SECTION 10

Electricity

The ability to utilize electrical energy is one of the major achievements of history. In terms of altering the way humans live, electricity's impact is surpassed only by the development of energy sources other than human and animal power in the Industrial Revolution.

Progress toward the full-scale use of electricity has had three basic phases, representing distinct challenges at different points in history. The first was to understand the phenomenon of electricity itself. The second was to take the necessary practical steps to make use of it. The third, which continues today, was and is to obtain the necessary energy resources to provide electrical power on a large-scale basis.

The existence of static electricity was known to the ancients, though its nature was not well understood at the time. The Greek philosopher Thales of Miletus made the first known observation of static electricity in about 600 BC. Other notable observations of this were later carried out by Cardano, Browne, and von Guericke in the 1500s and 1600s.

The 1700s saw significant advances in the understanding of electricity, such as Stephen Gray's discovery (1729) that it can flow and that some materials conduct it more readily than others. This was followed by a statement of the existence of positive and negative charges by du Fay (1733), which was also noted by Benjamin Franklin. Franklin then went on to describe the basis for the lightning rod (1747) and to conduct his famous "kite in a storm" experiment with lightning (1752). Aepinus (1759) rejected the idea that electricity is a mechanical force and supported the one-fluid theory of electricity espoused by Franklin.

Further advances of the 18th century included de Saussure's invention of a device to measure electric potential (1766), Galvani's discovery of the phenomenon that would come to bear his name, galvanism (about 1780), and de Coulomb's measurement of the forces between electric charges (1785). At the very end of the century Volta made the first major step toward the industrial utilization of electricity with his invention of Volta's pile, the first electric battery.

The quest for practical applications of electricity moved rapidly in the 19th century. Milestones in this effort included Davy's creation of the first arc light (1809), Faraday's conception of the basis for the electric motor (1821), and Pixii's design of the first practical mechanical generator (1832), based on concepts established by Faraday. Also in this decade of the 1830s came the first successful electric streetcar, the first reliable source of current, the induction coil, and the earliest prototype for an electric car. Most notably, in 1839 William Grove developed the Grove cell, the first primary electric cell and the forerunner to both the modern battery and the fuel cell.

Within a short period, from 1878 to 1882, the essential steps were taken for the use of electricity for public lighting, highlighted by the efforts of innovators such as Thomas Edison and Charles Brush. In 1878 Edison founded his Edison Electric Light Company, in 1879 he demonstrated his first incandescent bulb, in 1881 he established the first central power station for home lighting in New York City, and the following year the station began providing electricity for lighting. Brush developed a successful arc light in 1878, the same year he founded his own commercial electric company which would eventually merge with that of Edison. In 1880 Brush arc lamps began lighting public sites in Michigan and Indiana, and he also established a rival system to Edison in New York, using arc lighting to illuminate the city's famous Broadway thoroughfare.

Another major application for electricity that also developed in the late 19th century was transportation. Electric buses and streetcars came into widespread use at this time, and by the end of the century electric-powered cars were outselling gasoline ones in the U.S. This persisted until the 1920s, when electric cars virtually disappeared until their revival in recent times as an alternative (hybrid and fully electric) to gasoline cars. The use of electric vehicles for urban mass transit also was eventually supplanted by gas-powered vehicles, though in this case there has been no revival as with electric cars. The first electrified railroad, the New York, New Haven, and Hartford, began operation in 1907.

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The original energy sources for large-scale electricity generation were the same as those originally used to power machinery; i.e., steam and hydropower. Steam power was first utilized through the reciprocating steam engine which provided energy conversion by means of a piston. This method was replaced in the early 20th century by the more powerful and more efficient steam turbine, though the reciprocating engine is still employed in smaller-scale operations.

The first systematic use of hydropower to generate electricity was in 1869, at a wood pulp factory in the French Alps. This was followed by the first commercial hydroelectric plant, in Wisconsin in 1882. The huge Niagara Falls hydroelectric facility began operation in 1895, following the establishment of a smaller station there in 1881. A similar facility serving the Canadian side of the Falls began to distribute power to southern Ontario in 1910.

The era of large hydroelectric dams began in the U.S. in the late 1920s with the construction of Hoover (Boulder) Dam, followed shortly after by other such projects as the Bonneville, Shasta, Grand Coulee, and the various dams of the Tennessee Valley Authority (TVA). The building of large dams continues to the present day with projects such as the Itaipu in South America and Three Gorges in China.

Today electricity generation still features hydropower, but it has extended its reach to encompass virtually all other current energy sources. The traditional fossil fuels coal, oil, and gas are widely used, especially the first of these which is by far the largest current generating source (an issue of concern with respect to carbon emissions). Nuclear energy came into use in the early 1950s and is now a major source, though its use is now being discouraged or phased out in some countries.

Various alternative energy sources are also employed. Two of these are ancient sources with new applications for electricity; i.e., naturally occurring wind used to turn turbines, and the capture of solar energy, both through large-scale heat concentrators and small-scale photovoltaic panels. Along with these are newer sources such as biomass and waste fuel combustion, fuel cells, geothermal energy, ocean thermal energy conversion (OTEC), and wave/tide energy. The latter two of these are still essentially in the experimental phase.

At present these alternative methods represent only a small fraction of electricity energy sources. A recent survey of global net electricity generation indicated that about two-thirds of this is still attributed to conventional thermal power from fossil fuels. Another 30 percent comes from hydroelectric and nuclear power. This leaves only a little over 3 percent from the newer sources described above. However, many initiatives are now underway worldwide to address this imbalance for the long-term benefit of the planet.

CHRONOLOGY

ca. 585 BC *First known observation of static electricity*

The Greek philosopher Thales of Miletus notes that an amber rod attracts light materials such as straw to itself when it is rubbed. Though not well understood at the time, this is the first known observation of the phenomenon of static electricity.

1551 *Electricity and magnetism distinguished*

Jerome Cardan (Girolamo Cardano), an Italian mathematician, distinguishes electricity from magnetism by observing that while amber will attract various light objects, a lodestone (magnetic stone) will attract only metals.

1600 *Important early study of electricity and magnetism*

English scientist William Gilbert publishes a six-volume work titled De Magnete, which is regarded as an important founding work in the fields of electricity, magnetism, and electrochemistry.

1646 *Word "electricity" first used*

English physician Sir Thomas Browne publishes *Pseudodoxia Epidemica*, in which he discusses his experiments with static electricity and magnetism and introduces the words "electric" and "electricity" into the English language.

1663 *First electric generator*

Otto von Guericke develops the first electric generator, which consists of a revolving ball of sulfur inside a glass globe, mounted on a wooden frame. This produces a static electric spark when a pad is held against the ball as it rotates.

1672 *Electroluminescence identified*

Otto von Guericke recognizes that the static electricity produced by his sulfur ball device (see 1663) will cause the surface of the sulfur to glow, thus identifying the phenomenon of electroluminescence. Guericke also notes that like charges repel each other.

1705 *Neon light is developed*

The neon light is born when Francis Hauksbee of England creates electrical effects by putting mercury into a glass globe, pumping out the air, and then turning it with a crank. When he does this in the dark, and then rubs the globe with his bare hand, it glows brightly.

1709 *Newton's electric generator*

Sir Isaac Newton builds an electric generator consisting of a rotating glass sphere.

