# 1

# Introduction

The electric energy industry ranks among the largest global industries. As per [1], the electric energy generated in 2022 was close to 30,000 TWh. The main sources of electricity generation are coal, gas, oil, hydro, nuclear, wind, and solar. Table 1.1 shows the worldwide energy mix for the years 2014 and 2022 [1]. Fossil fuel-based greenhouse gas emitting generation sources have reduced their share from 67% in 2014 to 61.26% in 2022. The share of low-carbon-emitting sources such as hydro and nuclear has also declined from 26.95% to 24.14%. However, to offset these, the share of wind and solar power generation has increased from 3.88% to 11.89%. Wind and solar power generation are projected to experience rapid growth over the next 10–15 years. The percentage energy mix is shown in Figure 1.1.

A better picture of the generation mix is given in Table 1.2, where the total energy generation is shown for the years 2014 and 2022. It can be seen from this table that energy generation has increased by about 4,898 TWh between 2014 and 2022, where the energy output from all the sources has increased, except for oil, which has decreased. Another important statistic that has been reported in [1] is the share of electricity from low-carbon sources, including nuclear, hydro, wind, solar, biomass, geothermal, wave, and tidal. The total share of these sources has increased from 32.99% in 2014 to 38.73% in 2022.



## 1.1 A Brief History of Electricity

The use of electric energy is ubiquitous these days with applications in every facet of human endeavor. However, to reach this stage, it has taken several centuries and spanned many countries. The history of electricity is really interesting with many geniuses and talented individuals contributing to its development. In this section, a brief history of the modern discovery and origin of electricity is presented.

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**Table 1.1** Worldwide energy mix in percentages.

| Energy sources | Percentage share | |
|---|---|---|
| | **2014** | **2022** |
| Coal | 40.61 | 35.63 |
| Gas | 21.61 | 22.48 |
| Hydropower | 16.43 | 14.96 |
| Nuclear | 10.52 | 9.18 |
| Wind | 3.04 | 7.32 |
| Solar | 0.84 | 4.57 |
| Oil | 4.78 | 3.15 |
| Bioenergy | 1.84 | 2.36 |
| Other renewables | 0.33 | 0.34 |

*Source:* Adapter from Ritchie and Rosado [1].

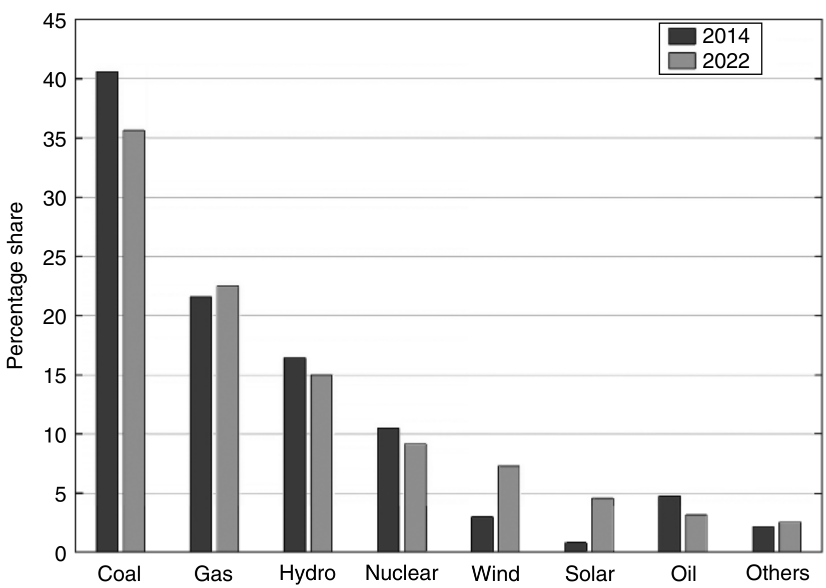


**Figure 1.1** Comparison of energy mix percentage between the years 2014 and 2022. *Source:* Adapter from Ritchie and Rosado [1].

**Table 1.2** Worldwide energy mix in TWh.

| Energy sources | 2014 (TWh) | 2022 (TWh) |
|---|---|---|
| Coal | 9,226.71 | 10,212.22 |
| Gas | 5,402.71 | 6,443.60 |
| Hydropower | 3,872.76 | 4,288.59 |
| Nuclear | 2,504.73 | 2,632.06 |
| Wind | 828.60 | 2,098.46 |
| Solar | 255.79 | 1,310.02 |
| Oil | 1,120.57 | 904.15 |
| Bioenergy | 470.66 | 675.11 |
| Other renewables | 80.30 | 96.80 |
| Total | 23,762.83 | 28,660.98 |

*Source:* Adapter from Ritchie and Rosado [1].

### 1.1.1 The Dawn of Electricity

In the beginning, the early pioneers carried out experiments to satisfy their intellectual curiosity. William Gilbert was a Doctor of Medicine who was the personal physician of Queen Elizabeth I of England. Despite being a physician, he is known for his work on the Earth's magnetic field because he speculated that the magnetic north pole attracts compasses. He was the first one to propose that the Earth is a giant magnet. However, about 1,000 years before Gilbert, ancient Indian philosopher Varhamihira, described the effects of the Earth's magnetic field, even though he could not predict the Earth's magnetic field like Gilbert. Interestingly, Gilbert studied static electricity using amber, which is called *elektron* in Greek. Thus, Gilbert called its effects *electric force*. The term *electricity* was coined in 1646 by English polymath Sir Thomas Browne using Gilbert's work.

