Chapter 13

Two Evolving Energy Technology Pathways

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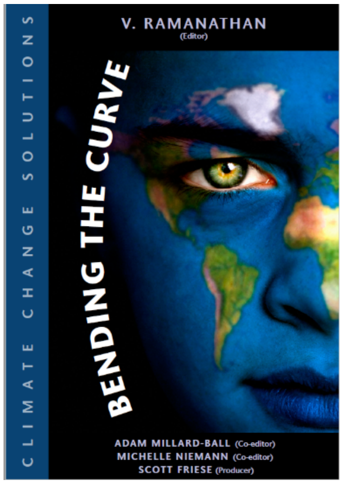

CHAPTER 13

Two Evolving Energy Technology Pathways

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CHAPTER CONTENTS

Learning Objectives

At the end of the chapter, the reader should be able to do the following:

1. Identify the roles of electric power generation and transportation in both climate change and the degradation of urban air quality.
2. Explain the role of combustion in both the generation of electricity and the powering of vehicles today, as well as the role of combustion in climate change and the degradation of urban air quality.
3. Identify the alternatives to combustion for the generation of electricity and the powering of vehicles.
4. Understand fuel cell technology and the application of fuel cells to the generation of electricity and the powering of vehicles.
5. Delineate the attributes and challenges associated with the generation of (1) renewable electric power and (2) renewable hydrogen.
6. Describe the two major pathways that are evolving in the electric grid, the evolution of vehicle engines and fuels, and the merging of the electric grid with transportation in response to mitigating climate change and the degradation of urban air quality.
7. Explain smart grid technology.

Nomenclature

°C	Degrees Celsius
AC	Alternating current
BEV	Battery electric vehicle
CCHP	Combined cooling, heat, and power
CH_4	Methane
CHP	Combined heat and power
DC	Direct current
DER	Distributed energy resources
DG	Distributed generation
FC	Fuel cell
FCEV	Fuel cell electric vehicle
G2V	Grid-to-vehicle
GHGs	Greenhouse gases
GT	Gas turbine
ISO	Independent system operator
MCFC	Molten carbonate fuel cell
MW	Megawatts
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
PEV	Plug-in electric vehicle
PFCEV	Plug-in fuel cell electric vehicle
PM	Particulate matter
SMR	Steam methane reformation
SOFC	Solid oxide fuel cell
V2G	Vehicle-to-grid
WDAT	Wholesale distribution access tariff

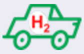
Symbols


BEVs

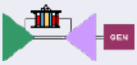

Central combustion plants


Electric batteries

Electrolyzers

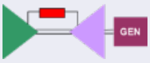


FCEVs



Fuel cell/gas turbine hybrid (fuel cell/GT hybrid)


Fuel cells (FCs)



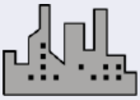
Gas turbines (GTs)


Gasoline stations

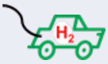

Hydroelectric plants


Hydrogen batteries


Hydrogen dispensers

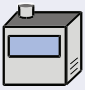

Industries


Nuclear plants



PFCEVs


Residences


Small gas turbines


Solar photovoltaic panels


University, hospital, office, commercial buildings


Wind generators

Overview

Climate change and the degradation of urban air quality are forcing paradigm shifts in the two key sources emitting carbon dioxide (CO_2) and other pollutants into the atmosphere: electric power generation and transportation. Combustion of fossil fuels is the reason, serving as both (1) the conversion technology for both the generation of electricity and the powering of vehicles and (2) the principal source worldwide of CO_2 and "criteria" pollutants (that is, ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, lead, and particulate; see Box 13.1). While CO_2 is a concern for global climate change, criteria pollutants are primarily a concern because of their local impacts on human health. As emissions of carbon are reduced, attention to the concomitant reduction in the emission of criteria pollutants must be addressed as well.

To reduce the emission of CO_2 and criteria pollutants, the historical reliance on combustion needs to be displaced. This chapter outlines two pathways that are evolving to transform both the electricity and transportation sectors from a classic combustion-dominant construct (that has supported the economic growth and evolution of a myriad of societal conveniences over the last century) to a renewable-dominant construct (that is evolving in the new millennium in response to environmental impacts, geopolitics, and fossil fuel resource constraints). Among the notable characteristics of the two pathways is the merging of the transportation and electricity sectors (for example, plug-in electric vehicles charging with electricity) and the deployment of energy storage technologies to buffer and manage the idiosyncrasies (for example, temporal variation, intermittency, low capacity factor) associated with renewable wind and solar power generation. While the pathways are identical early in the transition, they differ in the future years. In particular, the first pathway projects that electric battery technology and pumped hydro will alone manage the solar and wind resources now and in the future. The second pathway projects that, in addition to battery energy technology and pumped hydro, the following two additional resources will be required in the future:

- Renewable hydrogen "battery" technology.
- 24/7, clean, load-following renewable power generation.

For both pathways, the goal is to establish a 100% renewable electricity sector and a 100% renewable transportation sector with the following characteristics: (1) zero emission of greenhouse gases (to mitigate climate change), (2) zero emission of criteria pollutants (to mitigate degraded urban air quality), and (3) energy sourced locally (to mitigate dependency on other countries for energy).

As a foundation to placing the two pathways into perspective and understanding the underlying technologies, the chapter reviews the historical role of combustion, the rapidly emerging deployment of wind and solar resources as an option to combustion, fuel cell technology for both the generation of electricity and the powering of vehicles, energy storage and clean 24-hours-a-day, 7-days-a-week (24/7) power generation to manage the idiosyncrasies of solar and wind, smart grid technology to manage the complexity of and interactions between the electricity and transportation sectors, and renewable hydrogen as both a transportation fuel and a resource for energy storage.

13.1 Introduction

Combustion is the principal technology that powers the energy economy. Simply stated, combustion is at the heart of our everyday lives, from the provision of electricity to our home and place of work, to the automobiles we drive, to the propulsion of jet aircraft we fly. Combustion is also the principal source of the environmental impact we experience, from climate change to degraded urban air quality.

The following four principal forces are driving the paradigm shifts from our dependency on combustion to alternative technologies for the generation of electricity and powering of vehicles:

1. Degraded urban air quality (1943): The first evidence of persistently degraded urban air quality in the United States was

FIGURE 13.1.1 **Los Angeles 1943: Degraded urban air quality.** Reproduced with permission from Getty Images.

Box 13.1 Atmospheric Pollutants

In this chapter, two groups of anthropogenic emissions (CO_2 and criteria pollutants) are considered. The formal designation of criteria pollutants (ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, lead, and particulate) was established in 1970 by the US Clean Air Act based on demonstrated health and environmental impacts established by a series of "criteria" studies. Some of the criteria pollutants ("primary" criteria pollutants) are emitted directly from the exhaust of combustion and other sources, while other criteria pollutants ("secondary" criteria pollutants) are formed in the atmosphere from reactions of primary criteria pollutants. The concentration of criteria pollutants emitted in the exhaust is very low (often less than 10 parts of pollutant per million parts [ppm] of exhaust), but when the emissions accumulate from the large population of sources in an urban basin, they result in a health impact.

In 2009, carbon dioxide was classified by the US Environmental Protection Agency (EPA) as a pollutant that poses a danger to human health and welfare. The typical concentration in the exhaust of a combustion source is approximately 120,000 ppm (that is, 12% of the volume). Unlike criteria pollutants, which affect public health within hours to days of exposure near the source of their emission, CO_2 has a more insidious impact, taking years to generate demonstrable and unambiguous climate change worldwide.

chronicled in the *Los Angeles Times*, describing a tenacious haze that seemed to irritate eyes and cause many to cough (Figure 13.1.1). Today, urban regions throughout the world (for example, in India, China) are affected by degraded air quality.

2. Finite petroleum resources (1980s): Automobile companies recognized that petroleum was finite and demand may outweigh discovery in the next millennium.
3. Climate change (1990s): The world recognized that anthropogenic sources may be affecting the climate, leading to the signing of the UN Framework Convention on Climate Change in 1992 (Chapter 10).

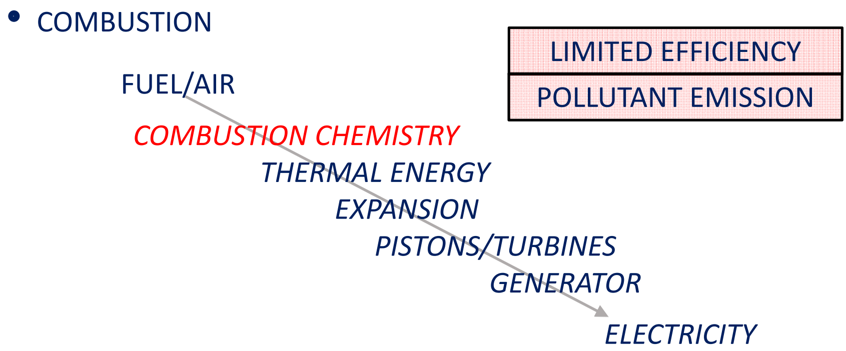


FIGURE 13.1.2 Combustion.

4. Fuel independence (2001): The assault on the World Trade Center enhanced the urgency to reduce US dependence on foreign sources of petroleum.

Combustion

Depending on the type of engine, either air is compressed to a high pressure and fuel is added, or a fuel-air mixture is compressed to a high pressure. In both cases, the fuel-air mixture is then ignited, initiating a **combustion** process (essentially "burning" the fuel-air mixture) that transforms the energy bound in the fuel (for example, gasoline) to high-temperature gas (thermal energy). The high-pressure, high-temperature gas then pushes on a piston (to power the transmission in a traditional gasoline vehicle, or generate electricity in a gasoline hybrid vehicle) or expands through a turbine (to generate electricity for the home and business). From this process, depicted in Figure 13.1.2, you can intuitively deduce that (1) the efficiency (the percentage of energy bound in the fuel that is transformed to useful power) will be limited by the friction associated with all of the mechanical steps, and (2) criteria pollutants will be formed because of combustion chemistry and emitted in the exhaust.

When you consider the role of combustion in everyday life, the examples seem limitless (for example, cooking; heating water; space heating; generating electricity; propelling aircraft and rockets; and powering automobiles, buses, trucks, locomotives, and ships). Simply stated, combustion is interwoven into the fabric of both the quality of life and the economics of the world's markets.

