reactors can be used for hydrogen production through water electrolysis or thermochemical processes. Efficient hydrogen production may be achieved by raising the water temperature to 700–1000°C before electrolysis or by a thermochemical process. However, LWRs and advanced LWRs operating at temperatures under 350°C cannot be used for such purposes, but advanced coolants have been proposed which can operate at temperatures above 700°C. According to the Electric Power Research Institute (EPRI), nuclear reactors can potentially be used more economically to supply the heat needed in the steam methane reforming process than their use for water electrolysis [16]. Nuclear-assisted SMR would reduce the use of natural gas as well as the emission of undesired gasses to the environment.

1.5.3.4 Hydrogen Production by Water Electrolysis The process of separating water molecules into hydrogen and oxygen is called electrolysis. This process has been in use around the world for many years, primarily in chemical plants, to meet their hydrogen needs. Electrolysis is currently more expensive than steam reforming of natural gas, but it may play an important role in the transition to a hydrogen economy. Electrolysis facilities can be placed in existing service stations to produce hydrogen for FCVs, or at residential buildings for use with FCs, provided their safe operation can be achieved. Electrolyzers can allow FCDGs to use stored hydrogen to generate additional power during utility peak-demand hours. They can use utility power to generate hydrogen and store hydrogen during off-peak hours, therefore improving utilities' load factors.

Current electrolysis technologies fall into two basic categories: solid polymer using a proton exchange membrane (PEM) and liquid electrolyte, most commonly potassium hydroxide (KOH). In both technologies, water is introduced into the reaction process and subjected to an electrical current that causes dissociation, after which the resulting hydrogen and oxygen atoms are separated.

A PEM electrolyzer is essentially a reverse-operating PEMFC. The liquid KOH electrolyte system operation is analogous to a PEM electrolyzer. In both systems, oxygen ions migrate through the electrolyte, leaving hydrogen gas dissolved in the water stream. The hydrogen is then extracted from the water and directed into a separating channel for storage. The operation principles of PEMFC and KOH electrolyzers are discussed in Chapters 2, 3, and 5.

The electricity used for electrolysis can be either from the utility grid or that generated from renewable energy sources, such as wind and solar power. Electrolysis is well matched to intermittent renewable technologies. A brief description of the technologies which use renewable energy sources to generate H_2 follows.

1.5.3.5 Solar Energy to Hydrogen Hydrogen from solar energy can be produced through conversion of solar energy to electricity using a photovoltaic cell and then to hydrogen through the electrolysis of water. In an alternate method, photoelectrochemical cells are used for direct hydrogen production. The latter method is in the early stages of development and cannot be counted on for any foreseeable future.

Currently, over 80% of commercial PV modules used for electricity production are based on single crystal or polycrystalline silicon. A second type of PV technology is based on deposition of thin films of amorphous as well as microcrystalline silicon. Thin-film technology appears to hold better promise for cost reduction. However, the cost of the thin-film technology is presently higher than the cost of silicon-based PV modules.

1.5.3.6 Wind Energy to Hydrogen Wind-generated electricity has a promising potential to be used for pollution-free water electrolysis for production of a significant amount of hydrogen, particularly during the transition, when the need for hydrogen is limited, as well as in the long term. It is the most affordable renewable technology deployed today with wind-generated electricity being as low as 4 cents/kWh. Both energy security and environmental quality, which are strong factors motivating a H_2 economy, can be addressed by the conversion of wind energy to H_2. With improved performance and efficiency of wind turbine generators (WTGs), their capacity factors, which are currently in the neighborhood of 30%, could be increased, therefore capturing the maximum amount of available wind energy. These advancements can be achieved through improved turbine design and power electronic controls.

Wind–electrolysis–H_2 systems still face many barriers to deployment and deserve continued attention by the government, including incentives both for manufacturers and end-users. Increasing the efficiency and reducing the cost of electrolyzers, and advances in hydrogen storage systems to be adapted with WTG-electrolyzer systems, are essential for a successful wind-H_2 program.