Benjamin Franklin was an American statesman and one of its founding fathers. He is known for his role in several administrative capacities and with the Declaration of American Independence (his picture can be seen on $100 bills in the USA). He was a multitalented person who has been credited for several inventions such as the lightning rod, bifocal lens, and flexible urinary catheter. In 1752, he flew a kite with a metal key attached; possibly even a metallic rod to see sparks being generated from clouds. To temper scientific curiosity, he risked his life by flying a kite in cloudy conditions. Franklin is credited with the discovery of static electricity. Other notable individuals such as Charles-Augustin de Coulomb discovered electrostatic force attractions and repulsion (Coulomb's law) in 1785.

Meanwhile, Italian physician and scientist Luigi Galvani studied the effects of electricity on living organisms. He discovered that the muscles of dead frogs twitch when electricity is passed through them, therefore inspiring many high school experiments today. Galvanic isolation (which refers to the isolation between two electrical systems) and galvanometer (for measuring electric current) are named after him. Alessandro Volta invented a voltaic pile by putting alternate layers of zinc and copper with isolation between them. This inspired the development of electric batteries.

Hans Christian Ørsted and André-Marie Ampère made significant strides in recognizing that there is a relationship between electricity and magnetism. In 1820, Ørsted discovered that a compass needle deflects in the near vicinity of an electric current. In his honor, the unit of the magnetic field is named Oersted. Building on this, Ampère demonstrated that parallel wires carrying electric currents attract or repel each other depending on the direction of current flow. Today, the unit of electric current, Ampere or Amp bears his name, recognizing his contributions to electromagnetism.

An English scientist Michael Faraday started developing a keen interest in science while working as an apprentice in a bookshop and bookbinder, where he had access to many scientific books. Later he was able to gather work as an assistant of English chemist Humphry Davy. In 1821, Faraday started developing an interest in working on electromagnetism. He realized that an electric current could be produced by passing a magnet through a copper wire. This is the basic principle based on which all motors and generators are constructed today. His series of experiments resulted in the discovery of electromagnetic induction in 1931. Faraday subsequently used his induction principle to build a machine to generate voltage. Around the same time, American engineer Joseph Henry also worked independently on the induction principle and applied his work to electromagnets and telegraphs. However, Faraday was the first to publish his results. It is only befitting that the units of capacitance and inductance are named after Faraday and Henry, respectively.

In 1827, German physicist and mathematician Georg Ohm found a direct proportionality between voltage applied to and current through a conductor. This has resulted in the well-known Ohm's law. The unit of resistance, as well as impedance, is named after him. Scottish physicist James Clark Maxwell explained electromagnetism in his paper "On physical lines of force" in 1861. The timeline for the early development of electricity is listed in Table 1.3.

### 1.1.2 Development of Electrical Power Plant

Another pioneer introduced earlier, Sir Humphry Davy, is famous for the invention of Davy's safety lamp in 1809. This was used for underground coal mines in the early 19th century to prevent flammable gases from igniting. In Davy's lamp,

**Table 1.3** Timeline for the early development of electricity.

| Name | Year | Contributions | Acknowledgment |
|---|---|---|---|
| William Gilbert | 1600 | He conducted experiments to conclude that the Earth is magnetic, and the center of the Earth is iron. He also studied the production of static electricity by rubbing ambers. | Recognized for proposing that the Earth is a giant magnetic field. |
| Sir Thomas Browne | 1646 | From the Greek word "electron" for amber, Brown coined the word electricity. | Recognized for coining the term electricity |
| Benjamin Franklin | 1752 | Franklin discovered static electricity by observing sparks generated by clouds. | His face appears in $100 bill of the USA. |
| C. A. de Coulomb | 1785 | Coulomb's law describes the electrostatic force for attractions and repulsions. | The unit of electric charge is named after him. |
| Luigi Galvani | 1791 | Galvani demonstrated that electricity is a medium by which nerve cells pass signals to muscles. | Galvanic isolation and galvanic meters are named after him. |
| Alessandro Volta | 1800 | Volta invented the Voltaic pile, which is the precursor of modern batteries. | The potential difference between two electric conductors is called voltage and is measured in volts in his honor. |
| Hans Christian Ørsted and André-Marie Ampère | 1819–1820 | They recognized there is a relation between electricity and magnetism. | Magnetic field is measured in Orsted. |
| Michael Faraday | 1821–1831 | Faraday started working on electromagnetic induction. | The unit of capacitance is named after him. |
| Joseph Henrey | 1832 | Electromagnetic Induction. | The unit of inductance is named after him. |
| Georg Ohm | 1827 | Ohm mathematically electrical circuit, which is the famous Ohm's law. | The unit of impedance is named after him. |
| Joseph Henry | 1832 | Electromagnetic induction. | The unit of inductance is named after him. |
| James Clerk Maxwell | 1861 | Maxwell explained electromagnetism in his paper "On physical lines of force." | Best known for Maxwell's equation of electromagnetism. |

an arc is produced when pieces of charcoal are connected to two wires of a battery. However, it took several decades to produce commercial arc lighting. The use of batteries for arc lighting was not commercially viable because the current requirement to generate arc would drain the batteries quickly. Moreover, the intense heat of the arc will also burn the charcoal. The generators started to become widely available following the development of dynamos. In 1870, Russian inventor Paul Jablochkoff devised a version of the arc lamp in which he used two carbon rods to increase the life span of the lamps [2]. Arc lamps were used in lighthouses and streets and rarely indoors due to the high intensity of these lights.