1729 *Discovery that electricity can flow*

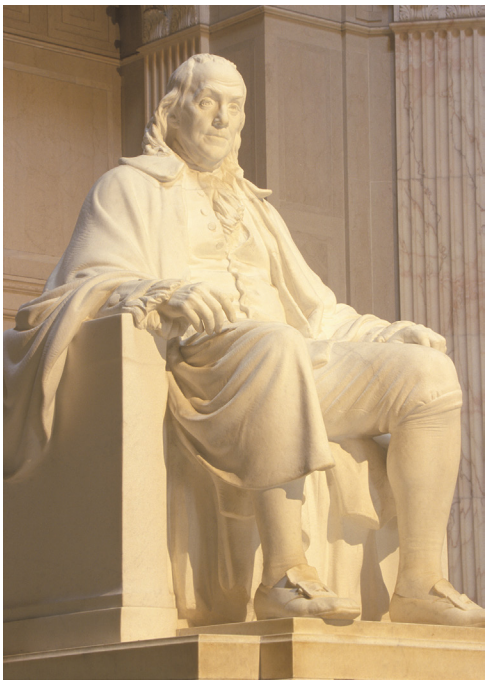
Through a series of experiments, Stephen Gray establishes that some materials conduct electricity better than others and that static electricity travels on the surface of objects rather than through the interior. This is considered to mark the discovery of the principle that electricity can flow.

1733 *Positive and negative charges observed*

French chemist Charles Francois de Cisternay du Fay states a "two-fluid" theory of electricity, dividing electrical charges into vitreous (positive) fluid and resinous (negative) fluid, and noting that like charges attract and differing charges repel. Benjamin Franklin also distinguishes between positive and negative charges, though he favors a one-fluid theory.

1746 *Capacitor invented*

Dutch scientist Pieter van Musschenbroek and German physicist Ewald Georg von Kleist independently invent the capacitor, an electricity-storage device that is the first practical way to store static electricity. It comes to be called the Leiden (Leyden) jar after Musschenbroek's employer, the University of Leiden.



Franklin The American patriot Benjamin Franklin is noted for his achievements in a multitude of fields, not the least of which is science. The best known of his scientific studies and discoveries is his identification of lightning as electricity through the famous experiment of flying a kite in a lightning storm. He also made other major contributions in electricity such as the identification of positive and negative charges and the proposal of the (now accepted) one-fluid theory as opposed to the then-prevailing two-fluid concept. (Joseph Sohm/American Spirit)

1747 *Franklin's basis for the lightning rod*

Benjamin Franklin describes his discovery that a pointed conductor can draw off an electrical charge from a charge body. This is the basis for his lightning rod, even before he proves the connection between electricity and lightning. In 1749 he installs a lightning rod on his home.

1752 *Franklin's kite in a lightning storm*

Benjamin Franklin conducts his famous experiment with a kite in a lightning storm, showing that lightning is a form of electricity.

1759 *Aepinus' conception of electricity*

Franz Aepinus rejects mechanical theories of electricity and suggests that ordinary matter repels itself in the absence of electricity, a theory of electrostatics similar to Newton's law of gravity and supporting Benjamin Franklin's one-fluid theory of electricity.

1766 *Electrometer invented*

Swiss physicist, geologist, and early Alpine explorer Horace-Bénédict de Saussure develops an electrometer, a device for measuring electric potential by means of the attraction or repulsion of charged bodies.

1767 *Priestley's rings explained*

English chemist Joseph Priestley offers an explanation for rings formed by an electrical charge on metal (now known as Priestley's rings) and proposes that electrical forces follow the same inverse square law that gravity does.

ca. 1780 *Galvanism first observed*

Luigi Galvani of Italy discovers that when he touches a dead frog's leg with a knife, it twitches violently. Alessandro Volta will later show this is because electricity is created when moisture (from the frog) comes between two different types of metal (the steel knife and a tin plate); this phenomenon will become known as galvanism.

1785 *Measurement of forces between electric charges*

French physicist Charles-Augustin de Coulomb is the first to measure accurately the forces exerted between electric charges.

1799 *First electric battery*

Alessandro Volta creates the first electric battery (known as Volta's pile). It consists of alternating zinc and silver disks separated by felt soaked in brine. It is the first source of a steady electric current. Volta announces this invention in 1800.

1806 *Description of electrochemical decomposition*
Sir Humphry Davy delivers a lecture titled "On Some Chemical Agencies of Electricity," in which he reasons that electrolysis, the interactions of electric currents with chemical compounds, offers the most likely means of decomposing all substances to their elements. This work leads directly to the isolation of sodium and potassium from their compounds (1807) and of the alkaline-earth metals from theirs (1808), and helps to establish the field of electrochemistry.

1809 *First arc light*
Sir Humphry Davy uses a high-powered battery to induce a bright light between two strips of charcoal 10 cm (4 in) apart, creating the first arc light. He does not use it for illumination, but over the coming decades many engineers use the arc to make practical electric lamps.

1820 *Magnetic effect of electric currents*
Danish physicist Hans Christian Ørsted is the first to note the magnetic effect of electric currents when, by accident, he observes that an electric current in a wire can deflect a nearby compass needle. Prior to this only one kind of magnetism was known, the one produced by iron magnets. The CGS unit of magnetic induction (oersted) is named in honor of him.

1820 *Invention of the galvanometer*
Johann Schweigger expands on Hans Christian Ørsted's experiments and invents the galvanometer to measure the strength of a current.

1820 *Repulsive/attractive properties of electricity*
Expanding on the work of Hans Christian Ørsted, Andre Marie Ampere finds that two wires carrying current in the same direction attract each other, while wires carrying current in opposite directions repel.

1821 *Basis for an electricity-powered motor*
Michael Faraday publishes the results of his research into electromagnetic rotation, providing the basis for his efforts to create an electricity-powered motor.

1821 *Discovery of thermoelectricity*
Thomas Johann Seebeck observes that if two dissimilar metals are joined with a heat difference between the juncture points, this will produce an electric current. This phenomenon is called thermoelectricity or the Seebeck effect; it will later be used in the development of the semiconductor.

1827 *Ohm's law formulated*
German physicist George Simon Ohm states that an electrical current is equal to the ratio of the voltage to the resistance (Ohm's law).

1832 *Practical mechanical generator of current*
Antoine-Hippolyte Pixii, a French instrument maker, builds the first practical mechanical generator of electrical current, using concepts demonstrated by Faraday. The machine contains a permanent magnet that is rotated by a hand crank. The spinning magnet is positioned so that its north and south poles pass by a piece of iron wrapped with wire.

1833 *First observation of semiconductor*
Michael Faraday makes the first documented observation of a material now known as a semiconductor. While investigating the effect of temperature on sulfurette of silver (silver sulfide), he finds that electrical conductivity increases with increasing temperature.

Faraday The English scientist Michael Faraday advanced the study of electricity in many ways, as by providing the basis for an electric motor, identifying a material as a semiconductor, and describing the concept of a generator. He also discovered electrolysis (independently of Joseph Henry) and electromagnetic induction. (From an 1846 engraving by John Cochran; photo by Georgios Kollidas)

1833 *Discovery of electrolysis*
Faraday derives the laws of electrical separation of compounds (electrolysis), and suggests that atoms contain electrical charges.

1833 *Discovery of electromagnetic induction*
Michael Faraday and Joseph Henry independently discover the principle of electromagnetic induction, which becomes the basis for the development of the electric generator and electric motor.

1834 *First electric streetcar*
Vermont blacksmith and inventor Thomas Davenport builds a small model streetcar, powered by an electric motor and moving on a circular track. This paves the way for the electric streetcar, which will become a major form of urban transportation.

1836 *First reliable source of electric current*
John Frederic Daniell invents the Daniell cell, the first reliable source of electric current; it represents a great improvement over the voltaic cell.