Since wind farms are generally located in rural areas, advances in H_2 distribution from the wind farms to urban areas are essential for widespread use of this technology. Further, matching (optimization) of WTGs with electrolyzers and H_2 storage systems are necessary for both stand-alone and wind farm applications. A modeling and simulation study, exploring the operation feasibility and power management of wind/PV/FC systems used for power and H_2 generation is given in Chapter 9.

1.5.3.7 Biomass Energy to Hydrogen Biomass energy can be used to produce hydrogen through biomass gasification. There are two types of biomass feedstock available for conversion to hydrogen: the bioenergy of crops, and the organic waste from agricultural farming and wood processing (referred to as biomass residues). The primary energy source for hydrogen production from the above sources is solar energy. Hydrogen production from biomass is not a thermodynamically efficient process; less than 0.5% of the total solar energy is converted to hydrogen. In addition to its low efficiency, biomass to hydrogen conversion is an expensive process; the current price of hydrogen from biomass is around

\$7/kg, which is not competitive with more mature H_2 production technologies such as steam reforming of natural gas, or coal gasification, which is estimated around \$1/kg. Due to the high costs of feedstock, and gathering and transporting biomass feedstock, biomass gasification plants have high operating costs. An optimistic projection estimate could bring the cost of H_2 production from biomass down to about \$1.2/kg, which is still about three times the projected cost of H_2 produced in large central coal gasification plants (\$0.46/kg). For the above reasons, it is unlikely that biomass gasification could play a central role in future H_2 production. On the contrary, because of its low emission of greenhouse gasses, biomass could play a significant role in meeting the goal of reducing the emission of greenhouse gasses. It is projected that biomass could be used in cofiring applications along with coal, where biomass could provide up to 15% of the total energy input of the fuel mixture [11].

1.5.4 Hydrogen Storage and Distribution

Key economic factors in any future hydrogen-based economy will be the cost and safety of the hydrogen distribution system from production sites to customers. While this is true of any fuel, it involves unique challenges in the case of hydrogen because of its high diffusivity, extremely low density (in gas or liquid form), and flammability. To overcome these unique challenges will involve special safety measures, and therefore cost. In particular, the safety measures for on-board storage of hydrogen in future FC vehicles are critical.

Hydrogen can be stored and transported as a pressurized gas or a cryogenic liquid. The common methods of storing hydrogen are as follows [3]:

- *Compressed Gas in High-Pressure Storage Tanks*: New materials have allowed the construction of pressure tanks and vessels that can store hydrogen at extremely high pressure (as high as 700 bars).
- *Hydrogen Absorbing Materials*: Hydrogen can be combined with metals and metal alloys (or with charcoal) to make a metal hydride (or charcoal) with a high hydrogen energy density. The hydrogen is released when the hydrides (or charcoal) are heated.
- *Liquid Storage*: Hydrogen will be converted to liquid when its temperature is reduced to −253°C. Storage and transportation of liquid hydrogen can be less costly compared to compressed gas, but it requires additional energy (cost) to keep the hydrogen at such low temperature. It is estimated that 25–30% of the energy content of

hydrogen is used to keep the hydrogen in liquid form. Another concern of storing liquid hydrogen is its loss through evaporation.

Hydrogen is a uniquely difficult commodity to transport on a wide scale, whether as liquid by pipeline or as pressurized gas in cylinders. On a weight basis, hydrogen has much higher energy content than gasoline (120 MJ/kg for hydrogen, 44 MJ/kg for gasoline). But on a volume basis, the energy content of gasoline is much higher than hydrogen: 3 MJ/L for hydrogen at 5000 PSI, 8 MJ/L for liquid hydrogen, and 32 MJ/L for gasoline [11].

Pipe-line transmission of hydrogen is expected to be more cost-intensive than pipeline transmission of natural gas. The diameter of pipelines for hydrogen transmission will need to be at least 150% of natural gas pipelines to achieve the equivalent energy transmission rate. Further, more costly steel and valve and metal seal connections will be required for hydrogen pipelines in order to avoid the possibilities of leakage. Major safety codes will have to be in place for hydrogen storage, transportation, and distribution as hydrogen needs grow.