From the work of Davy and others, it was well-known that a current-carrying conductor could be heated to the point of incandescence. However, incandescent materials burned very quickly in the atmosphere to be of no use for lighting. In 1879, American inventor Thomas Alva Edison devised the first incandescent lamp using carbonized cotton thread in a vacuum space inside a glass bulb. The first bulb glowed for 44 hours before it burned out. Edison improved the design of the lamp so that it could last longer.

The first demonstration of electric motors was done by Michael Faraday. He not only proposed electromagnetic induction but also invented the Faraday Disk in which a disk is placed between two magnetic poles. An electric current is produced when the disk rotates. The current is drawn through two sliding contacts (armatures) that are placed at the center and edge of the disk. Therefore, Faraday can be called the first pioneer of DC machines. Many other pioneers further improved the design of DC generators such as Werner von Siemens and Thomas Edison, which led to the development of power plants.

Edison set up the first commercial power station at 255 Pearl Street in New York City on September 4, 1882 (see Figure 1.2). The station had a capacity of 110 kW, which was powered by 14 boilers and 4 direct current generators. Initially, the station supplied 82 customers in the lower Manhattan area with enough power to light 400 lamps. There were several advantages of a DC system at that time – it could be used for incandescent lamps and DC motors, which were the principal loads in the 1880s. DC generators can directly be used for battery charging and can be easily paralleled. These factors, along with the fact that AC machines were not available at that time, made DC systems the prime power supply candidates at the beginning of electricity supply.

Edison's DC system needed heavy distribution conductors. For the convenience of lamp manufacturers, the operating voltage was chosen as 110 V. To reduce the cost of copper conductors, a three-wire distribution system was used in which 0 V neutral was placed between +110 V and -110 V. However, even with this innovation, the voltage drop due to conductor resistance was so high that the generating plant could only supply customers that were located within 1–2 km from the plant.

Long-distance power transmission became a reality in 1895 when George Westinghouse opened the first major power plant in Niagara Falls using alternating


**Figure 1.2** Pearl Street power station and Edison. Generated with AI using ChatGPT (version GPT-4).

current. This was able to transmit power to a distance of 200 miles (360 km) to the city of Buffalo, New York. It was the partnership between Westinghouse and Nikola Tesla (see Figure 1.3) that made this possible. Tesla was a Serbian-born, naturalized American citizen, whose genius made the alternating current feasible.

**Figure 1.3** Nikola Tesla. Generated with AI using ChatGPT (version GPT-4).

He invented the induction motor that would run on AC power. It is still the workhorse of many industries. He also conceptualized the polyphase system, which was the game changer that made the AC system feasible. During his lifetime, Tesla was awarded 101 US patents. He also invented Tesla Coil, which can transmit and receive energy wirelessly when the coils are tuned at the same frequency. Even though Guglielmo Marconi is credited with the invention of wireless and received the Nobel Prize in 1909, both Tesla and the Indian physicist Jagadish Chandra Bose have made separate contributions to this technology. There are some very interesting anecdotes about Tesla. He had a deep friendship with Samuel Langhorn Clemens, better known as Mark Twain, the author of the adventures of Tom Swayer and Huckleberry Finn. Tesla passed away on January 7, 1943, in a hotel in New York City. Upon his death, the US government ordered the FBI to seize all his papers under the suspicion that they might contain advanced weapons technology. However, the papers were scrutinized by MIT professor John G. Trump (the uncle of 45th and 47th American President Donald J. Trump). Professor Trump concluded that there were no weapon technologies of interest in Tesla's papers.

The AC versus DC resulted in the famous *War of Currents*, with Edison proposing the continuation of DC, while Tesla and Westinghouse proposed AC (see Figure 1.4). This war resulted in disinformation campaigns, litigation, etc., and,

**Figure 1.4** War of currents. Generated with AI using ChatGPT (version GPT-4).

in general, was quite contentious. In 1886, William Stanley developed a prototype system for power transformers to boost up or step down voltages. Westinghouse started pilot projects of using transformers in his laboratory in Pittsburg. The transformers were then used in Buffalo. This was the beginning of AC power generation and transmission.

When the dust settled after the War of Currents, AC won, and DC lost. The AC prevailed over DC due to the following factors:

- At that time, power electronics were unheard of. Therefore, DC voltages could not easily be converted to higher or lower voltages.
- Due to lower operating voltages, the DC power distribution had a limited range due to voltage drop.
- Transformers could boost AC voltage for transmission and could step it down for distribution. Therefore, power could be transmitted over long distances at higher voltages, reducing losses.
- AC systems use thinner copper wires, thereby reducing costs.
- The construction of AC generators was simpler.
- The construction of AC motors was also simpler. Moreover, they were more robust and cheaper than the DC motors even though they were not very sophisticated.