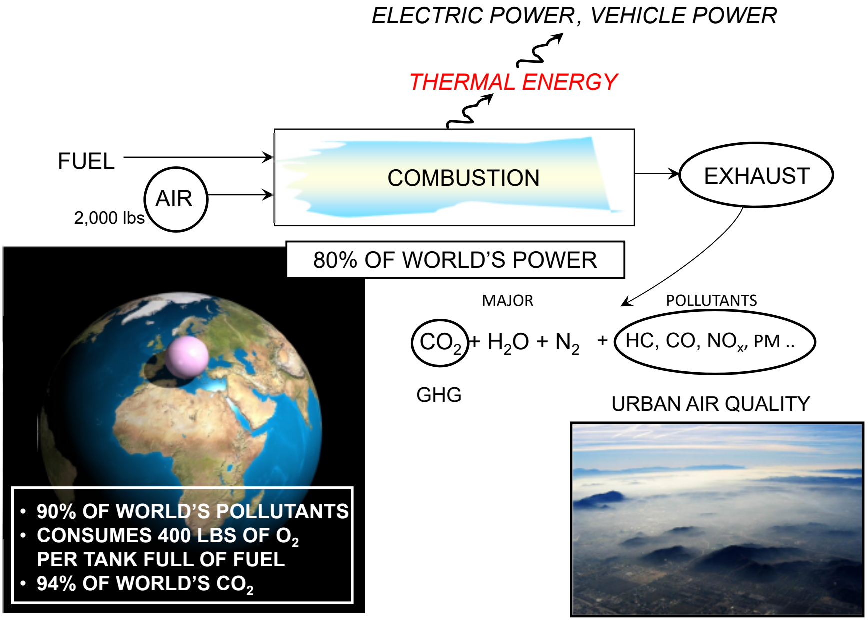


FIGURE 13.1.3 **Combustion impacts.** Image of earth reproduced with permission from Science Photo Library.

In Figure 13.1.3, the relationship between combustion and the environment is illustrated. Fuel and air are injected into a chamber, ignited to liberate the energy bound in the fuel into thermal energy, and expanded to produce a useful product.

Unfortunately, combustion has an exhaust as a by-product composed of criteria pollutants that degrade urban air quality (affecting the public health) and carbon dioxide (affecting the world's climate). Notably, the amount of criteria pollutant mass in the exhaust is minuscule and was historically ignored until the first consequences to public health in modern times surfaced in 1943 (Los Angeles) and 1952 (London).* It is as if Nature incorporated environmental impacts in the combustion of fossil fuels to counsel the world's population that combustion is not sustainable.

Why is it that such a minuscule emission of a few chemical criteria pollutant molecules affects the urban air basin, and a larger but still

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*Ramifications of combustion exhaust were observed centuries before, an example of which is "fumifugium" (Evelyn 1661).

relatively modest emission of CO_2 affects the world's climate? Consider that the atmosphere is evenly distributed in a thin layer around the Earth, barely 10 miles in depth. In Figure 13.1.3, the purple sphere in the image represents the volume of all the air if it were gathered together, relative to the volume of the Earth. The image conveys the surprisingly small air resource upon which life on Earth depends, and the relatively small volume of air into which products of combustion are injected. Within this small volume, CO_2 and other greenhouse gases (GHGs) accrue to affect climate, and secondary criteria pollutants are formed and primary criteria pollutants amass to degrade urban air quality. As noted in Figure 13.1.3, combustion is responsible for over 90% of the world's emission of CO_2 and criteria pollutants.

In addition to contaminating the air resource with CO_2 and criteria pollutants, the combustion process has an impact not widely recognized: namely the consumption of oxygen from the air. For every tankful of gasoline in your car, a ton of air (2,000 pounds) passes through your engine, and 400 pounds of oxygen are consumed. Given the finite resource of oxygen in the atmosphere, this is sobering. While Nature appears to be replenishing the oxygen removed to date, an increasing demand for oxygen could lead to an additional point of environmental stress. Fortuitously, the evolving transition from a classic "combustion-dominant construct" to a "renewable-dominant construct" will, in parallel with reducing the emission of CO_2 and criteria pollutants, serve to mitigate the likelihood of this environmental stress.

The electric grid

A principal role of combustion is the generation of electricity. The electric grid is represented in Figure 13.1.4 in its classic form. Electric power is generated at large, central power plants in the general range of 100 to 1,000 megawatts (MW). While hydro and nuclear contribute to varying degrees, combustion fueled by fossil fuels (natural gas, oil, or coal) has historically been the dominant strategy for the generation of electricity.

The classic form of the electricity grid, however, is not the only way in which electricity can be provided to houses, businesses, and factories. Figure 13.1.5 illustrates the following four potential paradigm shifts from the classic to the future electric grid.

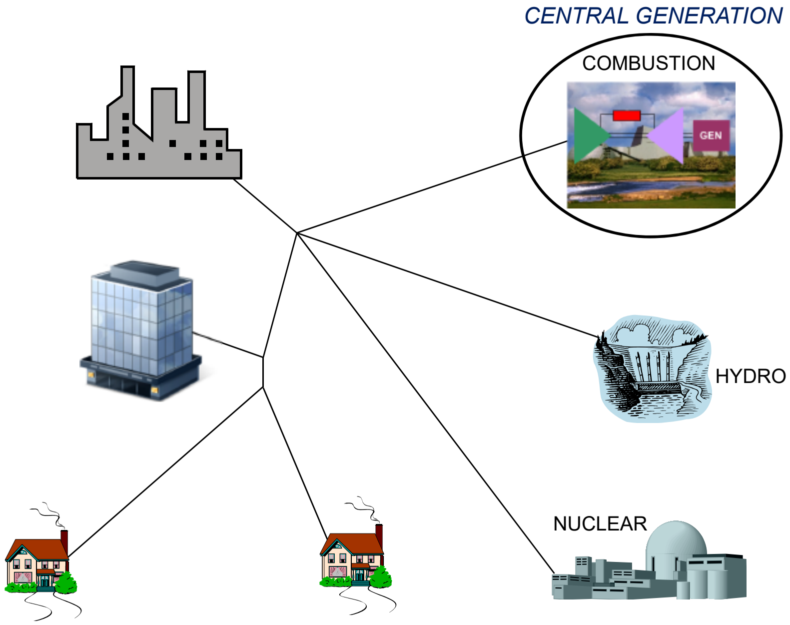

FIGURE 13.1.4 The classic electric grid.

1. Use **distributed generation** (DG), the generation of power at the point of use (Figure 13.1.5 ①). This could take the form of fossil fuel power plants such as gas turbines, solar panels, fuel cells, or ground source heat pumps that extract heat from under the ground. The advantages of this paradigm are threefold:
   - Avoiding transmission losses. By generating electricity at the point of use, the loss in energy due to conveying electricity from central power generators to the urban loads, estimated to be in general 7%, is avoided.
   - Increasing reliability. Generating electricity at the point of use increases the reliability of the electricity supply to the customer. Should the grid experience an outage, for example, DG can power critical circuits (at a minimum) and, if needed, power all circuits.
   - Capturing and using exhaust heat. With generation at the point of use, the heat in the exhaust can be captured and used to serve thermal loads (such as steam, hot water, and chilled water) and thereby displace electricity and natural gas that

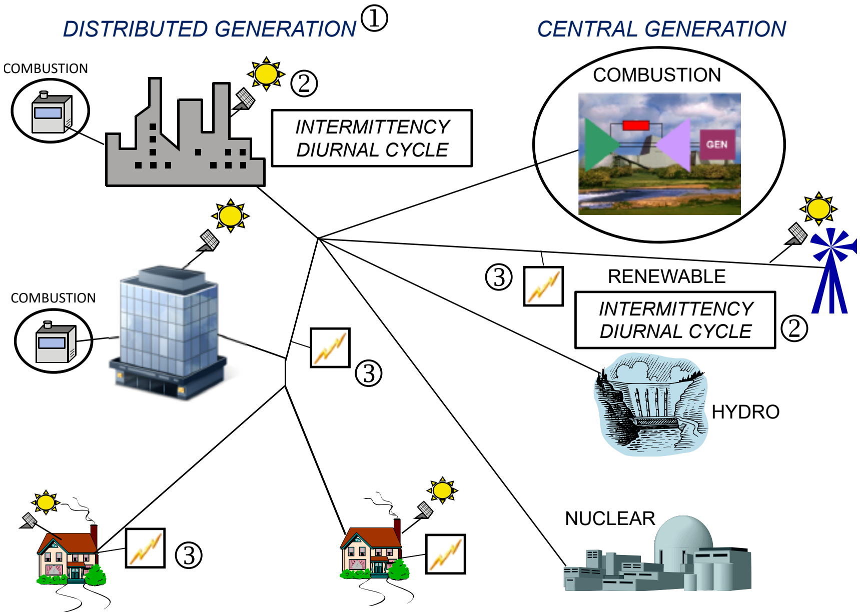

FIGURE 13.1.5 The emerging electric grid.

would otherwise be required for these purposes. This gives rise to high overall efficiencies that can exceed 90%. Terms used to describe this attribute are *combined heat and power* (*CHP*) and *combined cooling*, *heat*, *and power* (*CCHP*).

2. Provide direct current power. The clean power generators emerging for the DG market (for example, photovoltaic panels, fuel cells, and microturbine generators) produce direct current (DC) that is converted to alternating current (AC) with a concomitant loss of energy estimated to be 10%. Then, the AC power is converted back to DC (with another estimated loss of 10%) to serve DC loads in a building, examples of which are lighting, personal computers, and servers. By serving these loads directly with DC, DG can avoid the conversion inefficiencies.
3. Deploy renewable power generation. The third paradigm shift is the deployment of renewable solar and wind resources in central generation, as well as the deployment of solar in distributed generation (Figure 13.1.5 ②). The advantage of this paradigm is the displacement of the fossil fuel generation of power, by utilizing the

sun as the fuel resource, and the transition from combustion to a sustainable future that supports a clean, inexhaustible fuel supply (the sun) and protection of the environment. In California, for example, the penetration of renewable solar and wind resources has increased dramatically in the past decade (exceeding 30%) and is on course to meet a target of 60% in 2030 (Figure 13.1.6). California's renewable energy policies are discussed further in Chapter 9.

In contrast to traditional central generating plants that produce electricity continuously around the clock, renewable solar and wind resources vary **diurnally**—that is, the power produced varies throughout the day due to the presence and angle of the sun and the availability and strength of the wind. They also experience **intermittencies**, such as from a cloud momentarily shading a photovoltaic resource and dropping the generation, or a burst or drop in wind momentarily increasing or decreasing generation from a wind source. Diurnal variation refers to the daily cycle, while intermittencies are short-term and less predictable.

Renewable resources also have a low capacity factor, defined as the percentage output divided by the maximum (often called "name plate") output over a month, year, or other period of time. For example, traditional central plants have capacity factors of approximately 50%, whereas renewable resources have capacity factors of approximately 25% (solar) and 32% (wind). The capacity factors of 24/7 base load generators* are below 100% because of load following (that is, plant operators or controllers turning down the generation to match the load), whereas the capacity factors for renewable resources are low because of the diurnal variation.