1836 *First induction coil*
The Irish priest and scientist Father Nicholas Joseph Callan contributes significantly to the understanding of electrical induction and the development of the induction coil. He does this through a series of experiments that make the inductive transient phenomena visibly clear.

1837 *Prototype for an electric car*
Scottish inventor Robert Davidson constructs a prototype for an electric car.

1839 *Early electric cell*
English scientist Sir William Robert Grove builds a device that will combine hydrogen and oxygen to produce electricity; this is the world's first primary electric cell, precursor to both the battery and the fuel cell. The Grove cell uses zinc and platinum electrodes exposed to two acids and separated by a porous ceramic pot. Michael Faraday invites Grove to present his discoveries at the prestigious Royal Institution. The precise mechanisms of Grove's cell are later explained by Friedrich Wilhelm Ostwald.

1844 *Place de la Concorde lit by electric light*
Jean Foucault brings electric light to Paris, the City of Light, when he illuminates the Place de la Concorde, the largest public square in the city.

1846 *Weber's force law*
Wilhelm Eduard Weber develops a force law that is dependent on velocity and acceleration, which will be crucial to James Clerk Maxwell in his electromagnetic theory of light. He also invents the electrodynamometer, an instrument for measuring small currents.

1845 *Kirchhoff's laws of electrical networks*

German physicist Gustav Kirchhoff publishes two sets of independent concepts in circuit theory and thermal emission that will become known as Kirchhoff's laws of electrical networks.

1853 *Improved arc lighting*

British engineer Frederick Hale Holmes demonstrates that magneto-electric generators can provide a continuous current that will produce a brilliant electric arc for lighting. In 1856, he patents a system to use the magneto to light a lighthouse, which is demonstrated to Michael Faraday in 1857 at Blackwall.

1857 *Geissler tube*

Heinrich Geissler invents a glass tube that demonstrates the principles of electrical glow discharge. A Geissler tube contains a rarefied gas such as neon or argon. When a high voltage is applied to the terminals, an electrical current flows through the tube. The current will disassociate electrons from the gas molecules, creating ions, and when electrons recombine with the ions, different lighting effects are created. The Geissler tube is an important precursor to the fluorescent lamp and neon signs.

1861 *Maxwell's landmark paper*

Scottish physicist James Clerk Maxwell publishes "On Physical Lines of Force," a landmark four-part paper that forms the basis for classical electromagnetic theory. His work unites all previously unrelated observations, experiments, and equations of electricity, magnetism, and optics into a consistent theory. Maxwell's equations demonstrate that electricity, magnetism, and light are all manifestations of the same phenomenon, namely the electromagnetic field.

ca. 1862 *Measurement of conductance proposed*

Werner von Siemens proposes the measurement of electrical conductance; later the name *siemens* will be used for a basic unit of conductance.

1866 *Dynamo-electric principle discovered*

Werner von Siemens discovers the dynamo-electric principle. This means it is no longer necessary to use direct current batteries to generate continuous current and high voltage, and provides the crucial advance needed to supply electric power at commercially reasonable prices.

1869 *First efficient direct-current dynamo*

Belgian engineer Zénobe-Théophile Gramme builds the Gramme machine, the first efficient direct-current dynamo, two years after building an efficient alternating-current dynamo. In 1873 it is demonstrated that the Gramme type dynamo can function as an electric motor, a major step in the development of electric power.

1869 *First systematic use of hydroelectric power*

In the French Alps, Aristide Berges sets up a pipeline to transport a pressurized stream of water to his wood pulp factory. He then uses a dynamo to transform the water power into electricity. This is regarded as the first systematic use of hydroelectric power.

1870 *Jules Verne describes ocean thermal energy*

The pioneering French science fiction author Jules Verne introduces the concept of ocean thermal energy conversion (OTEC) in his famous novel *Twenty Thousand Leagues Under the Sea.* The main character Captain Nemo tells a visitor to his fantastic undersea vessel *Nautilus:* "I owe it all to the ocean; it produces electricity, and electricity gives heat, light, motion, and, in a word, life to the *Nautilus.*"

1873 *Key selenium discovery*

Willoughby Smith of England and his assistant Joseph May note that when selenium is exposed to light, its electrical resistance decreases. This discovery provides the means to transform images into

electric signals, and leads to the manufacture of photoelectric cells and other light sensors. It also lays the foundation for the development of television.

1874 *Systematic incineration of waste to produce electricity*
The "Destructor" goes into operation in Nottingham, England. This is the first known example of a systematic incineration of urban solid wastes. The Destructor burns mixed waste and produces steam to generate electricity. Several hundred similar facilities are built in the coming decades.

1874 *Rectifying effect of semiconductor*
German physicist Ferdinand Braun is the first to demonstrate the rectifying effect of semiconductors when he probes a galena crystal (lead sulfide) with the point of a thin metal wire and observes that current flowed freely in one direction only.

1877 *Yablochkov Candle*
Russian telegraph engineer Pavel Yablochkov (Jablochkoff) develops one of the first arc lamps to be used in large quantities. The Yablochkov Candle is cheap and simple compared to previous arc lamp designs, it burns far brighter than gas lamps, and it helps bring the electric light to public attention. By 1880, the system had grown in size to 120 lamps. The first electric street lighting in England operates on the Thames Embankment, London in 1878 using Yablochkov Candles.

1878 *Edison Electric Light Company founded*
Thomas Edison founds the Edison Electric Light Company to finance his efforts to invent a practical incandescent electric lamp. This and various other electric companies established by Edison will later be combined in what becomes the General Electric Company.

1878 *Innovations by Charles Brush*
U.S. inventor Charles F. Brush develops an efficient dynamo and goes on to produce a commercially viable arc light, which is used to illuminate a private home in Cincinnati and a public square in Cleveland. The arc light precedes Thomas Edison's incandescent light bulb in commercial use. He then founds Brush Electric Company, which will eventually join Edison's General Electric Company.

1879 *Incandescent lamp demonstrated*
The inventor Thomas Edison makes the first public demonstration of incandescent lighting in Menlo Park, New Jersey. Independently Joseph Swan in England produces a similar lamp (see Lighting, 1878). Edison's first bulb burns for 40 continuous hours, and only a year later he opens the first electric generation station used primarily for lighting.

1879 *Hall effect discovered*
U.S. physicist Edwin Herbert Hall finds that when a metal strip carrying a current is placed in a magnetic field, a voltage difference is produced across the strip. The Hall effect is important in the development of semiconductors and materials for solar cells.

1879 *Innovative electric train*
The Siemens Company builds the world's first electric train in which power for the train is supplied through the tracks rather than from overhead wires.

1880 *Brush lamps provide illumination*
Michigan's Grand Rapids Electric Light and Power Company is created. It begins generating electricity by means of a Brush dynamo belted to a water turbine, and it lights up a set of Brush arc lamps to provide theater and storefront illumination.

1880 *Thomson-Houston Electric Co.*
U.S. engineers and inventors Elihu Thomson and Edwin J. Houston form the American Electric Company. In 1883 the company is bought by Charles A. Coffin and becomes the Thomson-Houston Electric Company based in Lynn, Massachusetts.

1880 *First city lit entirely by electric light*
Wabash, Indiana becomes the first city to be lit entirely by electric light, using the Brush dynamo and arc light system.

1880 *New York illuminated by arc lighting system*
Charles Brush's Electric Light and Power Company successfully demonstrates an arc lighting system by lighting up New York City's famous avenue Broadway for the first time, and soon thereafter builds New York's first central power station. Broadway will later become known as the "Great White Way" because of its dazzling array of electric lights.