However, DC has made a strong comeback from the second half of the 20th century and is now considered one of the preferred modes of transmission in many instances, as will be discussed in Chapter 10.

## 1.2 Interconnection of Electricity Grids

Electricity supply was mandated by most countries by the public utility act. A public utility is an organization that maintains infrastructures for a public service, such as electricity and gas. Using these infrastructures, it provides a public service at the consumer level, be it residential, commercial, or industrial consumers. Electric utilities are subject to forms of public control and regulations. Public electric utilities usually were, and even now in many places are, statewide government monopolies. The utilities are regulated by public service commissions that fix their prices and services.

In the beginning, the electric utilities were responsible for generation, transmission, and distribution. However, starting in the 1920s, the utilities formed joint operations in the United States. The advantages of these were that the peak load could be covered, and backup power could be provided. As the transmission technologies improved, long-distance transmission became feasible and grids from different regions got interconnected to form a mega grid. Some of the advantages of forming interconnected grids are as follows:

- *Improving Reliability*: Electric power can be shared among the different utilities reliably, thereby reducing the requirement of spinning reserve.
- *Reducing Investment*: By sharing the generating resources, individual utilities do not need to add to their generating capacity.

From 1967, the East and West interconnections in the United States were directly connected together. However, the AC ties did not have high capacity and were subject to oscillations, so their connection proved unreliable. In 1975, the AC ties were disconnected because DC ties were found to work more reliably.

The US power system, including Canada and a portion of Mexico, is divided into three major grids: the Western interconnection, the Eastern interconnection, and the Texas interconnection. All these regions are coordinated by the *North American Electric Reliability Corporation* (NERC). European power grid is a massive synchronous grid that spans about 24 countries and is managed by the European Network of Transmission System Operators for Electricity (ENTSO-E). In addition to the countries in continental Europe, some of the African countries (e.g., Morrocco, Algeria, and Tunisia) are also synchronized with this grid. In Australia, all the eastern seaboard states of Queensland, New South Wales, Victoria, and South Australia are connected through AC ties, while Tasmania is connected to Victoria through a subsea 370 km high-voltage DC (HVDC) link called Basslink. Similar interconnections can also be found on the continent of Africa and other countries. In India, the National Grid is a state-owned 50 Hz synchronous grid that is managed by the Power Grid Corporation of India. The state-owned State Grid Corporation of China is the largest utility company in the world.

Usually, AC connections are the more prevalent interconnection types. However, they can observe stability problems, some of which can be solved by power system stabilizers, which will be discussed in Chapter 7. The inclusion of flexible AC transmission system (FACTS) devices can alleviate stability problems. As mentioned earlier, the east–west connection in the NERC system resulted in system oscillations. To counteract these oscillations, the AC ties were disconnected in 1975 and were replaced by HVDC tie lines. The DC tie lines can isolate disturbances of one region from propagating to the other region, and therefore, are preferred in many interconnections.

## 1.3 Deregulation

The Energy Policy Act (EPACT) was established in 1992. Under the act, the power transmission companies were required to allow smaller electric generation companies to give access to their networks. This policy aimed to foster competition in power generation. The power generation, transmission, and distribution can now be split among various companies so that customers are benefited overall. The EPACT of 2005 was more stringent. It allowed incentives for alternate energy technologies to reduce greenhouse gas emissions. The key aspects of power system deregulation are as follows:

- *Unbundling*: The vertical integration of electricity utilities is broken down into separate entities for generation, transmission, and distribution. This allows for competition in electricity generation and sometimes in retail supply.
- *Competition*: Deregulation aims to introduce competition, especially in the generation and retail segments. Independent power producers can enter the market, and consumers can choose their electricity supplier.
- *Wholesale Markets*: Establishment of wholesale electricity markets where electricity is bought and sold. These markets are often managed by independent system operators (ISOs) or regional transmission organizations (RTOs).
- *Retail Choice*: Consumers, including residential, commercial, and industrial users, have the option to choose their electricity provider, similar to choosing a phone or internet service provider.
- *Regulation of Transmission and Distribution*: While generation and retail are open to competition, the transmission and distribution networks often remain regulated due to their natural monopoly characteristics. Access to these networks is typically provided on a nondiscriminatory basis.
- *Market Efficiency*: Deregulation is intended to improve efficiency by encouraging competition, which can lead to lower prices, innovation, and better customer service.
- *Challenges and Risks*: Deregulation can present challenges such as market manipulation, price volatility, and ensuring reliability of supply. Effective regulatory oversight and market design are crucial to mitigate these risks.

An ISO is an entity responsible for overseeing the operation of the electricity grid of a region. It ensures reliable electricity delivery and facilitates competitive wholesale electricity markets. ISOs are typically independent of electricity generators and transmission owners to prevent conflicts of interest and to ensure impartial management of the grid. They are responsible for the management of the electricity grid to ensure a balance between supply and demand in real time by monitoring grid conditions and coordinating the flow of electricity across transmission lines. Furthermore, they operate competitive wholesale electricity markets where electricity is bought and sold through auctions and manage market transactions to ensure fair pricing and market efficiency. The ISOs are also responsible for maintaining reserve margins, managing grid stability, and coordinating emergencies.