Renewable resources cannot load follow, generating instead whenever the "fuel" (sun or wind) is available. As a result, renewable wind and solar are "must take" resources, and other technologies must be used to meet the load demand. If the load is less than the renewable generation capacity, either the excess energy must be stored (for example, in electric batteries,

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*A base load generator is an electric power plant that provides a constant supply of electricity to meet the minimum load demand.

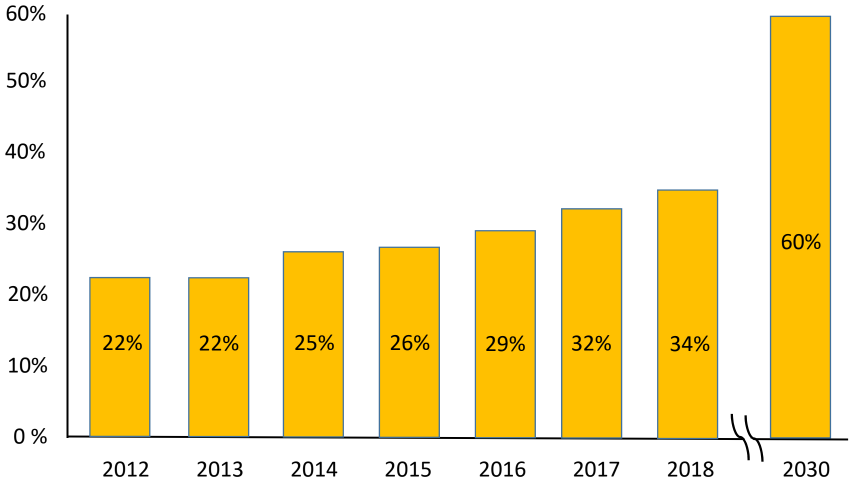

FIGURE 13.1.6 **California annual renewable percentage estimates.** Data from California Energy Commission 2018.

as pumped hydro, or in the generation of hydrogen), or the renewable generation resources must be **curtailed**. Curtailment is the action of reducing (in the extreme, turning off) the renewable wind or solar generation resource when load on the grid (that is, demand) is insufficient to utilize the electricity that would otherwise be produced.

4. Improve energy storage. A fourth paradigm shift is the deployment of battery storage at both the central and distributed generation levels (Figure 13.1.5 ③) to buffer and manage (1) the diurnal variation and intermittencies associated with wind and solar renewable resources, (2) uncontrolled vehicle charging loads,* and (3) the demand for rapid ramping of spinning reserves**

*Uncontrolled vehicle charging loads result from the charging of plug-in electric vehicles (PEVs) with no control over key variables (for example, the time of day the charging occurs, the duration of the charging, and the rapidity with which charging occurs). As the population of PEVs grows, control over these variables will be required to protect grid resources (for example, transformers) and assure that generation resources are available to meet the charging load.

***Spinning reserves* refers to rotating machinery (for example, gas turbines) that are spinning but generating little or no electricity and ready thereby to immediately (with a short delay) generate electricity if called upon. (This is similar to an aircraft with engines idling at the beginning of takeoff.)

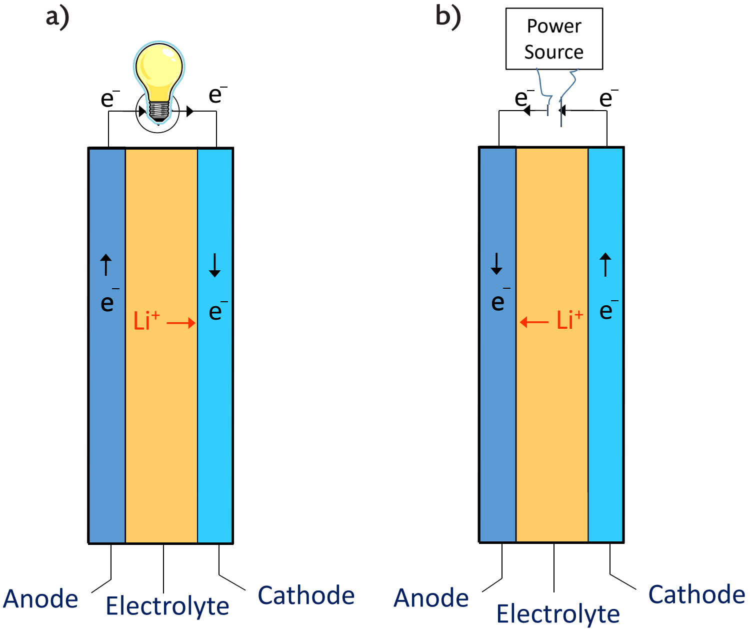

FIGURE 13.1.7 **Lithium-ion battery.**

with the goal to provide a resource that can absorb an increase in generation in the absence of load and also discharge energy when the load exceeds the generation capacity.

The most pervasive electric battery technology used today, from cell phones to multimegawatt applications, is the lithium-ion (Li-ion) battery (Figure 13.1.7). Just like your flashlight battery, the Li-ion battery stores energy (by charging on demand) and dispatches energy (by discharging on demand).

While the electrolyte allows lithium ions to flow in both directions, electrons are rejected by the electrolyte and must instead flow through an external circuit from one electrode to the other. When the battery is fully charged, all of the lithium ions are in the anode. When the battery is discharging (Figure 13.1.7a), the lithium ions travel through the electrolyte to the cathode while the electrons travel through the external circuit and energize a load (for example, a lightbulb). When the battery is charging, energy from a power source (for example, the grid) creates a flow of electrons from the positive cathode back to the negative anode.

Anodes in a Li-ion battery are typically composed of a carbon material that is able to absorb and store the electric charge. The cathode is an oxide of lithium such as lithium nickel manganese cobalt oxide, or lithium manganese oxide.

In the future, energy storage technologies may be required in addition to electric batteries to (1) absorb the enormous amount of otherwise curtailed energy, (2) provide the **ramp rates** (rate at which the generation resource responds to load change) required for both the absorption and reuse of the energy, (3) store the energy for months (for example, from one season to another), and (4) counter the self-discharge associated with electric batteries. While pumped hydro is expected to complement electric batteries, opinions differ as to whether additional, more flexible and higher-capacity energy storage technologies (for example, flow batteries and/or hydrogen “batteries”) will be required.

13.2 Fuel Cell Technology

Electricity has historically been generated 24/7 by combustion-based power plants. With the deployment of diurnally varying and intermittent renewable solar and wind generation, the 24/7 plants are being operated more dynamically, namely ramping up and down in response to the varying renewable resources. Because combustion emits carbon dioxide and criteria pollutants as unavoidable by-products, an alternative to combustion that can operate (1) more efficiently than combustion (thereby reducing CO_2 per megawatt hour), (2) with a zero-carbon fuel (thereby emitting no CO_2), and (3) without the emission of criteria pollutants would be preferred.

An emerging alternative to combustion is **fuel cell technology** (Figure 13.2.1), which converts fuel and air to electricity in a single step. Intuitively, you can imagine a higher efficiency in the absence of mechanical friction. You can also imagine virtually zero formation and emission of criteria air pollutants, due to relatively low-temperature and relatively benign electrochemistry. In addition, fuel cells are quiet—a welcomed attribute for deployment as a distributed generator in the midst of where the public resides (homes) and works (industry, office buildings, and hospitals, for example).

The manner by which fuel cells operate is illustrated in Figure 13.2.2. Similar to the electric battery presented in Figure 13.1.7, the fuel cell is composed of an anode and cathode separated by an electrolyte. But rather than storing energy, a fuel cell generates electricity continuously as long as fuel (hydrogen) and oxygen (from the air) are provided.

Hydrogen enters and is dissociated at the anode into protons (H^+) and electrons (e^-). While the electrolyte is receptive to transporting the protons to the cathode, electrons are rejected and required to find an alternative path. Engineers take advantage of this by providing a path for the electrons to travel through a load, represented in Figure 13.2.2 by

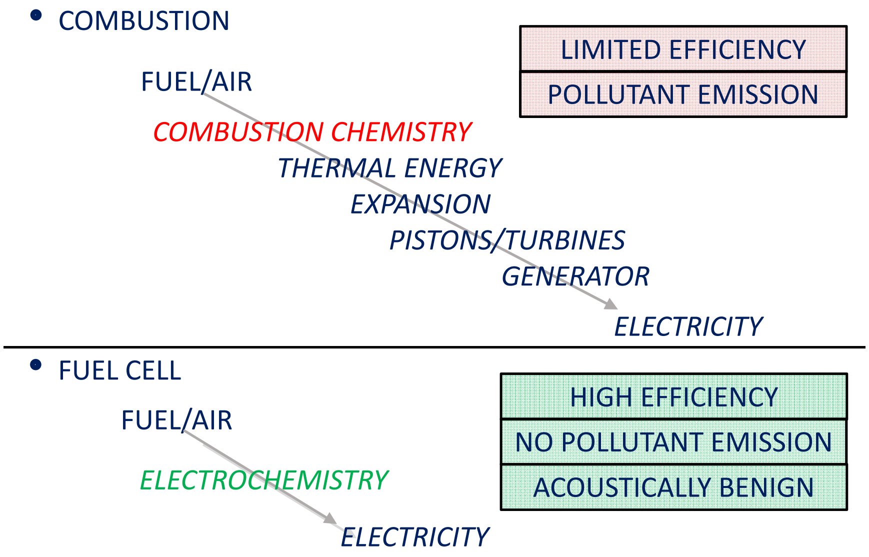

Figure 13.2.1 Power generation options.

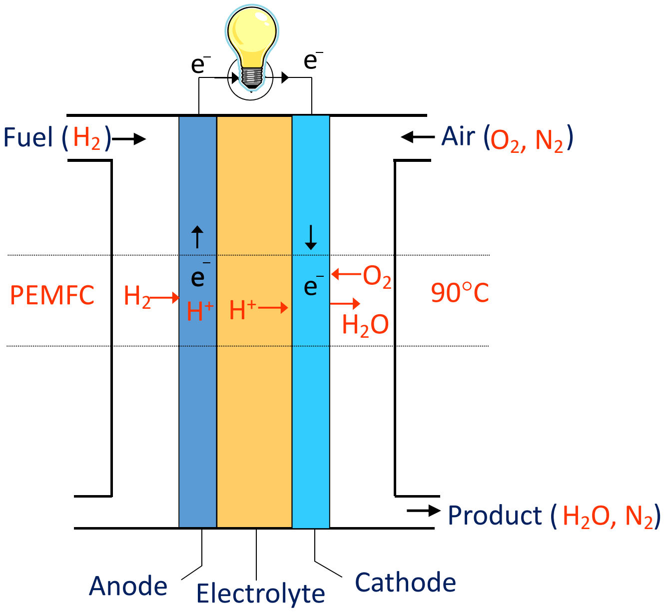

FIGURE 13.2.2 Proton exchange membrane fuel cell stack.

a lightbulb. The electrons transfer energy to, and thereby support, the load. While “spent,” the electrons are sufficiently energetic to react with the oxygen entering the cathode channel and the protons exiting the electrolyte, and they close the electrochemical reaction by generating water. The water then mixes with the nitrogen from the air to comprise the fuel cell exhaust.