1880 *Pressure electricity discovered*
Pierre and Jacques Curie discover that some crystalline materials, when compressed, produce a voltage proportional to the applied pressure, and that when an electric field is applied across the material, there is a corresponding change of shape. This is called piezoelectricity or pressure electricity.

1880s *Electric arc lamps compete with gas lamps*
Electric arc lamps begin competing with manufactured gas for the lead in the street lighting market in the United States.

early 1880s *Debate between AC and DC current*
A "current war" is underway over the choice between DC current, promoted by Thomas Edison, and AC current, promoted by George Westinghouse. An intense battle for public opinion and political support ensues.

1881 *First central power station in New York City*
Thomas Edison develops the first central power station in New York City that supplies power for home lighting and directly competes with interior gas light. Edison had wisely based his distribution system on that of the gas industry, constructing an electrical analog to the gas system.

1881 *Hydroelectricity at Niagara River*
The first hydroelectric generating station operated on the Niagara River begins power generation. An 85-foot cascade of water generates electricity to run the machinery of local mills and to light some of the village streets.

Edison Thomas Alva Edison in his laboratory. Edison, the principal developer of electric lighting as a commercial enterprise, became so well known as an inventor and industrialist that his name became an honorific for others, such as the Danish Edison (Poul la Cour), the Black Edison (Granville T. Woods), and the Edison of His Time (Steve Jobs). (National Portrait Gallery/Photo by Richie Lomba)

1882 *Edison supplies electricity for lighting*
Thomas Edison's power generating company in New York City begins providing electricity for lighting. Three 125-horsepower "Jumbo"

generators at the Pearl Street station provide power to 5,000 lamps in 225 homes, for about 24 cents per kilowatt-hour.

1882 *Early electric power station*
The United States Electric Illuminating Company establishes an electric power station in Charleston, South Carolina.

1882 *First commercial hydroelectric plant*
The first commercial hydroelectric power plant goes into operation on the Fox River in Appleton, Wisconsin. It is used to power one residence and two paper mills, and eventually the town's streetcar system as well.

1884 *Compound steam turbine invented*
English engineer Charles Parsons invents the compound steam turbine, which converts the power of steam directly into electricity; it ultimately becomes the preferred power plant of electric power stations and ships, and it is considered among the most important inventions of the nineteenth century.

1884 *Tesla's methods to generate current*
The Serbian-American electrical engineer Nikola Tesla designs practical methods for generating alternating current, a prerequisite for long-distance transmission of electricity. Called the "Master of Lighting," Tesla will receive more than 100 patents relating to electric power generation and transmission and radio communications. His work stands among the most influential in the history of electricity.

1886 *Westinghouse Electric Co. founded*
George Westinghouse forms the Westinghouse Electric Company, the predecessor of the corporation that still operates today as a huge consumer electronics company.

1886 *AC transformer invented*
William Stanley, Jr., an American inventor, receives a patent for an induction coil, a transformer that creates alternating current (AC) electricity. AC current will prove to be much safer and easier to transmit over long distances than direct current.

1886 *Electric light socket with a pull chain*
Harvey Hubbell of Bridgeport, Connecticut, receives a patent for an electric light socket with a pull chain.

1886 *First AC power plant in United States*
The first alternating current power plant in the United States goes into operation in Great Barrington, Massachusetts. The plant is opened by William Stanley, Jr., the inventor of the transformer that creates alternating current (AC) electricity.

1887 *Edison demonstrates dangers of AC power*
In an attempt to demonstrate the dangers of AC power, Thomas Edison conducts a demonstration in West Orange, New Jersey, in which he kills large numbers of cats and dogs by luring the animals onto a metal plate wired to a 1,000 volt AC generator. Newspapers describe these proceedings in detail.

1887 *Hydroelectric plant in western United States*
High Grove Station in San Bernardino, California becomes the first hydroelectric plant in the western United States.

late 1880s *Electric street vehicles in use*

Electric vehicles begin to appear on the streets of the United States and Britain, including an electric bus company making regular trips in London.

1888 *Tesla advocates use of AC current*

Serbian-American inventor Nikola Tesla delivers a lecture entitled "A New System of Alternating Current Motors and Transformers," describing the equipment that allows efficient generation and use of alternating currents. Tesla's work stands among the most influential in the history of electric power generation and transmission.

1888 *Debate over use of electric chair*

The New York Legislature passes a law establishing electrocution as the state's new official method of execution. However, since two potential designs (AC and DC) of the electric chair exist, it is left to a committee to decide which form to choose. Thomas Edison, a proponent of DC current technology, actively campaigns for the selection of a chair powered by AC current, reasoning that consumers will not want the same type of electrical service in their homes that is used for execution.

1888 *Ampere-hour meter patented*

Oliver B. Shallenberger, an electrician at the Westinghouse Electric Manufacturing Company, receives a U.S. patent for an ampere-hour meter, which accurately measures the amount of electricity used.

1888 *First AC hydropower*

The streets of Oregon City, Oregon are illuminated by power from Willamette Falls, the first alternating current (AC) hydroelectric plant. The power plant is a 200-horse, 450 light Edison dynamo in the Excelsior and Shoddy Mill on the west bank of the river.

1888 *First large-scale electric streetcar system*

In Richmond, Virginia, Frank Julian Sprague establishes what is regarded as the first large-scale, successful streetcar system powered by electricity. Similar systems are soon established in many other American cities and the streetcar becomes the preferred mode of urban mass transit.

1888 *Overhead conducting line system for railroads*

Granville T. Woods develops and patents a system for overhead electrical conducting lines for railroads, which is adopted for the railway system of various large cities. Through this and other innovations in electricity and telegraphy, the African-American inventor Woods becomes known as "the Black Thomas Edison."

1888 *Riker Electric Vehicle Company founded*

Andrew Lawrence Riker founds the Riker Electric Vehicle Company in Elizabethport, New Jersey, which becomes one of the country's largest manufacturers of electric cars and trucks. Riker produces his first electric car in 1894, using a pair of bicycles as a base.

1889 *First long-distance electricity transmission*

The first long-distance transmission of electrical energy for commercial purposes in the United States occurs when the hydropower facility at Willamette Falls, Oregon City, Oregon generates electricity that is sent over 14 miles of wire and lights 55 carbon arc street lamps in downtown Portland.

1889 *Paris is known as "The City of Light"*

Paris becomes known as "The City of Light" during the 1889 World's Fair, since it is the first large city to switch to all electric lighting.

1889 *Thomson-Houston acquires Brush*

Thomson-Houston Electric Company of Lynn, Massachusetts buys out the Brush Company (founded by Charles F. Brush) resolving the arc lamp and dynamo patent disputes between them. Thomson-Houston then merges with the Edison General Electric Company to form the General Electric Company. Charles Coffin, owner of Thomson-Houston, becomes the first president of General Electric corporation.

1890 *Radioconduction discovered*

French physicist and inventor Edouard Branly discovers radioconduction, now called the Branly Effect. He observed that an electromagnetic wave changes the ability of metal filings to conduct electricity. Branly uses his discovery to make a very sensitive detector called a coherer, improved versions of which became the first practical wireless signal receivers.

1890s *Electric group drive*

Electric group drive begins to replace line shaft drive in U.S. manufacturing. Electric group drive is much more efficient than the prevailing line shaft drive system that relied on waterwheels or steam turbines to drive rotating shaft for power transmission in factories.

1891 *Transmission of three-phase alternating current*

The first transmission of three-phase alternating current using high voltage takes place during an international electricity exhibition in Frankfurt, Germany.