An RTO also performs the same task as an ISO. However, while an ISO typically operates within a single sector or smaller region, an RTO covers a larger geographic area covering multiple regions. ISOs often cater to local needs and market conditions, while RTOs must comply with the Federal Energy Regulatory Commission (FERC) order of 2000, which mandates that they meet specific characteristics and functions, such as ensuring open access to transmission and maintaining regional grid reliability.

In general, the potential benefits and drawbacks of deregulated markets are as follows:

- *Lower Prices*: Increased competition can drive down prices for consumers.
- *Innovation*: Competitive markets can foster innovation in technologies and services.
- *Customer Choice*: Consumers can choose their provider based on price, service quality, or other preferences.
- *Market Power*: Large players can dominate the market, reducing the intended benefits of competition.
- *Reliability Issues*: Deregulation can sometimes lead to underinvestment in infrastructure, affecting the reliability of supply.
- *Price Volatility*: Without proper market mechanisms, deregulated markets can experience significant price fluctuations.

Some of the examples of deregulated markets are as follows:

- *United States*: Various states have undertaken deregulation with different levels of success. Texas (ERCOT) is often cited as a successful example, while California faced significant challenges during its deregulation process in the early 2000s.
- *United Kingdom*: The United Kingdom was one of the first countries to deregulate its electricity market, beginning in the late 1980s and early 1990s.
- *European Union*: Many EU countries have moved toward deregulated electricity markets as part of broader energy market liberalization initiatives.
- *Australia*: The Australian Energy Market Operator (AEMO) was established in July 2009 to manage the National Electricity Market (NEM) in the eastern and southeastern states of the country and the Australian gas markets.

However, if a deregulated energy market does not follow a strict regulatory framework, it can lead to price gauging by the corporate bodies at the expense of the public. One example is the California energy crisis in 2000–2001, which resulted in widespread blackouts and soaring energy prices. This was caused primarily due to market manipulation by Enron and other minor players. Enron created artificial shortages by intentionally taking power plants offline or rerouting energy to other states and falsely reporting maintenance issues. After investigations, Enron was found guilty and the company collapsed in 2001.

In response to Enron's market manipulation, *Sarbanes-Oxley (SOX) Act* was passed by the US Congress in 2002 [3]. The threefold aims of the act were to combat fraud, improve financial reporting, and restore investor confidence. The act mandated the following:

- The company CEOs must personally certify all financial reports.
- The financial statements must be verified by external auditors.
- Strict rules must be set for record keeping and penalties will apply for falsifying or destroying records.
- Protections must be provided for whistleblowers who report corporate fraud.

This act restored public confidence not only in the energy deregulation but also the in US capital markets.

## 1.4 Renewable Energy

Water is the essential element of all lifeforms on this planet. It also has been used for the production of electric energy, which is termed hydropower or hydroelectricity. Two of the largest hydropower projects are the Three Gorges Project on the Yangtze River in Yichang in China and Itaipu Dam on the Parana River which is located on the border between Brazil and Paraguay. Even though hydropower is a form of renewable energy, its production is location dependent. It requires large catchment areas, continuous flow of water, and water height. The other forms of hydropower, which are still mostly in the experiment stages, are as follows:

- *Wave power plant*, which utilizes continuous wave movement in oceans to generate energy basically converting wave energy to potential energy.
- *Tidal power plant*, in which the rising and falling of sea levels due to the gravitational attractions of the Moon and the Sun alter the potential energy of water, which is converted into electricity.

The other form of location-dependent renewable power generation that is in existence is geothermal energy, in which water is injected into the Earth's mantle, which is always hot. The water is converted into steam, which is used to drive turbines to produce electricity. Basically, there are three types of geothermal plants. These are as follows:

- *Dry steam plant*, which uses steam extracted directly from geothermal reservoirs through production wells to turn generator turbines. After passing through turbines, the steam can be condensed back into water and reinjected back into the well.

- *Flash steam plant*, which uses high-pressure hot water from geothermal reservoirs. As the pressure is reduced, some hot water flashes into steam that is used to drive turbines. Flash steam plants can handle higher temperature resources compared to dry steam plants.
- *Binary cycle plant*, which requires moderate-temperature geothermal water to heat a secondary fluid with a lower boiling point than water. The secondary fluid vaporizes and drives the turbines. Binary cycle plants can utilize lower temperature resources and have the advantage of being able to operate without emitting any geothermal fluids or gases.

The first geothermal plant was established at Larderello, Italy in 1911. This is a dry steam-type plant. The world's largest geothermal field is located at Geysers in northern California. It contains 18 dry steam plants. Flash steam geothermal plants are located in regions with high-temperature geothermal resources, where water is present under pressure at temperatures typically above 182 °C. This is the most popular form of geothermal power that is located in several countries. Major flash steam plants are the Geysers in California, Larderello, and Wayang Windu in Indonesia. Major binary cycle plants are Blue Mountains in Nevada and Berlin Geothermal Field in Germany. Several other countries, including New Zealand, Iceland, the Philippines, Japan, and Kenya, have also geothermal power plants.