Types of fuel cells

The fuel cell stack depicted in Figure 13.2.2 is associated with a particular type of fuel cell, the proton exchange membrane fuel cell (PEMFC). In addition to the PEMFC, the three other major fuel cell types are shown in Figure 13.2.3—the phosphoric acid fuel cell (PAFC), the molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). The types vary by the chemistry utilized, the electrolyte used (which provides the name of each fuel cell type), the operating temperature, the time required to turn the fuel cell on and off, and the rate and extent to which the power output can be changed. All operate on hydrogen but can also run off fuels containing hydrogen (for example, natural gas, biogas, and propane) that are re-formed (usually at high temperature with the addition of steam) to release the hydrogen for fueling the stack.*

Because PEMFCs turn on and off like an automobile engine, operate at a relatively low temperature, and rapidly change power output in response to load, they are ideal for powering both ground-based vehicles (from forklifts, to automobiles, to heavy-duty trucks) and space vehicles (for example, space modules, space stations) and for providing backup power in the event of a grid outage (for example, for servers and telephone cell towers). Ballard is an example of a manufacturer of PEMFC systems with applications that include buses, trucks, and urban light-rail trams.

The other fuel cell types require several hours to turn on and off.

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*Reformation (or re-formation) is a process to extract hydrogen from the hydrogen embedded in fossil and bio fuels. The most common fossil fuel reformed is natural gas, which is rich in methane (CH_4), using a steam methane reformation (SMR) process. When methane is exposed to heat and steam, the hydrogen can be separated and purified for industrial applications and the refining of gasoline, as two examples.

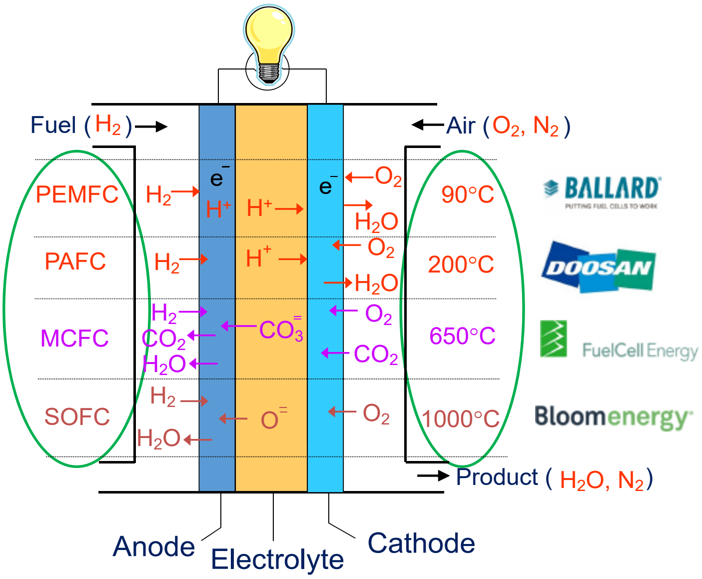


FIGURE 13.2.3 **Fuel cell types.**

As a result, they are dedicated to generating electricity for facilities that have a relatively constant 24/7 load. These loads, while relatively constant, can vary. For example, the load can be different during the day than at night, or during a weekday than on the weekend. The extent to which each fuel cell type can load follow varies. PAFCs are flexible in this regard, whereas MCFCs and SOFCs are less flexible.

PAFCs were the first fuel cell product to be commercialized (in 1992), and today Doosan (their sole manufacturer) offers systems from 400 kilowatts (kW) to 40 megawatts (MW) based on a 400 kW module. (A few kilowatts would be adequate for a home, whereas a megawatt would be appropriate for a hotel.) While the vast majority of the systems deployed worldwide operate on natural gas that is converted to hydrogen through a reformer external to (that is, separated from) the fuel cell stack, Doosan has deployed a 40 MW system that operates directly on hydrogen supplied by a waste stream at a petrochemical plant in South Korea. PAFCs operate at an elevated temperature (200°C), which allows combined heat and power (CHP) and combined cooling, heat, and power (CCHP) applications with efficiencies exceeding 90%.

The basic module of the MCFC commercial unit, 1.4 MW, is replicated to achieve the power ordered by the customer. For example, ten 1.4 MW modules provide 14 MW of power. Typical systems are 2.8 MW, with the largest system, 59 MW, in service in South Korea. MCFCs were first commercialized in 1993 by FuelCell Energy, the sole manufacturer, as the first high-temperature system (650°C). The higher temperature provides both attractive options for CHP and CCHP and the ability to internally reform the fuel (for example, natural gas). The technology has also led to

- The operation of fuel cells on biogas (sourced from water resource recovery facilities), thereby generating carbon-neutral renewable electricity.
- The generation of carbon-neutral hydrogen as well as electricity and heat, referred to as tri-generation.

Bloom Energy has pioneered the introduction of high-temperature (1,000°C) SOFC technology beginning with commercialization in 2009. While the size of the basic module has varied, 250 kW is representative. The technology is purpose-built to be solely an electric generator (that is, not equipped for CHP/CCHP), using the heat instead to generate more electricity with overall fuel-to-electricity efficiencies exceeding 60% and exhaust temperatures as low as 65°C. Similar to MCFCs, SOFCs use internal reformation. A second SOFC manufacturer entering the market is Mitsubishi Hitachi Power Systems with a 250 kW and 1 MW fuel cell (FC) module integrated with a gas turbine (GT) to create a fuel cell/GT hybrid.

Deployment of fuel cells

As shown in Figure 13.2.4, fuel cells are deployed as distributed generators, with sizes ranging from hundreds of kilowatts to tens of megawatts, across a myriad of market segments on the customer side of the electric meter.* These include

- Industry① (Figure 13.2.4).

**Side of the meter* refers to the customer side or utility side of the electric utility meter. The customer side of the meter encompasses the circuits owned and managed by the customer. The utility side of the meter encompasses the circuits and electrical resources owned and managed by the utility.

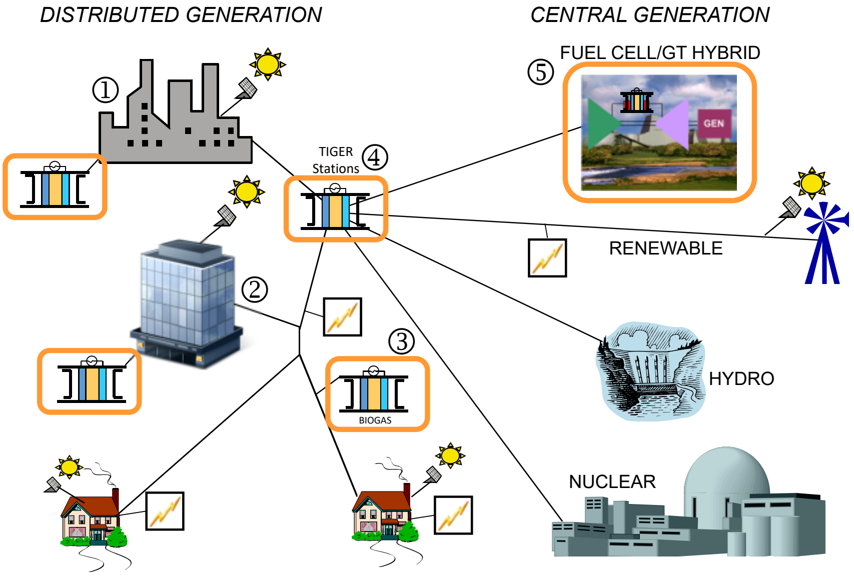


FIGURE 13.2.4 **Fuel cell deployment.**

- Office buildings, commercial developments, universities, and hospitals②.
- Water resource recovery facilities③.

Fuel cell technology has been installed throughout the world, with initial market concentrations in Korea, Japan, Europe, and California. In California, over 250 MW of product is installed throughout the state (Figure 13.2.5), with higher concentrations in the two major population centers of northern California and southern California.

On the utility side of the meter, large fuel cell systems are being deployed as **TIGER** (transmission integrated grid energy resource) stations to support local grid constraints (Figure 13.2.4 ④). Rather than serving a single customer, these TIGER stations are integrated into the electricity grid. Examples include 10 MW TIGER stations powering "cloud" server farms (for example, eBay, Apple, and Microsoft); a 15 MW TIGER station in Bridgeport, Connecticut; a 30 MW TIGER station in Delaware; and a 59 MW TIGER station in South Korea. Also depicted are fuel cell/GT hybrid systems being developed for 1,000-MW-scale central generation (Figure 13.2.4 ⑤).

Notable in Figure 13.2.4 is the absence of combustion sources of

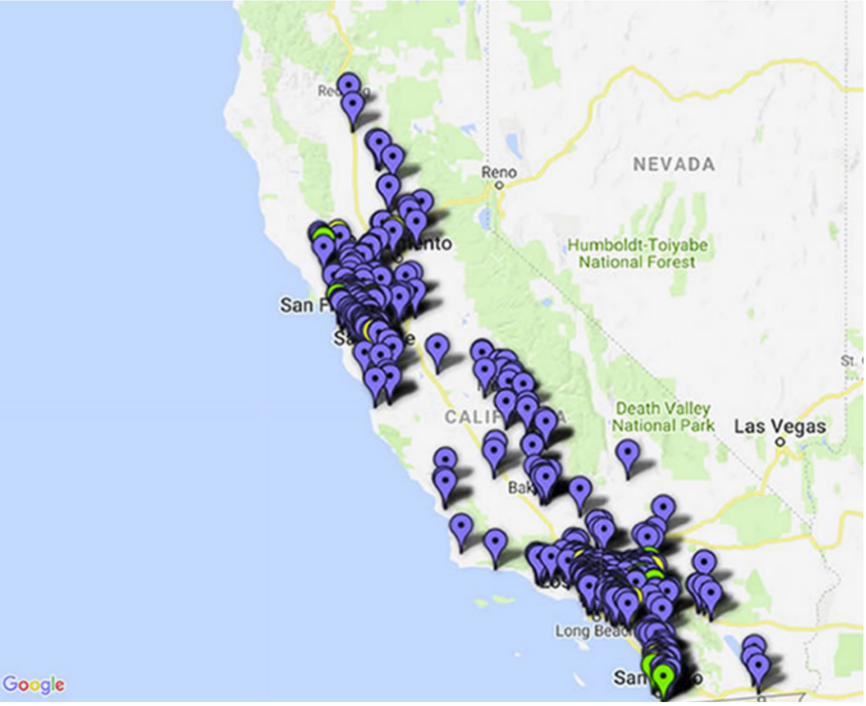


FIGURE 13.2.5 **Plot of fuel cell sites in California in 2019.** Reproduced from California Stationary Fuel Cell Collaborative.

electricity, representing the culmination of the paradigm shift from a combustion-dominant electric grid, with the associated limited efficiencies and emission of criteria pollutants, to an electrochemical-dominant electric grid, with high efficiencies and virtually zero emission of local air pollutants such as nitrogen oxides. While this is notable, it is important to recognize that this paradigm, while having zero emissions of local air pollutants, may not have zero emissions of carbon. If the fuel cells are operating on natural gas, biogas, or syngas, carbon dioxide generated in the reformation process will be liberated in the exhaust. If the fuel cells instead are operating on renewable hydrogen (from otherwise curtailed solar and wind, for example), Figure 13.2.4 represents a 100% renewable grid.