1891 *Early practical demonstration of AC power*

The Ames Hydroelectric Generating Plant, near Telluride, Colorado, produces electricity that is transmitted 2.6 miles over rugged terrain to provide power for a mill at the Gold King Mine. This pioneering demonstration of the practical value of transmitting AC power is a significant precedent in the United States for much larger plants at Niagara Falls and elsewhere. Electricity at Ames is generated at 3,000 volts, 133 Hertz, single-phase AC, by a 100-hp Westinghouse alternator.

1891 *High-voltage electricity line in Germany*

The first long-distance high-voltage electricity line is established between Lauffen and Frankfurt am Main, Germany, a distance of over 100 miles.

1891 *Poul la Cour's work with wind turbines*

Inventor Poul la Cour, the "Danish Edison," begins a series of experiments with wind turbines. His work will establish a foundation for modern use of wind energy. He develops the first electrical output wind machine to incorporate the aerodynamic design principles (low-solidity, four-bladed rotors incorporating primitive airfoil shapes) used in the best European tower mills. By 1920, the use of 25 kilowatt electrical output machines had spread throughout Denmark.

1891 *Tesla coil invented*

Nikola Tesla invents the Tesla coil, an air-core resonant transformer that can generate extremely high voltages at high frequency. Tesla coils can produce spectacular lightning-like discharges and have often been used in the film industry for special effects.

1893 *Commercial three-phase AC generator*

The Mill Creek No. 1 project begins generating electricity, the first commercial use of three-phase alternating current generators in the United States. Power from the 250 kW generator is transmitted 7.5 miles to the city of Redlands at 2,400 volts.

1895 *First U.S. electric elevated rail line*

The Metropolitan West Side Elevated Railway begins service in Chicago; it is described as the nation's first electric elevated rail line.

1895 *Niagara Falls hydroelectric plant in operation*

The Adams No. 1 generating station of the Niagara Falls Power Company first supplies electric power to local industries in Niagara Falls, New York. This station is the first large-scale multiphase power station with commercial operations at Niagara Falls, and it represents a key victory for alternating-current systems over direct-current.

1896 *Electric stove patented*

William Hadaway of the United States receives a patent for an electric stove.

1896 *Electricity directly from coal*

Boston entrepreneur William W. Jacques attempts to build an electrochemical generator that converts coal directly into electricity. The apparatus consists of 100 cells arranged in series and placed on top of a furnace that keeps the electrolyte temperature between 400 and 500°C. The output is measured as 16 amps at 90 volts. Further research demonstrates that the current generated by this apparatus is not obtained through electrochemical action, but rather through thermoelectric action.

1897 *First hydroelectric plant in Chile*

The 1,430 kW Chivilingo Plant is the first hydroelectric plant in Chile and the second in South America. A 10 km line feeds the Lota coal mines and the railway extracting minerals from under the sea 12 km from shore. It represents a key new technology and a new source of electrical energy in the region as a tool for economic development.

1897 *First motor vehicle service in United States*

Henry Morris and Pedro Salom form the Electric Carriage and Wagon Company to operate electric cabs on the streets of New York City. This is described as the first motor vehicle transportation service in the United States. Prior to this Morris and Salom had developed an electric car known as the Electrobat.

1897 *Nernst lamp*

Walther Nernst patents an early form of the electrically powered incandescent lamp, with a filament consisting of oxides of rare earths. He uses zirconium dioxide doped with about 10% of yttrium oxide (yttria-stabilized zirconia, YSZ), a material now known as a Nernst mass. The Nernst lamp, or Nernst glower, is eventually replaced by the more efficient tungsten filament incandescent light bulb. Nernst's experiments with solid electrolytes will later be used by Baur and Pries (1937) in their development of solid oxide fuel cells.

1898 *Early power transmission in Canada*

The Decew Falls Hydro-Electric project, St. Catharines, Ontario, Canada transmits power at 22,500 volts, 66 2/3 Hz, two-phase, a distance of 56 km to Hamilton. This is a pioneering project in the generation and transmission of electrical energy at higher voltages and at greater distances in Canada.

1898 *First underground powerhouse*

The world's first subterranean powerhouse in a hydroelectric facility is built at Snoqualmie Falls on the Snoqualmie River between Snoqualmie and Fall City, Washington. The underground cavity, which initially holds four horizontal impulse type waterwheel turbines and four stationary field 3-phase Westinghouse generators, is carved out of solid bedrock 270 feet below the surface.

1900 *Electric cars outsell gasoline cars*

Electric cars outsell gasoline and steam-powered cars in the United States. Electric vehicles do not require a hand starter or gearshift, and they are quieter and operate with less vibration. Gas-powered cars take over in the 1920s due to cheap gasoline, the elimination of the hand crank, mass production, and the relatively limited range and speed of electric vehicles.

1900 *AC hydroelectricity for mining*
The Georgetown, Colorado Steam-Hydro Generating Plant is completed; it is unusual for the time in employing both steam and water power. The ability to provide inexpensive electricity with alternating current over long distances will revolutionize the mining industry in this region, providing critical power to the isolated mines.

early 1900s *Electric unit drive*
Electric unit drive begins to replace electric group drive in U.S. manufacturing. Electric unit drive more than doubles the full-load efficiency of power production, transmission, and distribution in manufacturing compared to electric group drive and its predecessor line shaft drive.

1901 *Point-contact semiconductor rectifier*
Indian physicist Jagadish Chandra Bose files a U.S. patent for a point-contact semiconductor rectifier for detecting radio signals.

1901 *Thermionic emission*
English physicist Owen Willans Richardson begins researching the emission of electricity from hot bodies; he demonstrates that the current from a heated wire seems to depend exponentially on the temperature of the wire with a mathematical form similar to the Arrhenius equation. This becomes known as Richardson's law, and the phenomenon is called thermionic emission. He is awarded the Nobel Prize in Physics in 1928.

1902 *Poulsen-arc transmitters*
The Danish engineer Valdemar Poulsen invents an arc converter as a generator of continuous-wave radio signals. Poulsen-arc transmitters are used internationally until they are superseded by vacuum-tube transmitters.

1903 *GE starts gas turbine division*
The General Electric (GE) company starts its gas turbine division. GE will grow to be one of the dominant producers of turbines for electric power generation.

1904 *Thermionic valve patented*
English electrical engineer John Ambrose Fleming patents the thermionic valve, which is the first electronic rectifier of radio waves. Along with the amplifier grid of Lee de Forest (see Communication, 1906), Fleming's invention is the forerunner of the triode and other vacuum tubes and thus a foundation of the modern electronics industry.

1904 *Electricity produced from geothermal energy*
Prince Piero Ginori Conti of Italy successfully produces electricity from geothermal energy in an experimental "indirect cycle," using pure steam produced from a heat exchanger.

1904 *High-frequency alternator developed*
Swedish-American electrical engineer Ernst Alexanderson develops a high-frequency alternator that provides the means for effective long-distance radio communication.

1905 *First rail carrier with main line electrification*
New York's Long Island Railroad is the first major rail carrier to install extensive main line electrification.

1906 *Pinawa generating station*
The Winnipeg Electric Railway Co. transmits electric power from the Pinawa generating station on the Winnipeg River to the city of Winnipeg at 60,000 volts. It is the first year-round hydroelectric plant in Manitoba and one of the first to be developed in such a cold climate anywhere in the world.

1907 *Railroad electrification*

The New York, New Haven & Hartford Railroad is electrified, a pioneering venture in mainline railroad electrification. It establishes single-phase alternating current as a technical and economical alternative to direct current.