Alternate energy technologies that have enormous potential are hydrogen and nuclear fusion. While green hydrogen production or hydrogen production with carbon capture and storage is within the realm of possibilities, hydrogen storage, transportation, and utilization will require significant investment in research and development. However, effective utilization of hydrogen can alleviate greenhouse gas emissions through both electricity generation and automotive applications. Nuclear fusion can solve energy problems forever. However, so far, no experiment has been able to show net energy gain, that is, the energy output is more than the energy input. It is unclear when commercial-scale nuclear fusion will be feasible.

Currently, the most popular form of renewable energy sources is wind and solar. It can be seen from Tables 1.1 and 1.2 that their combined share is still less than hydropower. It is indeed true that wind or solar power potential varies from region to region. However, they are not totally location-sensitive. In most parts of the world, large-scale solar and wind farms are getting connected to the power grid. It is expected that the total share of these two energy sources will climb rapidly in the coming decade.

However, solar and wind energy are inherently intermittent, as the Sun does not always shine and the wind does not always blow. Consequently, these renewable sources cannot provide continuous energy generation all year around. Therefore, these sources are called *intermittent*. The dictionary definition of intermittent is that "which occurs at irregular intervals or that is not steady." Following this definition, defining these sources as intermittent may not be grammatically correct because they can produce steady power for hours. However, the fact remains that environmental conditions play a crucial role in the power generation capability of solar and wind power.

Consider, for instance, solar PVs. A passing cloud can partially or fully shade an array thereby causing fluctuations in the output of the power level. Different types of clouds and their heights are listed in [4]. Clouds that are below the height of 2,000 m have a major impact on solar PV power output. Cumulus clouds, due to their fluffy, white appearance, are one of the most recognizable types of clouds. These clouds are commonly associated with fair weather, though they can develop into more significant storm clouds under the right conditions. Stratocumulus clouds, on the other hand, typically appear as a blanket of gray or white patches, often with darker spots, covering a large portion of the sky. They are one of the most common types of clouds and can be seen in a variety of weather conditions. While both cumulus and stratocumulus clouds will affect the PV output, cumulus clouds can cause fluctuations in the PV power output when they pass overhead causing shadows in solar arrays. To smoothen such fluctuations, battery energy storage (BES) units may be required to be connected in parallel with PVs such that they can supply the sudden power shortfall.

When a fault occurs in some location in a transmission system, the voltage on the faulted phases will be zero. Due to the low impedance of transmission lines, a large voltage drop would be experienced across large areas of the transmission system until the fault is cleared by the opening of circuit breakers. Older types of wind turbines can trip even when voltages transiently drop to 70% from their nominal values. Wind turbines employing induction generators tend to increase their reactive power demand, thereby causing further voltage depression. This will slow down the voltage recovery process once the fault is cleared. This is why the fault ride-through regulations of wind turbines have been mandated by several authorities.

## 1.5 Blackouts

The primary causes of blackouts include the following:

- *Equipment Failure*: Aging or malfunctioning equipment can lead to failures and cascading outages.

- *Human Error*: Mistakes in grid management, maintenance, or operations can trigger blackouts.
- *Natural Disasters*: Severe weather events such as storms, hurricanes, earthquakes, and floods can damage infrastructure and cause widespread outages.
- *Cyber Attacks*: Increasing reliance on digital communication and control systems makes grids vulnerable to malicious attacks.
- *Demand Overload*: Excessive demand, especially during peak times, can overwhelm the grid if not properly managed.
- *Inadequate Infrastructure*: Poorly maintained or outdated infrastructure increases the risk of failures.

There have been several blackout events affecting several millions of people that have occurred in this century. Some of these are described below:

- *Northeast Blackout of August 2003*: Occurred in northeastern United States and Canada lasting up to two days and affecting 50 million people. The cause of the blackout was a software bug in the alarm system at an Ohio control room, which led to a cascade of failures after power lines brushed against trees.
- *Italy Blackout of September 2003*: A tree falling on a power line in Switzerland triggered a cascading failure across the interconnected European grid. Entire Italy was blacked out affecting 56 million people for 12 hours.
- *Java-Bali Blackout of August 2005*: A transmission line failure that led to a cascading failure in the grid, impacting 100 million people.
- *European Blackout of November 2006*: A routine disconnection of a high-voltage line over the Ems River in Germany triggered a cascading failure affecting 10 million people in Western Europe.
- *Brazil and Paraguay Blackout of November 2009*: This was caused by a failure at the Itaipu Dam impacting 87 million people.
- *Indian Blackout of July 2012*: Overdraw by states from the grid, combined with maintenance issues resulted in affecting 620 million people in northern, eastern, and northeastern India. This is the largest blackout in history so far.
- *South Australia Blackout of September 2016*: A severe storm with high winds and lightning caused multiple transmission lines to trip and a cascading failure. The entire state of South Australia lost power, affecting about 1.7 million people due to lack of fault ride-through capability of wind turbines.

### 1.5.1 Power System Oscillations

Most power system calculations are performed using phasor analysis, which assumes that the power system is in a sinusoidal steady state. However, in practice, oscillations resulting from small perturbations (such as load changes) are always present due to different mechanical components in the grid. Fortunately, these oscillations are well-damped and do not cause many problems to the systems operation and stability. The most concerning are the oscillations that result in high energy exchange that can result in system instability.