13.3 100% Renewable Grid

This section sets out two pathways toward a 100% renewable electricity grid, using the four new paradigms discussed in Section 13.1 and the fuel cell technologies discussed in Section 13.2. These pathways, illustrated in Figure 13.3.1, are being implemented today in many regions of the world, particularly Europe and California. The two pathways differ in the management of (1) load balancing, reliability, and dynamics associated with diurnal and seasonal variation, intermittency, and the limited capacity factors that accompany a high penetration of solar and wind power generation; and (2) the uncertainty in forecasting intermittent solar and wind resources. Both scenarios hold in common that energy storage is required, but they differ in (1) the amount and types of energy storage and (2) the need for a clean, firm, 24/7 power generator in addition to solar and wind power generation.

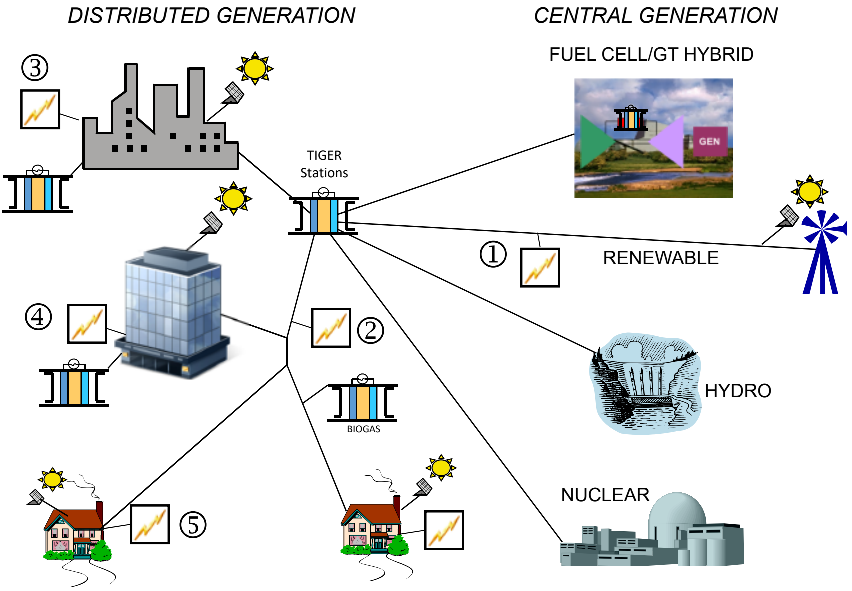
Pathway 1

Pathway 1, depicted in Figure 13.3.1a, assumes that electric battery technology and pumped hydro storage alone will be sufficient to manage the diurnally varying and intermittent solar and wind resources. To this end, Li-ion batteries are being deployed at the transmission① and distribution② levels of the utility grid, at industry③, at hotels/hospitals/universities④, and at homes⑤. The basic strategy is for the batteries and pumped hydro to absorb the excess electricity generated by solar and wind resources when loads on the grid are below the renewable generating capacity, and then to recover the energy as electricity from the electric batteries and hydro reservoirs when the utility loads exceed the renewable generating capacity (particularly at times solar and wind resources are not generating during their diurnal cycles).

Pathway 2

Pathway 2, depicted in Figure 13.3.1b, argues that electric battery and pumped hydro storage alone, while providing a cornerstone to storing

(a) Pathway 1



(b) Pathway 2

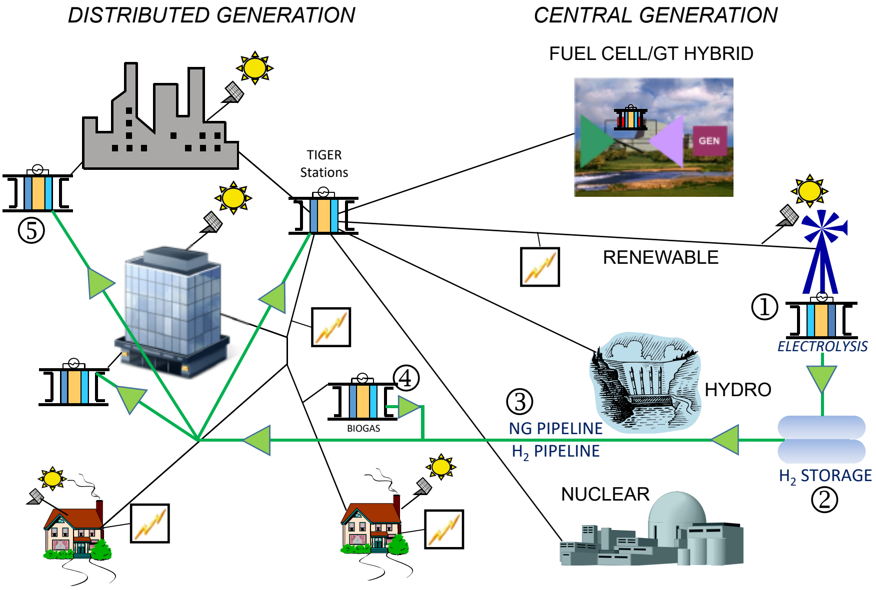


FIGURE 13.3.1 100% renewable grid.

energy available from otherwise curtailed wind and solar resources, are insufficient to provide a reliable electricity supply. To systematically and rigorously evaluate the requirements, energy systems analyses tools have been developed to explore the technologies required to enable and manage the solar and wind resources associated with a 100% renewable grid. Under the auspices of the California Energy Commission, for example, a systems analysis tool, the Holistic Grid Resource Integration and Deployment (HiGRID) code, was developed to guide planning for a modern electric grid. From evaluation of a myriad of scenarios to determine the resources needed to manage the intermittency, diurnal variation, and constrained capacity factor associated with solar and wind, two key resources emerged as being required: (1) a "hydrogen battery" resource and (2) a 24/7, clean, load-following renewable power-generating resource.

"Hydrogen battery" resource Due to the massive amounts of energy that are projected to be (1) available from otherwise curtailed solar and wind resources, (2) required to support the grid when loads exceed the available wind and solar, and (3) required to overcome the limitations of electric batteries (degradation, cost, self-discharging, and inability to accommodate seasonal shifts in energy demand), systems analyses such as HiGRID are consistently demonstrating that hydrogen in general, and renewable hydrogen in particular, is required as a major cornerstone in achieving a 100% renewable grid. To this end, a number of sources of renewable hydrogen are emerging. Here are some examples:

- Electrolytic renewable hydrogen: The generation of renewable hydrogen through electrolysis (Figure 13.3.1b ①) is expected to be the largest source that can absorb the levels of projected curtailed energy, store the energy by injection into the natural gas or dedicated hydrogen pipeline (Figure 13.3.1b ②), and convey the energy to the points of use (Figure 13.3.1b ③).
- Tri-generation: A smaller-scale source is the generation of carbon-neutral hydrogen from a stationary fuel cell operating on biogas produced, for example, at waste water recovery facilities that process human sewage and food waste, landfills that store biodegrading

human waste, and dairies that deal with large volumes of cow manure (Figure 13.3.1b ④). These facilities typically produce biogas rich in methane, which, if emitted, is significantly more climate change intensive than CO_2. Tri-generation captures and uses the biogas to produce carbon-neutral electricity and heat. By operating the fuel cell with more biogas than required for the electricity and heat alone, excess carbon-neutral biohydrogen is made available at the stack and can be extracted and injected into the natural gas or dedicated renewable hydrogen pipeline. At waste water recovery facilities and dairies, the heat can be used to support the digesters and thereby displace fossil fuel boilers, further reducing CO_2 emissions. Tri-generation is the epitome of sustainability, namely recovering and converting the energy from human and animal waste to renewable electricity, renewable heat, and renewable hydrogen.

24/7, clean, load-following renewable power-generating resource
Stationary fuel cell systems, of the designs discussed in Section 13.2, are emerging as a technology to generate the required clean, 24/7, load-following, renewable power with the added attribute of virtually zero emission of pollutants. Already meeting initial market demand for base load power generation, more than 30% of the fuel cells operating today in California are generating renewable power by operating on locally derived and directed biogas. To meet the challenge of the next-generation 100% renewable grid, stationary fuel cell systems are being deployed today with the requisite load-following attributes and also the ability to operate on hydrogen as well as natural gas and biogas. Simply stated, stationary fuel cell systems are

- A resource, along with energy storage, to enable and manage a 100% renewable grid.
- A match for the utilization of the renewable hydrogen generated from otherwise curtailed wind and solar resources (Figure 13.3.1b ⑤).

13.4 Merging of Transportation

The next generation of vehicles is emerging in response to environmental pressures and a goal of fuel independence. The environmental pressures, which include the mitigation of climate change and air quality degradation, require a dramatic reduction in the emission of GHGs and air pollutants from the transportation sector as well as the electric sector. Fuel independence requires removing reliance on the international sourcing of carbon-rich fossil fuels and the associated geopolitics. In response, vehicles of all sizes are transitioning from combustion engines and mechanical drivetrains to alternative vehicles with battery and fuel cell engines and electric drivetrains. The transition began with light-duty vehicles, expanded into medium-duty vehicles, and is now emerging with heavy-duty vehicles including buses. This transition involves a merging of the transportation system with the electricity generation system.