1907 *Public service commissions to regulate electricity*

Georgia, New York, and Wisconsin establish the first state public service commissions to regulate the growing electric utility industry. Basic state powers include the authority to franchise the utilities, to regulate their rates, financing, and service, and to establish utility accounting systems.

1907 *First company to sell semiconductors*

Wireless Specialty Apparatus Company (WSA) is formed by Col. John Firth, Greenleaf W. Pickard, and Pickard's patent attorney, Philip Farnsworth. It is considered the first company to make and sell silicon semiconductor devices.

1909 *First reliable high-voltage power fuse*

S&C Electric Company in Chicago, Illinois uses the first reliable high-voltage power fuse. This invention provides an economical, reliable means for interrupting high-current short-circuits in electric utility substations.

1909 *Early long-distance power line*

The Shoshone Transmission Line begins to carry power from a hydroelectric generating station on the Colorado River to the city of Denver. It operates at 90 kV over a distance of more than 150 miles. It is notable not only for its length but also for the rugged terrain over which it travels (it crosses the Continental Divide three times and reaches a maximum altitude of 13,500 feet).

1910 *Niagara Falls power transmission*

The Niagara Transformer Station of the Hydro Electric Power Commission of Ontario begins collecting power from several generating stations at Niagara Falls, Ontario and distributing power from Niagara Falls over a network of transmission lines to loads throughout southern Ontario. It is the first time that power is distributed to an entire region over a long-distance network of high voltage transmission lines.

1911 *Superconductivity discovered*

Dutch physicist Heike Kamerlingh Onnes discovers superconductivity; i.e., the loss of electrical resistance in a metal (in this case mercury) near absolute zero temperatures. It is soon determined that other metals and alloys become superconductors at very low temperatures.

1913 *U.S. surface ship powered by electricity*

USS *Jupiter,* a transport and coal-carrying vessel, is commissioned in California. This is the first surface ship in the U.S. Navy to be propelled by electric motors.

1923 *Landing fields first lit by electricity*

Forty-two airplane landing fields on the Chicago–Iowa City–Omaha–North Platte–Cheyenne route are lit by electricity. Thirty 6-inch electric arc signals are employed. The light is visible for 50 miles.

1926 *Patent for field-effect transistor*

Polish-American physicist and inventor Julius E. Lilienfeld files a patent for a three-electrode structure using copper-sulfide semiconductor material. Today this device is called a field-effect transistor.

1928 *First moving electric sign*

The New York Times mounts the first moving electric sign in the United States around the top of its headquarters building in Times Square, New York City. The sign is used to report the 1928 election returns and is called "The Zipper" from the way it encircles the building.

Shannon Scheme Workers on the Shannon Scheme for the Electrification of the Irish Free State. This was a large civil engineering project to bring electricity to rural areas of Ireland, undertaken shortly after Ireland gained independence from Britain. It was named for Ireland's longest river, which supplied hydropower for the project, and was carried out by the prominent German firm Siemens. (Photo from kieranmcarthy.ie)

1928 *Electric light bulb with inside coat*
A patent is assigned to Marvin Pipkin for an electric light bulb coated on the inside, which is stronger and has less glare than existing outside-coated bulbs. He goes on to develop an improved version of this in 1947.

1929 *First large pumped storage facility in United States*
The Rocky River Pumped Storage Hydro-Plant, New Milford, Connecticut, begins operation, becoming the first major pumped storage hydroelectric project in the United States.

1929 *Shannon power project*
The Shannon Scheme for the Electrification of the Irish Free State, near Ardnacrusha, Ireland, begins power generation. It is one of the largest civil and electrical engineering projects of its type at the time, and is an important commercial and political success for the Irish government. It also launches Siemens, the German company building the project, as one of the world's leading engineering and electronics companies.

1930 *Photovoltaic effect in Cu_2O*
Walter Hermann Schottky, working in the Siemens Laboratory, demonstrates the photovoltaic effect in Cu_2O. He also identifies what becomes known as the Schottky barrier, a potential barrier formed at a metal-semiconductor junction which has rectifying characteristics, suitable for use as a diode.

1936 *Hoover Dam goes into operation*
The first generator, N-2, goes into full operation at the Hoover Dam (Boulder Dam) at Black Canyon on the Colorado River between Arizona and Nevada, one of the major engineering feats of modern times and the source of much of the electric power consumed in the Southwest.

1936 *Rural Electrification Act signed*
The Rural Electrification Act is signed into law by President Franklin D. Roosevelt to address the fact that rural America is still largely without electricity. Within two years, cooperative projects financed by the REA will provide electricity to 1.5 million farms, and by the mid-1950s virtually all American farms will be electrified.

1938 *Rectification explained*
Physicists Boris Davydov (Russia), Nevill Mott (England), and Walter Schottky (Germany) independently explain rectification when they attribute the phenomenon to a concentration of electrons on the semiconductor surface that set up an asymmetric barrier to current flow.

1940s *Biogas to electricity in sewage treatment*
Many municipal sewage treatment plants in the United States and Europe now use anaerobic digestion to capture methane that is used to generate electricity for the plant.

1941 *Grand Coulee Dam completed*

Power is generated at Grand Coulee Power Plant, Washington, harnessing the great Columbia River. It is the largest hydroelectric dam in the world at this time (in fact, the largest concrete structure of any kind), and still remains the largest dam in North America.

1947 *Invention of the point-contact transistor*

John Bardeen, William Shockley, and Walter Brattain, scientists at the Bell Telephone Laboratories in Murray Hill, New Jersey, demonstrate the first transistor, a device composed of semiconductor material that can both conduct and insulate. Bell Labs publicly announces the revolutionary solid-state device at a press conference in New York in 1948. By 1952, transistors are being used in radios and hearing aids.

1947 *Barium titanate used commercially*

Barium titanate is the first piezoelectric (electricity produced by mechanical pressure) ceramic to be used commercially, in its application as a phonograph needle.

1947 *First induction log*

While employed by Schlumberger oil field services company, the French-American scientist Henri George Doll records the first induction log in a Humble Oil well in Tyler, Texas. The induction log of formation resistivity is based on the principle of inducing alternating current loops in the formation and measuring the resultant signal in a receiver. Induction logs help distinguish oil-bearing from water-bearing rock layers when the borehole contains fluid that does not conduct electricity.

1948 *Plans to commercialize nuclear power*

The U.S. government's Argonne National Laboratory, operated in Illinois by the University of Chicago, and the Westinghouse Corporation's Bettis Atomic Power Laboratory in Pittsburgh, announce plans to commercialize nuclear power to produce electricity for consumer use.

1949 *Snowy Mountains hydro facility*

Construction begins on the Snowy Mountains Hydroelectric Scheme in Australia's Southern Alps, one of the most complex integrated water and hydropower systems in the world. Eventually completed in 1972, the scheme virtually reverses the flow of the Snowy River and includes 16 dams, 7 power stations, 90 miles of tunnels, and 50 miles of aqueducts.

1949 *First gas turbine for power generation in United States*

The first gas turbine used for electric utility power generation in the United States begins operation at the Belle Isle Station of the Oklahoma Gas & Electric Company. It represents the transformation of the early aircraft gas turbine, in which the engines seldom ran more than 10 hours at a stretch, into a long-life prime mover. This 2-stage expansion turbine, which runs on natural gas, has a 15-stage axial compressor. Through a reduction gear, it drives a 3,500 kilowatt alternator at 3,600 revolutions per minute.