Power system oscillations are of two types: natural and forced. These are defined in the NERC report as follows [5]:

- *Natural*: These are low-frequency oscillations that can be of different types, such as
  - *Local*: Occurs when a plant or a generating unit oscillates with the rest of the system.
  - *Intraplant*: Occurs when two or more units of a plant oscillate against each other.
  - *Inter-area*: Occurs when several coherent units oscillate against other coherent group(s).
  - *Torsional*: Occurs when a series compensated system oscillates with the turbine shaft modes. This is usually called subsynchronous oscillations.
- *Forced*: These can result in sustained oscillations at any frequency resulting from events such as equipment failures and control interactions.

Oscillation analyses for different parts of the North American system are analyzed in [6].

The detection and countermeasures to mitigate forced oscillations are recommended in [5]. There are five steps involved in the detection process. The first step is to detect the presence of oscillations. It has been suggested that supervisory control and data acquisition (SCADA) or phasor measurement unit (PMU) data can be used for the detection of oscillations. The second step is to determine or estimate the magnitude and frequency of the oscillations. This might require advanced tools for accurate detection. The third step is to detect the extent of the oscillations, that is, are they localized or are they spread over a large area? The last two steps involve the determination of the general proximity of oscillations and the determination of the specific component that is causing the oscillations. The most predominant source of forced oscillations is the generating resources. Other components of power systems, such as renewable energy sources due to their converter control actions, FACTS devices, and HVDC lines, can also force oscillations in a power system. Mitigation of these oscillations is not an easy process. Obviously, control systems play a crucial role in damping oscillations. Therefore, careful tuning actions must be performed on various control elements such as generator excitation systems, FACTS and HVDC controllers, and converter control actions of renewable energy resources.

## 1.6 Smart Grid

The population of the world has doubled in the last 50 years. At the same time frame, the per capita income has risen by two and a half times worldwide. With the increasing prosperity, we now have bigger houses, more appliances and heating/cooling apparatus, and electric vehicles, which are increasing the demand for electricity. At the same time, the electricity infrastructure in many places is aging. The high volume of electricity trading is resulting in power flow and uncertainties in the systems, which were not designed to handle these. Moreover, due to the concerns of climate change, more and more renewable energy resources are getting connected to the power grids resulting in voltage rise, reverse power flow, and steep ramp rate in generation, causing further stress in the power infrastructure.

Against the backdrop of a deteriorating energy delivery system, it was decided that the power grid needs unprecedented innovations to improve the efficiency, reliability, and sustainability of electricity production and distribution. Smart grid was mandated under the Energy Independence and Security Act of 2007, which was approved by the US Congress and signed as law by the American President in the same year. The American and European definitions of smart grid are somewhat overlapping. However, the common theme among them is that the smart grid is the advancement of the power grid by integration of information and communication technology (ICT) with the power systems operation and infrastructure to create a dynamic and responsive system.

Some of the key components that a smart grid must include are as follows:

- *Data Communication*: Secure and fast communication networks that connect various components of the grid, including smart meters, sensors, and control centers.
- *Advanced Metering*: Two-way digital communication between the utility and customers for electricity usage and consumer participation.
- *Demand Response*: The consumers adjust the demand for electricity in response to supply conditions and real-time pricing signals.
- *Renewable Energy Integration*: Integration of solar, wind, and other renewable energy sources, along with battery storage systems to maximize greenhouse gas emission reductions.
- *Grid Automation and Control*: To operate a safe grid that can self-heal through the use of sensors, PMUs, FACTS devices, and HVDC systems.
- *Cybersecurity*: Protection against cyberattacks against grid operation and data confidentiality breaches.

Some of the benefits of the smart grid are as follows:

- *Reliability*: Enhancing the system reliability through early detection of potential hazards that can lead to outages and automatically reroute power and restore service after disruptions through self-healing processes.
- *Efficiency*: Improving system efficiency by reducing transmission losses through better infrastructure and better management of energy usage.
- *Greenhouse Gas Emission Reduction*: Through better utilization and integration of renewable energy sources in both power transmission and distribution systems.
- *Customer Awareness*: By providing customers with detailed information about their energy usage, real-time pricing, and reducing peak demand through demand response programs.

Overall, smart grid will play a crucial role in the power delivery systems in the 21st century and beyond. A truly smart grid will incorporate generators of all sizes and technologies. It will mitigate environmental impacts by facilitating the integration of renewable energy sources. It will improve the system reliability and improve the quality of service and will enable customer participation in energy usage and conservation. The comparison between smart grid and traditional grid is shown in Figure 1.5.