Alternative vehicles encompass **fuel cell electric vehicles** (**FCEVs**) and **plug-in electric vehicles** (**PEVs**). Examples of PEVs are **battery electric vehicles** (**BEVs**) and **plug-in fuel cell electric vehicles** (**PFCEVs**). All of these vehicles have a few key characteristics in common. First, alternative vehicles are designed to operate on fuels that portend (1) a potential of zero emission of both GHG and criteria pollutants and (2) an opportunity to be generated locally and thereby achieve the goal of fuel independence. Second, alternative vehicles have no tailpipe emissions of carbon or criteria pollutants. The GHG and criteria pollutant emissions, if any, come solely from the fuel supply chain, such as the generation of electricity or production of hydrogen. Electricity and hydrogen are the two fuels emerging to power alternative vehicles.

Electricity as a fuel

For PEVs, the electric grid becomes the source of the fuel. As shown in Figure 13.4.1, PEVs garner electricity from the home, from the place of work, and in the conduct of business at commercial centers such

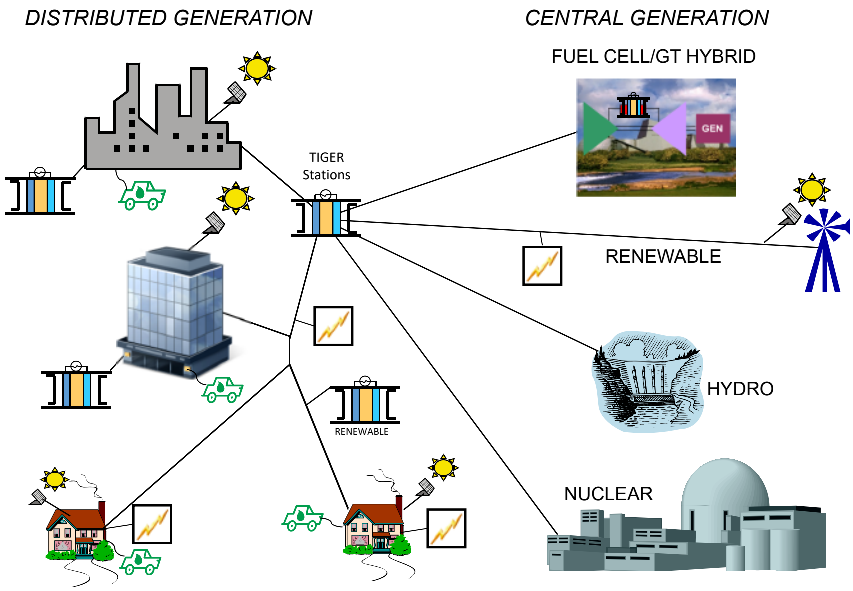


FIGURE 13.4.1 **Merging of transportation and the electric grid.**

as big-box stores, shopping centers, and hotels. Referred to as G2V (grid-to-vehicle), extracting energy from the grid adds a new load to the grid. Conversely, PEVs have the potential to provide beneficial attributes to the grid. With what is called V2G (vehicle-to-grid), energy can be extracted from qualified vehicles to serve loads when generating assets are strained.

The existing grid is able to accommodate modest charging events, but as the number of charging events increases (for example, at homes), local transformers may overload and fail. As a result, either upgrades to transformers or controlled charging (that is, smart charging), or both, will be required.

In Figure 13.4.1, while the emissions of pollutants from the tailpipes and electric grid are virtually zero and the emission of carbon from the vehicles is zero, the carbon emissions from the electric grid will not be zero with stationary fuel cells (as mentioned above) operating on fossil fuels (for example, natural gas) and biogas. What is required is a zero-carbon fuel.

Hydrogen as a zero-carbon fuel

For FCEVs, hydrogen is the fuel. For PFCEVs, hydrogen is the “long-range” fuel (300 to 400 miles) while electricity is the “short-range” fuel (50 to 150 miles). While the vehicles themselves emit zero carbon, the supply chain of electricity (as noted above) and hydrogen can be major sources of atmospheric carbon if not carefully planned. For example, hydrogen has been traditionally generated in large plants by the steam reformation of natural gas at elevated temperatures. The principal component of natural gas is methane (CH_4), with concentrations varying around the world from 70% to over 90%. Other components can be other hydrocarbons (for example, propane and ethane) and inert chemicals such as carbon dioxide and nitrogen.

Today, over 50 million metric tons of hydrogen from steam methane reformation (SMR; see Section 13.2) are produced annually worldwide, and 11 million metric tons are produced in the United States to support manufacturing (for example, of chemicals, foods, and electronics) and the refining of petroleum to generate gasoline. Notably, the amount of hydrogen needed to fuel 20 million FCEVs in California (today’s population of all vehicles in California) is just 20% more than the hydrogen generated today for the production of gasoline in California. If all the vehicles were PFCEVs, less than 80% would be required. However, SMR hydrogen has an associated emission of CO_2. What is required is the generation of renewable hydrogen without the emission of carbon.

A representative zero-carbon cycle is shown in Figure 13.4.2 for the future generation, distribution, and utilization of renewable hydrogen for the transportation sector as well as the electricity sector. As described in Figure 13.3.1b, an initial step in the production of renewable hydrogen is the generation of carbon-neutral biohydrogen using tri-generation (Figure 13.4.2 ①) for fueling FCEVs and PFCEVs as well as stationary fuel cells. As noted previously, the vast majority of renewable hydrogen is expected to be sourced from the generation of electrolytic zero-carbon hydrogen from otherwise curtailed solar and wind. Not only can electrolytic zero-carbon hydrogen be stored over long periods of time and used in stationary fuel cells as diurnal or seasonal demand requires (Figure 13.3.1b), it can also be used to fuel FCEVs and PFCEVs (Figure 13.4.2 ②).

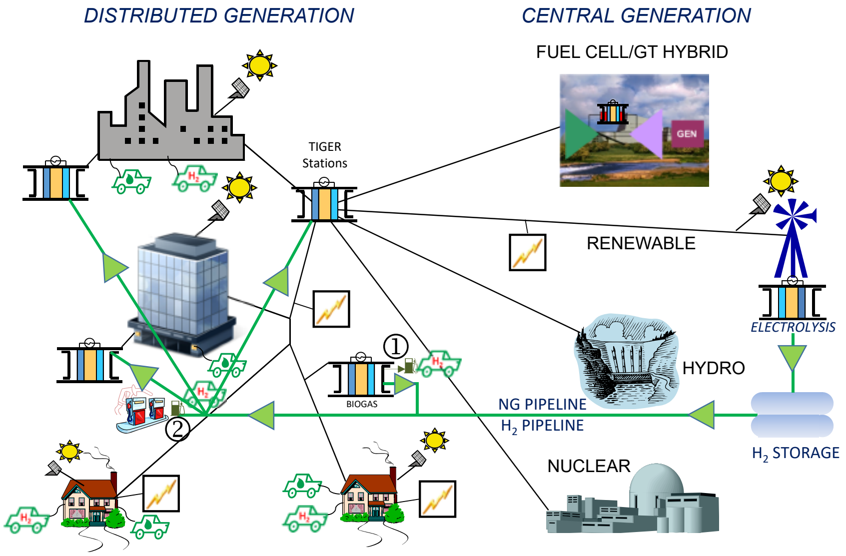


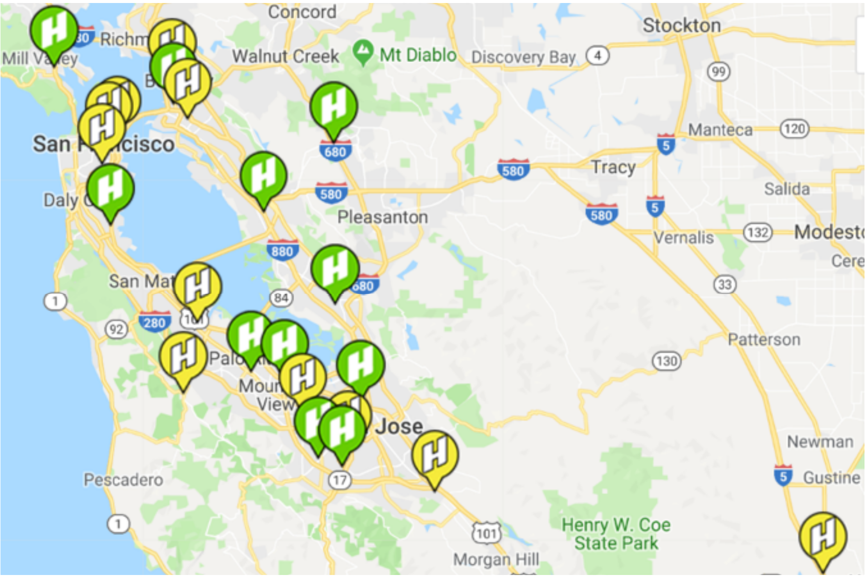
FIGURE 13.4.2 100% renewable grid and transportation.

To use the California example again, systems analyses show that the amount of renewable zero-carbon hydrogen generated by otherwise curtailed renewable resources will be more than ample to fuel FCEVs. While water is also required, fueling all the state's 20 million vehicles with electrolytic zero-carbon hydrogen would need less than 1% of the daily water flow in the California Aqueduct. If all vehicles were PFCEVs, less than 0.2% would be required.

For dispensing hydrogen to FCEVs, fueling stations are today being deployed at existing gasoline stations (Figure 13.4.2 ②). The locations are already zoned for fueling, and the public is familiar with the location as a fueling site. Hydrogen dispensing can be added to an existing island (displacing a gasoline dispenser) or on a newly established fueling island. Over time, gasoline dispensers could be replaced one by one as hydrogen-fueled vehicles displace gasoline-fueled vehicles.

California, again, provides an illustration of the scale of fueling infrastructure that will be required. Approximately 9,800 gasoline stations serve the California population, with multiple stations often sharing the same intersection. However, hydrogen dispensing will not be required at all of the existing gasoline stations. The reasons include the high

(a) Northern California



(b) Southern California

FIGURE 13.4.3 **Hydrogen fueling stations in California in 2019. Green, in operation; yellow, in development; gray, not operational.** Reproduced from California Fuel Cell Partnership.

efficiency of hydrogen vehicles, meaning they can drive farther before refueling than gasoline-powered cars can, and the replacement of competition from the fuel pricing at intersections (often leading to four gasoline stations at an intersection) to the smart phone. For example, it is estimated that a minimum of 1,600 hydrogen stations are needed to fuel a full build-out of FCEVs in 2050. While this number of stations gives drivers a maximum 6-minute access to a hydrogen dispenser, the actual number will likely be larger in order to not overcrowd any one station. If PFCEVs alone were deployed (that is, no FCEVs), the minimum number of stations required statewide would be 93. The larger the percentage of PFCEVs in 2050, the fewer the number of stations over and above 1,600.