1951 *First reactor producing usable power*

At the National Reactor Testing Station in Arco, Idaho, the Experimental Breeder Reactor I (EBR-1) becomes the first nuclear reactor in the world to produce usable quantities of electric power, lighting four 100-watt light bulbs.

1951 *Improved semiconductor production*

U.S. chemical engineers William Pfann and Henry Theurer of Bell Labs develop zone-refining techniques for production of ultra-pure semiconductor materials.

1954 *Bacon's alkaline fuel cell*

Francis Thomas Bacon demonstrates a 6-cell alkaline fuel cell that produces 150 W, operates at 15 bar (600 psi) and 200°C, and has electrodes 5 inches in diameter. This device provides significantly improved performance due to less corrosion of the electrode. In 1959 he develops a fuel cell device that can produce 5 kilowatts of power, enough to run a welding machine.

1954 *First nuclear-powered electricity generator*

An existing graphite-moderated channel-type plutonium production reactor, modified for heat and electricity generation, begins operation in the closed city of Obninsk at the Institute of Physics and Power Engineering in the Soviet Union. The AM-1 (*atom mirny*, meaning "peaceful atom") reactor is water-cooled and graphite-moderated, with a design capacity of 30 MWt or 5 MWe. AM-1 produces electricity until 1959 and is used until 2000 as a research facility and for the production of isotopes.

1954 *Prediction that nuclear power will be abundant*

Lewis Strauss, chairman of the U.S. Atomic Energy Commission, gives a speech to the National Association of Science Writers in New York in which he predicts that electricity produced by nuclear power will soon be so abundant that "Our children will enjoy in their homes electrical energy too cheap to meter."

1955 *Japan's nuclear technology limited to peaceful uses*

Japan passes the Atomic Energy Basic Law that strictly limits the use of nuclear technology to peaceful purposes. The law stresses democratic methods, independent management, transparency, and international cooperation as the basis of nuclear research activities. By 2000, Japan gets about one-third of its electricity from nuclear plants.

1955 *First U.S. town with all power from nuclear source*

Arco, Idaho, population about 1,300, becomes the first town in the United States to receive its entire supply of power from a nuclear source. Electricity produced in an experimental nuclear power plant operated by Argonne National Laboratory at the U.S. Atomic Energy Commission's National Reactor Testing Station, 20 miles from Arco, starts feeding energy into transmission lines supplying the small town. The experimental boiling water reactor BORAX-III produces approximately 2,000 kilowatts of electrical power for about 2 hours.

1956 *Commercial electricity from nuclear power*

The 50 MWe Calder Hall-1 nuclear reactor begins operation in England. This is the world's first industrial scale nuclear power station to demonstrate the commercial potential of generating electricity through nuclear fission. Early British nuclear reactors are fueled by natural uranium metal, moderated by graphite, and gas-cooled.

1957 *Early civilian nuclear unit*

Power from a civilian nuclear unit is generated for the first time in the United States by the Sodium Reactor Experiment at Santa Susana, California. The reactor powers about 1,100 homes in the Moorpark area of California until 1964.

1957 *First large-scale U.S. nuclear power plant*

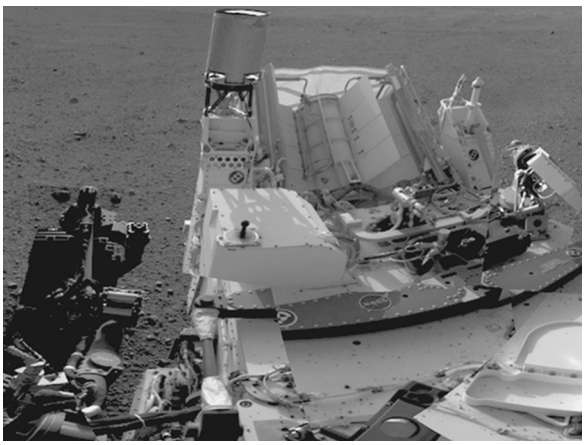
The first large-scale nuclear power plant in the United States begins operation in Shippingport, Pennsylvania. The plant reaches full power three weeks later and supplies electricity to the Pittsburgh area.

1957 *Nuclear plant connects to grid*

The Vallecitos boiling water reactor in Alameda County, California connects to the electrical grid and becomes the first privately funded nuclear power plant to supply power in megawatt amounts to the electric utility grid in the United States. It closes in 1963.

1958 *Star of Laufenburg Interconnection*

The Star of Laufenburg Interconnection is established near Laufenburg, Switzerland. This electric-power interconnection of three countries—Switzerland, Germany, and France—leads to the Union for Production and Transmission of Electricity (now UCTE). This installation pioneered international connections and technical and political cooperation for European integration.



RTGs RTG system (the rectangular device at center). RTGs (Radioisotope Thermoelectric Generators) provide electrical power for spacecraft by converting the heat generated by the decay of plutonium-238 (Pu-238) fuel into electricity. Since they have no moving parts that can fail or wear out, and can operate continuously independent of sunlight, RTGs have historically been viewed as a highly reliable power source. They have been used by the U.S. space program since the 1960s. (NASA)

1960 *Vapor deposition for transistors*

Researchers at Bell Labs use chemical-vapor deposition to add a thin epitaxial layer of silicon between the base and collector of a transistor. This raises the transistor's breakdown voltage while dramatically increasing its switching speed, two important circuit-design characteristics.

1961 *First radioisotope thermoelectric generator in space*

The first radioisotope thermoelectric generator (RTG) is used aboard a U.S. Navy navigation satellite as part of NASA's Systems for Nuclear Auxiliary Power (SNAP) program. The electrical power output of this RTG, which is called SNAP-3, is only 2.7 watts. An RTG is an electrical generator that obtains its power from radioactive decay. In such a device, the heat released by the decay of a suitable radioactive material is converted into electricity by the Seebeck effect, using an array of thermocouples.

1963 *United Kingdom's first major pumped storage power facility*

Ffestiniog Power Station in Wales goes into operation, the United Kingdom's first major pumped storage power facility. Pumped storage involves two reservoirs at different levels. Water is pumped to the higher of the two, then released to flow downward through high-pressure shafts linked to turbines, thus generating power for electricity.

1963 *Taum Sauk Plant comes on line*

The Taum Sauk Plant pumped-storage electric power plant comes on line, and is the largest of its kind in North America, producing 350 MW of power. Located in the Ozark Highlands on the east fork of the Black River 90 miles southwest of St. Louis, the plant's other pioneering features include its high capacity turbine generators and its ability to be operated from a remote location in St. Louis.

1963 *Kurobe River Hydropower Plant*

Kansai Electric Power Co. of Japan completes the innovative Kurobe River No. 4 Hydropower Plant, including the Kurobe Dam and a subterranean power station. The 275 kV long-distance transmission system delivers electricity to the Kansai region and solves serious power shortages, contributing to industrial development and enhancing living standards for the population.

1964 *First commercial analog integrated circuit*

The Fairchild μA702 op amp, created by engineer Dave Talbert and designer Robert Widlar, is the first widely-used, commercial analog integrated circuit.

1964 *Grande Dixence Dam*

The Grande Dixence Dam commences operation as a concrete gravity dam on the Dixence River at the head of the Val d'Hérens in the canton of Valais in Switzerland. At 285 m (935 ft) high, it is the tallest gravity dam in the world. Its installed electric generating capacity is 2,069 MW.