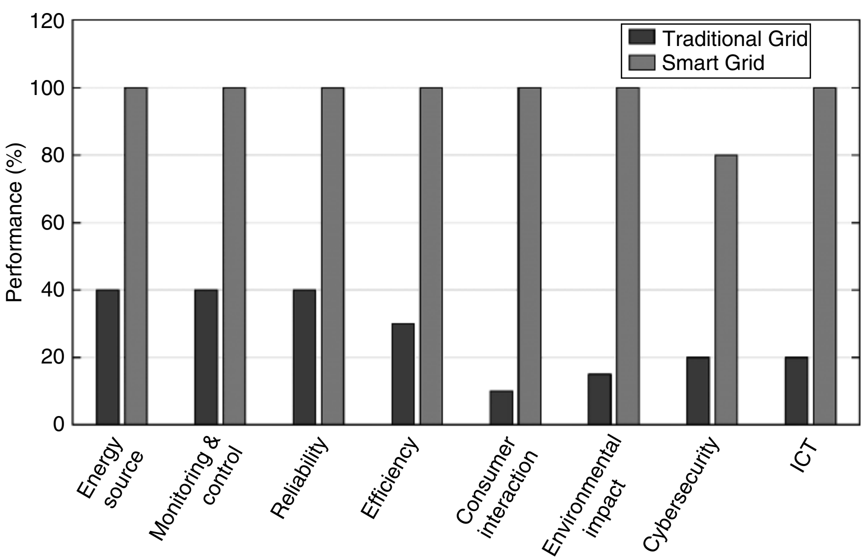


**Figure 1.5** Performance comparison between smart and traditional grids.

## 1.7 Phasor Analysis

Consider an AC voltage source, given by

$$v(t) = V_m \sin(\omega t + \phi) \tag{1.1}$$

where $\omega$ is the angular frequency in rad/s and $t$ is the time in seconds. Now assume that this voltage source is supplying a load containing a series combination of a resistor $R$, an inductor $L$, and a capacitor $C$. Let the current flowing through this load be denoted by $i$. Then, the loop equation is given by

$$v(t) = Ri(t) + L\frac{di(t)}{dt} + \frac{1}{C}\int i(t)dt \tag{1.2}$$

Combining (1.1) and (1.2), the following second-order differential equation is obtained.

$$\omega V_m \cos(\omega t + \phi) = \frac{1}{C}i(t) + R\frac{di(t)}{dt} + L\frac{d^2i(t)}{dt^2} \tag{1.3}$$

Even though it is possible to solve this second-order equation, a power system will involve multiple such equations. Solving several differential equations simultaneously will become a very complicated problem.

This problem was solved by another genius called Charles Steinmetz. He introduced the use of complex vectors for having both amplitudes and phases to represent voltages and currents in *sinusoidal steady state*. In this state, all voltages and currents oscillate at the same frequency with a stable amplitude and constant phase relative to each other. Note that the integration of the voltage given in (1.1) over a cycle will be zero. Therefore, to represent the voltage in the sinusoidal steady state, root mean square (rms) quantities were introduced. In this, the voltage in (1.1) squared over the cycle to obtain

$$v^2(t) = V_m^2 \int_0^{2\pi/\omega} \sin^2(\omega t + \phi)dt = \frac{V_m^2}{2} \tag{1.4}$$

The root mean square voltage is defined as

$$V_{RMS} = \sqrt{\int_0^{2\pi/\omega} v^2(t)dt} = \frac{V_m}{\sqrt{2}} \tag{1.5}$$

The phasor for the voltage in (1.1) is given by

$$V = \frac{V_m}{\sqrt{2}}\angle\phi \tag{1.6}$$

Note that the instantaneous quantities are denoted by lowercase letters, whereas the phasor quantities are denoted by uppercase letters.

In this book, complex power will be used extensively. For example, consider the following voltage and current:

$$V = |V|\angle 0^{\circ} \text{ and } I = |I|\angle -\theta$$

We know that real and reactive power are given respectively by

$$P = |V||I|\cos\theta \text{ and } Q = |V||I|\sin\theta$$

Now note that

$$VI^* = |V||I|\angle\theta = |V||I|(\cos\theta + j\sin\theta) = P + jQ \tag{1.7}$$

$$V^*I = |V||I|\angle -\theta = |V||I|(\cos\theta - j\sin\theta) = P - jQ \tag{1.8}$$

## 1.8 Concluding Remarks

Modern power systems are changing rapidly with the traditional way of power delivery system getting replaced by new technologies and power equipment. However, the power system analysis concepts and techniques still remain the same. They, however, are continuously getting upgraded as and when new technologies are incorporated into the systems. This book seeks to blend traditional power system analysis methods with emerging technologies.

## References

1 H. Ritchie and P. Rosado, "*Energy Mix: Explore Data on Where Our Electricity Comes from, and this is Changing*." Available. https://ourworldindata.org/electricity-mix

2 APS News, "This month in physics history," Vol. 19, No. 11, December 2010. Available. https://www.aps.org/publications/apsnews/201012/physicshistory.cfm#:~:text=British%20chemist%20Humphrey%20Davy%20is,component%20of%20his%20public%20lectures

3 S. Wagner and L. Dittmar, "The unexpected benefits of Sarbanes-Oxley," *Harvard Business Review*, Available. https://hbr.org/2006/04/the-unexpected-benefits-of-sarbanes-oxley

**4** F. Barbieri, S. Rajakaruna and A. Ghosh, "Very short-term photovoltaic power forecasting with cloud modeling: a review," *Renewable and Sustainable Energy Reviews*, Vol. 75, pp. 242–263, 2017.

**5** NERC (2017). *Reliability Guidelines: Forced Oscillations Monitoring and Mitigation*. Atlanta.

**6** NERC (2019). *Interconnection Oscillation Analysis: Reliability Assessment*. Atlanta.