In 2019, the number of hydrogen stations in California is approximately 50 (Figure 13.4.3). They are concentrated at population centers targeted for the introduction of FCEVs by the automobile manufacturers, along with key connector stations (for example, between northern and southern California) and destination stations popular with tourists (for example, Santa Barbara, Lake Tahoe, and Napa Valley).

13.5 Smart Grid Technology

With the introduction of distributed generation (DG), renewable generation, and PEVs, evidence of adverse impacts on grid operation is surfacing. These impacts include curtailed solar and wind, and increasing challenges in managing intermittent solar and wind—for example, by buffering intermittencies and by increasingly high afternoon ramp rates to augment the loss of solar late in the afternoon when loads increase. Arguably, to accommodate and manage DG, renewable generation, and PEV penetration, major changes in the operation of the grid must be developed and implemented. The deployment of DG and associated distributed energy resources (DER) such as energy storage requires visibility to, and control over, this new paradigm. Increasing the penetration of intermittent renewable resources requires an accurate forecasting of intermittent solar and wind resources, as well as a methodology to handle the uncertainty that these resources introduce into the modeling, planning, and operation of the system. Managing a high penetration of PEVs requires more visibility into the distribution system so that their impact on the load profile can be managed and they can be used as a grid resource for providing energy and ancillary services. Such "visibility" (that is, the amount and resolution of information that is accessible to system managers) includes real-time operating information on individual transformers.

Smart grid technology is emerging as a major strategy to handle these challenges. A smart grid is a grid with the intelligence to (1) maintain (and increase) the efficiency and reliability of the grid, (2) provide the grid operator with visibility and remote control of the system components through sensing throughout the transmission and distribution network, and (3) provide two-way communication and controls to enable a path for grid automation and electricity markets participation.

California provides an example of where the smart grid is emerging, with a focus on four major levels (Figure 13.5.1):

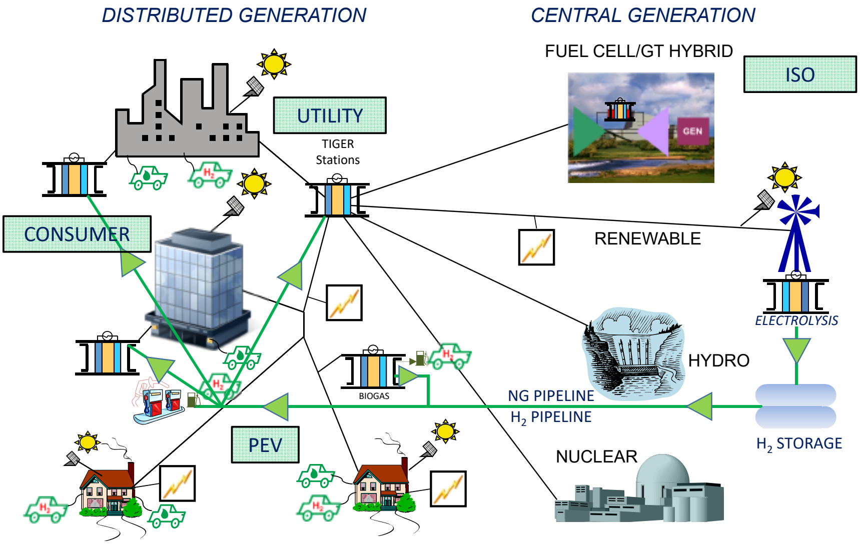


FIGURE 13.5.1 Smart grid.

- **Consumer level:** Facility energy management and control by residential owner, office building manager, industrial plant manager, or campus microgrid operator.
- **PEV level:** Automobile manufacturer and/or utility management schemes, control of PEV charging (smart charging), and potential V2G energy storage recovery.
- **Utility level:** Utility management and control of distribution system services and resources.
- **Independent system operator (ISO) level:** ISO management and control of the full portfolio of grid services and resources, including electricity markets, to ensure that loads are balanced and that supply is reliable and sufficient to meet the grid dynamics, namely load changes and rate of the load changes.

Smart grid technology in the country has developed and improved significantly during the past decade through investment in research and demonstration projects such as the California Public Utilities Commission's smart grid investment plan and the US Department of Energy's Irvine Smart Grid Demonstration program. These efforts resulted in advances and deployment of smart metering, smart appliances, automated substations and other distribution system upgrades, advanced sensing and controls, high-speed communications, smart inverters, and smart switches. The broad deployment of smart grid technology faces challenges, including these examples:

- **Interoperability:** A smart grid requires the various components of the system to communicate with one another or at least a central controller/operator. To achieve this, communication protocols, standards, and a robust communication infrastructure must be developed upon which vendors, utilities, and regulatory agencies can agree and comply.
- **Reliability and cost:** The reliability of the system must be ensured without having excessive redundancy, in order to minimize the overall cost of the system.
- **Data management:** The collection of high-resolution data is required to obtain an accurate picture of the system status and also verify the system load flow and transient models.
- **Cybersecurity:** As the system moves toward automation and remote control, the system must be secured through cybersecurity measures and encrypted communications.
- **Too much change, too quickly:** The smart grid paradigm will dramatically change the roles of utilities, independent system operators, aggregators, and service providers in a relatively short amount of time. Therefore, it is prudent to develop road maps and guidelines for the industry to follow and prepare for their revised roles. For example, with more distributed energy resources, the role of the utility changes from delivering energy to providing ancillary services and backup and/or serving as an aggregator of distributed energy resources.
- **Development of a wholesale electricity market:** First, the generating resource needs to establish an agreement with the utility to access the transmission system. Today this is done through wholesale distribution access tariffs (WDATs.) Second, the grid operators need to allow the distributed energy resources (DER) to participate in the market. This will present challenges since the DER can be very flexible (compared with conventional generation and even renewable

resources) and are located deep in the distribution system where the ISOs do not have visibility.

To achieve the compelling potential attributes of smart grids and microgrids (for example, high efficiency, lower GHG and criteria pollutant emissions, lower operating costs, the accommodation of grid ancillary and emergency services, and the ability to enable and expand the evolving electricity), research is required to advance smart communications, controls, energy storage, high-resolution and robust sensors, power electronics, load-following and high-ramping 24/7 clean power generation, smart PEV charging/discharging, and energy management systems. In parallel, research is required to establish and implement policies that support the development and deployment of the empowered concomitant electricity markets.

13.6 Microgrid Technology

A microgrid is a collection of generation resources, loads, and other DER that presents itself to the grid as a single controllable entity in order to (1) provide ancillary services to the grid in support of grid operations and (2) separate from the grid in the event of a grid outage and operate in an islanded mode. As shown in Figure 13.6.1, the normal operation of the microgrid is "grid-connected." In this mode, the grid provides power when microgrid generation resources are unable to alone support the load. In this mode, the microgrid is also able to provide resources to the grid, these are called **ancillary services**. These ancillary services include local load and generation management wherein the microgrid can shed or add loads and can reduce or increase generation in response to signals from the utility or ISO when the grid itself is experiencing a local deficit in generation resources (for example, no wind to drive wind generators, or no sun to drive solar generators) or a local excess in

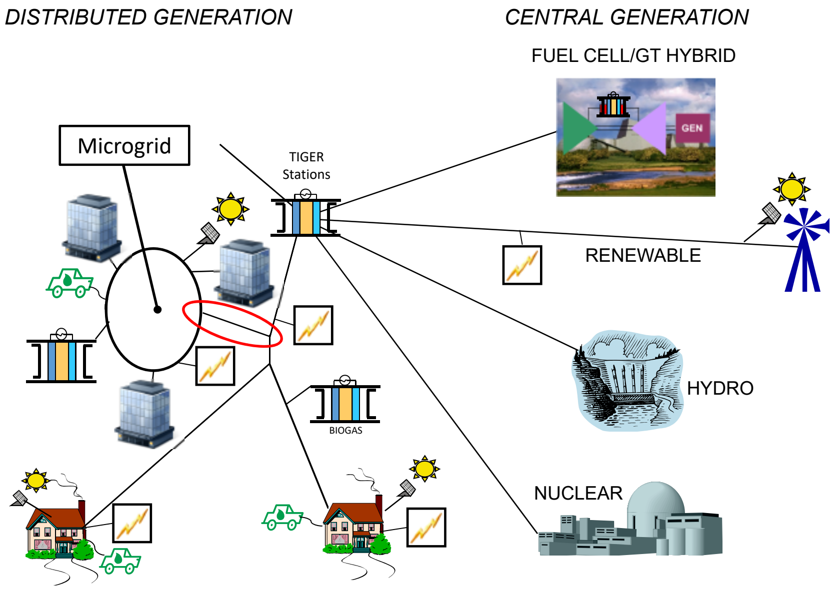


FIGURE 13.6.1 Microgrid technology.

generation (for example, generation from renewable resources that exceeds existing loads). Overall, microgrids reduce the impacts associated with intermittent and flexible resources on the grid.

Microgrids also increase the reliability and resiliency of the community served by the microgrid and the community adjacent to, but outside, the microgrid. In the case of a grid outage, the microgrid can seamlessly disconnect and remain in operation and maintain the microgrid community with electricity. While some loads may have to be shed to match the load to the microgrid generation resources, loads critical to the operation and safety of the microgrid community can be retained intact. An islanded microgrid can provide services such as shelter and food to the adjacent community. In principle, an islanded microgrid can provide electricity to grocery stores, fire stations, gasoline stations, and hospitals in the adjacent community and can assist the utility in restarting the grid.

The potential of microgrids is driving the evolution of microgrid controllers to communicate with loads, generation resources, and other DER (for example, energy storage systems) and thereby (1) optimize the grid-connected microgrid performance, (2) provide ancillary services, (3) support engagement in the electricity markets, (4) manage seamless islanding and reconnection, and (5) provide emergency services to communities adjacent to the microgrid.* In addition, the microgrid controller must communicate in the future with the utility, ISO, and other microgrids to provide (or buy) the services outlined.

A nanogrid (Figure 13.6.2) is a controllable grid within a microgrid, typically a smart building (equipped with a building management system, for example) that is capable of providing ancillary services to the microgrid and separating from the microgrid (retaining building critical loads in service) in case of a microgrid outage, and of managing DER, lighting, and plug-in loads within the nanogrid.

**Emergency services* refers to services provided during a natural disaster or other unforeseen occurrences. These services include energizing critical loads such as hospitals, shelters, and other critical facilities, as well as providing mobility to the community through providing electricity to PEVs and hydrogen to fuel cell vehicles.