1.5.5 Department of Energy Hydrogen-Related Activities

A Hydrogen Posture Plan [23], released by the DOE in December 2006, outlines the most recent coordinated plan for activities under the Hydrogen Fuel Initiative at the Department of Energy and the Department of Transportation. This document outlines the integration of ongoing and future hydrogen research, development, and demonstration activities into a focused Hydrogen Program.

The DOE Hydrogen research and development program activities are focused on advancing cost-effective, efficient production of hydrogen. It also includes a variety of related activities such as hydrogen storage, delivery, conversion (of hydrogen energy to electricity, i.e., fuel cells), applications and technology validation, safety, codes and standards, education, basic research, and systems analysis and integration. A summary of these activities and the DOE offices involved in each activity is given below.

1.5.5.1 Hydrogen Production

Hydrogen from Natural Gas The Offices of Energy Efficiency and Renewable Energy (EERE) and Fossil Energy (FE) focus on hydrogen production via steam methane reforming. The EERE Office is focused on distributed hydrogen production from natural gas and bio-derived liquid feedstocks. The FE office is focused on sub-centralized and centralized hydrogen production from natural gas. DOE does not consider natural gas as a long-term energy source for the production of hydrogen because of concerns about its long-term availability, security, and greenhouse gas emissions. However, natural gas is considered as a near-term energy source for hydrogen production by the DOE.

Hydrogen from Coal The FE Office is focused on developing the technologies needed to produce hydrogen from coal-derived synthesis gas. The FE Office also focuses on the development of zero-emission, high-efficiency power plant for coproduction of hydrogen and electricity from coal. Toward this goal, the FE Office is also investigating carbon sequestration technologies, in associated programs, as an option for managing greenhouse gas emissions from coal-fired plants.

Hydrogen from Nuclear Power The Office of Nuclear Energy (NE) is focused on developing hydrogen production technology using heat generated from nuclear energy systems. The NE Office R&D areas include high-temperature thermochemical cycles, high-temperature electrolysis, and reactor/process issues.

Hydrogen from Renewable Energy Resources The EERE Office is focused on research for developing advanced technologies for producing hydrogen from renewable energy resources. Key research areas include electrolysis, thermochemical conversion of biomass, photolytic and micro-organism systems, photoelectrochemical systems, and high-temperature chemical water splitting.

1.5.5.2 Hydrogen Basic Research The Office of Science's basic research has a major emphasis on fundamental understanding of photoinduced water splitting into hydrogen and oxygen by semiconductors and photocatalytic techniques using solar energy. This office also has emphasis on fundamental research in catalysis, membranes, and gas separation for more efficient and cost effective fossil-based hydrogen production.

1.5.5.3 Hydrogen Delivery The EERE and FE Offices, and the Office of Science are involved in infrastructure R&D for safe and cost-effective hydrogen delivery. These activities include developing improved materials for pipelines, breakthroughs in hydrogen liquefaction, light weight and strong materials for high-pressure hydrogen storage, and low-pressure solid and liquid carriers for hydrogen delivery and storage. These activities have a long-term goal of developing hydrogen delivery technologies for transportation and stationary power in a hydrogen-based economy.

1.5.5.4 Hydrogen Storage The R&D activities on hydrogen storage at high pressures and cryogenic temperatures are centered in the DOE's EERE Office. Activities in this area include on-board applications for transportation and off-board applications for refueling infrastructure and for stationary (hydrogen-based) fuel cell power generating stations.

Innovative materials development for hydrogen storage is handled by the EERE and FE Offices. These activities include development of carbon-based materials, metal-organic frameworks, and metal and chemical hydrides.

The Office of Science focuses on basic research in developing novel storage materials, including nanostructured materials.

1.5.5.5 Hydrogen Energy Conversion (Fuel Cells) The DOE activities in this area include the conversion of hydrogen to electrical or thermal power and the use of PEM fuel cells for auxiliary power units on vehicles and for stationary and backup power applications.

The Office of Science's basic research program and the EERE Office focus on improvements in cost, durability, and efficiency of PEM fuel cells. Their R&D activities in this area include improving catalysts, electrolytes (membrane), and electrode materials for PEMFCs

Although not related directly to the hydrogen initiative, R&D is also underway within DOE, on phosphoric acid, molten carbonate and solid oxide fuel cells. These technologies have a stronger tie to stationary power production and are mainly handled by the FE Office.

Other DOE hydrogen-related activities, including the development of safety codes and standards, systems analysis and integration, and education are mainly handled by the EERE Office. Basic research in these areas is handled by the Office of Basic Energy Sciences. The overview of the DOE goals for the transition plan to a hydrogen economy to year 2040 is given in Table 1.4.

Several DOE National Laboratories along with universities and industrial partners work with different DOE offices toward the goals of the above transition plan. The DOE laboratories heavily involved in hydrogen-related work are as follows:

- *National Renewable Energy Laboratory* (NREL): Hydrogen production from renewable resources, hydrogen detection and safety.

TABLE 1.4 Overview of the U.S. Transition to the Hydrogen Economy—A Projection [22]

		2000	2010	2020	2030	2040
Public policy framework		• Security • Climate • H_2 safety	Outreach activities and public acceptance		Public confidence in hydrogen as an energy career	
Hydrogen industry segments	Production processes	Reforming of natural gas/biomass Electrolysis using renewable and nuclear Thermochemical water splitting using nuclear		Gasification from coal		Biophotocatalyst Photolytics to split water
	Delivery	• Pipeline • Truck, rail, barges		Onsite “distributed” facilities		Integrated central-distributed networks
	Storage	Pressurized tanks (gases and liquids)	Solid state (hydrides)	Mature technologies for mass production Solid state (carbon, glass structures)		
	Energy conversion	Combustion	• Fuel cells • Advanced combustion	Mature technologies for mass production		
	End-use energy markets	• Fuel refining • Space shuttle • Portable power	• Stationary distributed power • Bus fleets • Government fleets	• Commercial fleets • Distributed CHP • Market: introduction of personal vehicles		• Utilities systems

- *Idaho National Laboratory* (INL): Hydrogen-based internal combustion engine vehicles, hydrogen production from nuclear energy, thermal plasma and alternative fuels, hydrogen storage technologies.
- *National Energy Technology Laboratory* (NETL): Hydrogen production from coal.
- *Pacific Northwest National Laboratory* (PNNL): Advanced nanoscale materials for hydrogen production and storage.

1.5.6 The Role of This Book

As we have seen throughout the previous section, fuel cells play a critical role in the future hydrogen economy, including in FC vehicles and stationary power generation. An understanding of the FC dynamic modeling and response prediction is necessary for students, as well as practicing engineers/scientists working in related areas, to be able to evaluate FC response and to design controllers to adapt them to particular applications. This book is intended to fill the present gap for two types of fuel cells—PEMFC and SOFC—with significant promise in distributed power generation applications. PEMFC is the fuel cell of choice for transportation, residential DG and backup power applications; and SOFC has the potential for a variety of DG applications from 5 kW to MW range. The focus of this book is on dynamic modeling and controller design for the above two types of fuel cells, PEMFC and SOFC.

Chapter 2 covers the principle of operation of major types of fuel cells and gives a comparative summary of their characteristics. Dynamic modeling of PEMFC and SOFC are covered in Chapters 3 and 4, respectively. Electrolyzer modeling is introduced in Chapter 5. Introduction and modeling of power electronic interfacing circuits for fuel cell applications is covered in Chapter 6.

Fuel cells face a variety of load and/or electrical disturbances. Proper controllers need to be designed for these power generation devices so that they can handle or mitigate the disturbances and ensure their safe operation in both stand-alone and grid-connected applications. Chapters 7 and 8 cover control methodologies and controller designs for stand-alone and grid-connected operation of FCDG systems, respectively.

As an example of applying the developed models and controller design methodologies, Chapter 9 covers the design and performance investigation of a hybrid wind/PV/PEMFC-electrolyzer system and a SOFC-CHP system. Chapter 10 gives a summary of future potential of fuel cells.

Although the applications of the fuel cell models and controller design methodologies are given for stand-alone and grid-connected power generation, the models can also be used to study other FC applications, for example, transportation applications.

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