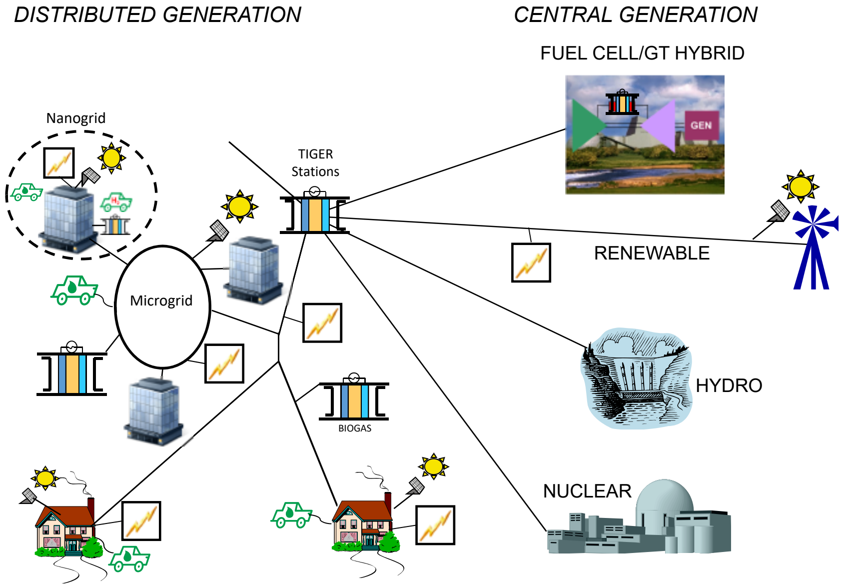


FIGURE 13.6.2 Nanogrid technology.

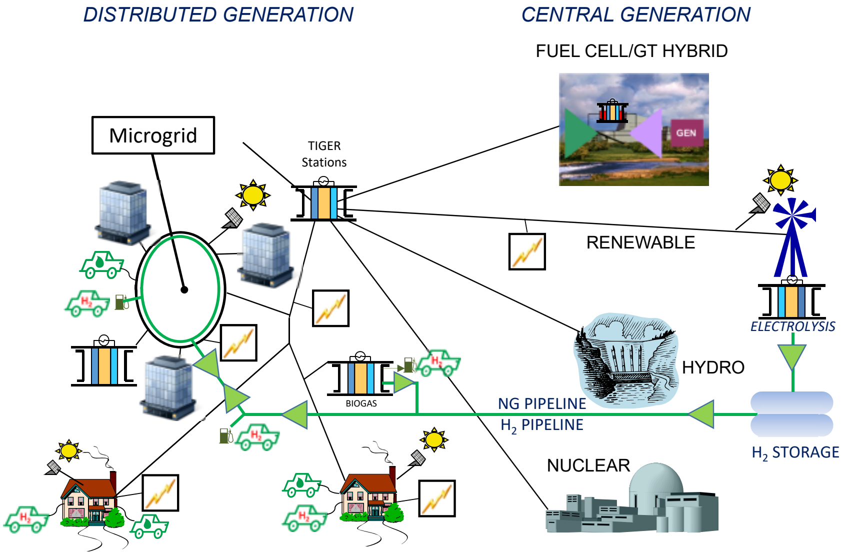


FIGURE 13.6.3 Hydrogen microgrid.

As the population of microgrids increases and the technology evolves, other possibilities emerge, including the following:

- Microgrids could become part of the hydrogen economy, not only utilizing hydrogen for generation and fueling FCEVs, but also generating hydrogen for use within the microgrid and potential export from the microgrid (Figure 13.6.3).
- Microgrids could operate at a frequency different from the grid, connecting to the grid through a power electronics connection, thereby eliminating the need to synchronize with the grid.

Nanogrids also have the potential to transform the manner by which electricity is distributed in a building. In addition to alternating current (AC), electricity can be distributed as direct current (DC), serving directly DC loads (such as computers, servers, and LED lighting). Since evolving distributed generators produce DC (for example, fuel cells, photovoltaic panels), the inversion of DC to AC and the rectification of AC to DC and the consequent losses of up to 20% can be avoided, as discussed in Section 13.1.

13.7 Summary

To address both climate change and the degradation in urban air quality, paradigm shifts in the electric and transportation sectors began at the turn of the century. However, they will need to evolve over decades before settling into the new paradigm. The principal attributes of the new paradigm are (1) the generation of electricity from diurnally varying and intermittent renewable wind and solar; (2) energy storage, to capture and later use energy from otherwise curtailed renewable resources; (3) the integration and electrification of transportation as a challenging load (on the one hand) and a potential source for the grid to tap for stored energy (on the other hand); and (4) smart grid control and management.

Two pathways are emerging, differing only in (1) the need for fuel cell electric vehicles, (2) the amount of energy storage required, and (3) the need for 24/7, clean, load-following renewable power generation in order to manage the diurnally varying and intermittent renewables.

Electric vehicles

Pathway 1 The opinion of many is that BEVs are sufficient and, with advances in battery technology, the energy density will dramatically increase, the charging time will dramatically decrease, and the weight will dramatically decrease to provide the range, fueling time, and size provided historically by petroleum-fueled internal combustion vehicles.

Pathway 2 Others believe that, while BEVs have a role, FCEVs and PFCEVs are needed to provide the range and refueling time to which the public is accustomed with conventional gasoline and diesel internal combustion vehicles. FC technology is also suitable for medium-duty vehicles (such as delivery trucks) and for heavy-duty vehicles (that is, buses and large trucks) where BEV technology is limited or insufficient.

FC technology is applicable as well for off-road construction vehicles, locomotives, and ships.

Energy storage

Pathway 1 The opinion of many is that electric storage batteries and pumped hydro are sufficient and, with advances in electric battery technology, the energy density will evolve to absorb the high levels of curtailed energy projected as the grid builds out.

Pathway 2 Others believe that a renewable hydrogen "battery" is required to

- Provide the massive storage capability to complement electric batteries in absorbing the high levels of curtailed energy projected as the grid builds out.
- Buffer the self-discharging character of electric batteries.
- Provide the capability of diurnal and seasonal shifts in energy stored and energy required.
- Provide zero-carbon renewable hydrogen transportation fuel for powering fuel cell vehicles on the transportation sector.

24/7, clean, load-following power generation

Pathway 1 The opinion of many is that technological advances in electric batteries will provide, along with V2G, the energy storage and ramping to manage and buffer the variability of solar and wind and thereby render 24/7, clean, load-following power generation unnecessary.

Pathway 2 Others believe power generation will be required that is clean (that is, emitting neither GHGs nor criteria pollutants), 24/7 (that is, around the clock, every day of the week), and load following (that is, able to ramp up and down to meet both load demand and diurnal variation and intermittency of wind and solar) to complement and buffer the variability of solar and wind and achieve the goal of a reliable and resilient 100% renewable grid and a 100% renewable transportation system.

The goal of this chapter is to present the key considerations

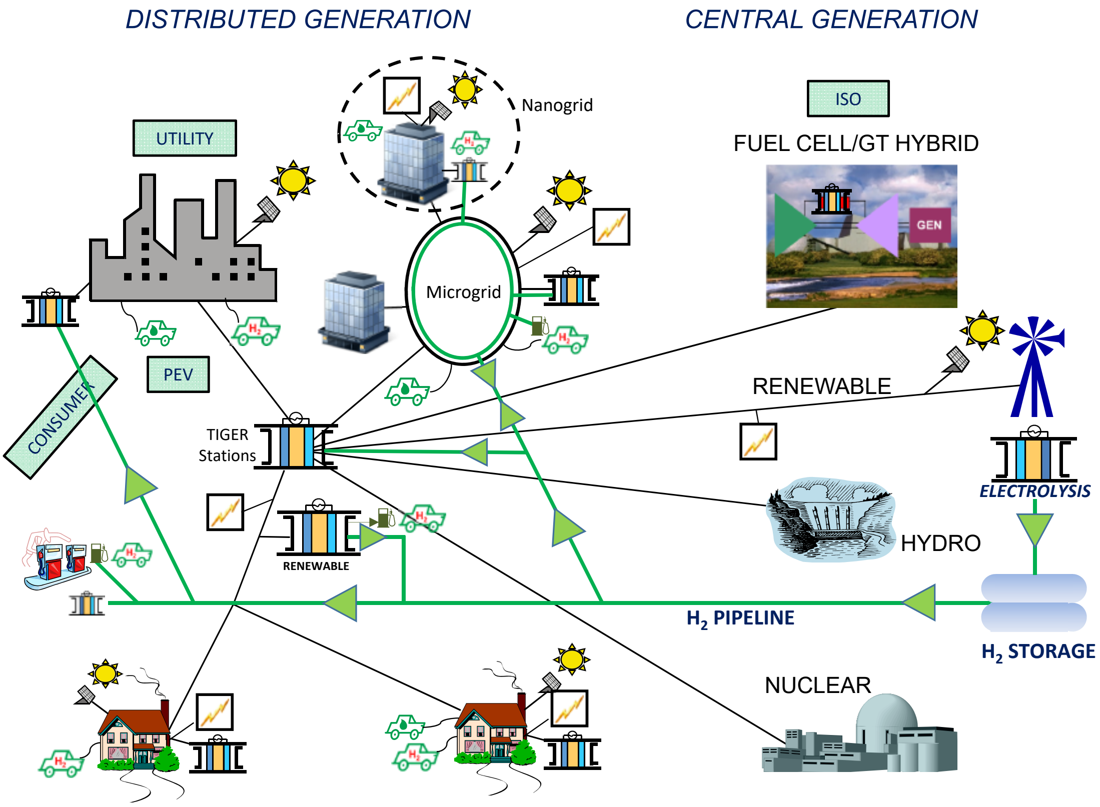


FIGURE 13.6.4 **Pathway 2: the future grid interwoven with transportation, microgrid technology, and smart grid technology.**

necessary to achieve 100% renewable electricity and transportation sectors (to address climate change) commensurate with zero emission of criteria pollutants (to address degraded urban air quality) while achieving fuel independence. To this end, two pathways have been described. Whether pathway 1 (Figure 13.3.1a) or pathway 2 (Figures 13.3.1b and 13.6.4) or another form is realized in the decades to come will depend upon factors such as (1) the evolution and practice of technology, market dynamics, and social dynamics (that is, public support and acceptance); (2) the impacts of climate change and degraded air quality; and (3) policies of the world's governments.

Sources for the Figures

All figures provided by the author unless otherwise indicated.

Figure 13.1.1: Getty Images. https://www.gettyimages.com/creative-images/royaltyfree.

Figure 13.1.3: Science Photo Library. https://www.sciencephoto.com/.

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Figure 13.2.5: California Stationary Fuel Cell Collaborative. http://www.casfcc.org/Map_Of_CA_Fuel_Cell_Installations.html.

Figure 13.4.3: California Fuel Cell Partnership. https://cafcp.org/stationmap.

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13.1 Introduction

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