1965 *Great Blackout of 1965*

The Great Blackout of 1965 covers 80,000 square miles of the northeastern United States and Canada. The failure affects 4 million homes in the New York City area, and leaves between 600,000 and 800,000 people stranded in the city's subway system. The events of the blackout become the subject of a Hollywood film, *Where Were You When the Lights Went Out?*

1965 *700 kV transmission*

Hydro-Quebec's 735,000-volt electric power transmission system is the first in the world to be designed, built, and operated at an AC voltage above 700 kV. This development extends the limits of long-distance transmission of electrical energy, when power is transmitted from the Manicouagan-Outardes hydroelectric generating complex to Montreal, a distance of 600 km.

1967 *Aswan High Dam*

Power generation begins from the Aswan High Dam on the Nile River in Egypt. The dam's capacity is 2,100 megawatts (MW), making it Africa's largest hydropower facility. When the facility first reaches peak output, it accounts for about half of Egypt's entire electricity generation.

1968 *Dispute over amorphous switch*

Prominent inventor Stanford Ovshinsky publishes a paper describing his amorphous switch in the prestigious journal *Physical Review Letters*, but leading North American electronics companies such as Bell Labs, ITT, Raytheon, and Texas Instruments dismiss the device. However, it proves to be revolutionary, and many attribute the initial skepticism to the novelty of Ovshinsky's ideas and to his lack of academic credentials (he is self-taught, with his formal education ending at high school).

1972 *Large-scale commercial waste-to-energy facility*

The first large-scale commercial waste-to-energy facility is used by the Union Electric Company's Meramec Plant in St. Louis, Missouri. Refuse is shredded and burned with coal to generate electricity.

1972 *Nelson River transmission system*

The Nelson River high-voltage direct current (HVDC) transmission system begins delivery of electric power in Winnipeg, Manitoba, Canada. It uses the highest operating voltage to deliver the largest amount of power from a remote site to a city in history.

1972 *Solid-state converter station.*

The Eel River Station in New Brunswick, Canada, commences operation as the world's first commercial solid-state high-voltage DC converter station. The 320 MW interconnection facility

incorporates high-current silicon solid-state thyristors to convert AC from Hydro Quebec to DC and back to AC, allowing asynchronous, stable power transfers to serve its customers.

1973 *EPRI formed*
America's public and private utilities form the Electric Power Research Institute (EPRI) in Palo Alto, California. EPRI will grow to be one of the world's most influential electric power research and development organizations.

1973 *Lake Michigan's pumped-storage facility*
A huge pumped-storage facility goes into operation on Lake Michigan. The Ludington power plant pumps water uphill from the lake to a storage reservoir when demand is low, then releases the water to flow back downhill and generate electricity as needed by turning giant turbines.

1974 *Largest earth-filled dam*
Tarbela Dam on the Indus River in Pakistan begins operation. It is the second largest dam in the world by structural volume and the largest earth-filled dam in the world. The dam is 485 feet (148 m) high above the riverbed. The dam forms the Tarbela Reservoir, with a surface area of approximately 250-square-kilometers (97 sq mi). The dam stores water for irrigation, flood control, and the generation of hydroelectric power.

1974 *Salter's Duck*
Scottish engineer Stephen Salter of Edinburgh University invents one of the first practical wave-power machines. Known as Salter's Duck, it employs wave impact to induce the rotation of gyroscopes located inside a pear-shaped floating "duck." An electrical generator converts this rotation into electricity.

1974 *CitiCar produced*
Entrepreneur Robert Beaumont revives the consumer electric vehicle market with his CitiCar. Several thousand of these will be produced, due to interest in alternative vehicles spurred by the oil crisis of 1973. However, the CitiCar is essentially a glorified golf cart and by the late 1970s it is no longer produced.

1977 *Black Thunder coal mine*
The Thunder Basin Coal Company opens Black Thunder Mine in the Powder River region of Wyoming. It is the world's largest single coal-mining complex, which will grow to produce more than 10% of annual U.S. coal supply. On an average day, Black Thunder loads more than 25 miles of rail cars that transport coal to 25 different states to generate about 6% of the nation's electricity.

1977 *New York experiences major blackout*
New York City and neighboring Westchester County are plunged into darkness as lightning downs major transmission power lines. Looting and violence erupt, and within a span of 2 days, police arrest nearly 4,000 looters and the city suffers an economic loss estimated at $300 million.

1977 *FERC established*
The Federal Energy Regulatory Commission (FERC) is established in the United States, succeeding the Federal Power Commission. FERC is a quasi-independent agency within the DOE with jurisdiction over such issues as interstate electricity sales, wholesale electric rates, hydroelectric licensing, natural gas pricing, and oil pipeline rates.

1978 *Public Utility Regulatory Policies Act*
The U.S. Public Utility Regulatory Policies Act (PURPA) mandates the purchase of electricity from qualifying facilities (QFs) meeting certain technical standards regarding energy source and efficiency; this especially favors independent sources that are not fossil fuel-based, helping wind and other

Andasol The Andasol solar power station, Europe's first commercial parabolic trough solar power plant, located near Guadix in Andalusia, Spain. Andasol (Andulusia Sun) has a thermal storage system that absorbs part of the heat of the solar field during the day and then produces electricity by a turbine using this heat during the evening or when the sky is overcast. Spanish companies such as Abengoa have opened solar thermal power plants at various other sites, making Spain the world leader in this technology. (Wessel Cirkel/Dreamstime)

renewables. PURPA establishes the first national feed-in law. By 2005, at least 32 countries and 5 states/provinces adopt feed-in laws or policies.

1979 *James Bay hydropower commences operation*
Phase 1 of the James Bay hydropower project in northern Quebec, Canada is completed, producing 10,000 megawatts.

1979 *Solar thermal power in Spain*
The 150 MW Andasol solar power station commences operation near Guadix in Andalusia, Spain. It is Europe's first commercial parabolic trough solar thermal power plant. Over the next several years, Spain will open additional solar thermal power plants at various other sites, making it the world leader in this technology.

1979 *First electricity from OTEC*
The Natural Energy Laboratory of Hawaii demonstrates the world's first production of net electrical power via closed-cycle ocean thermal energy conversion (OTEC). Mini-OTEC is a 50-kilowatt electric (kWe) plant mounted on a converted U.S. Navy barge moored 2 kilometers off Keahole Point. The plant uses a cold-water pipe to produce 52 kWe of gross power and 15 kWe net power.

1980 *Tajikistan hydropower facility*
The Nurek Dam begins electricity generation on the Vakhsh River in Tajikistan. The earthfill embankment dam is the world's tallest dam at 300 meters (984 ft), and operates nine 335 MW Francis turbines with an installed capacity of 3,000 MW.

1980s *Heavy oil in Venezuela*
Intevep, the research affiliate of the state oil company Petróleos de Venezuela S.A., develops a new method to increase utilization of the nation's extra-heavy oil/natural bitumen resources. The resulting product is called Orimulsion, which is exported as a fuel for electricity generation.

1983 *Itaipu Dam begins operation of first unit*
The Itaipu Dam, a joint project of Brazil and Paraguay on the Parana River, begins operation of its first unit. When completed, Itaipu will become the largest hydroelectric power facility in the world and will eventually supply about one-fourth of Brazil's electrical power and nearly all of Paraguay's.

1984 *First large hydropower facility in Amazon*
The Tucuruí Dam begins electricity generation in the State of Pará, Brazil, with a maximum capacity of 8,370 MW. It is the first large-scale hydroelectric project in Brazil's Amazon rainforest.

1985 *Largest pumped storage faculty*
The Bath County Pumped Storage Station begins operation as the largest pumped storage hydroelectric power plant in the world, with a generation capacity of 3,003 MW. The station

is located in the northern corner of Bath County, Virginia, on the southeast side of the eastern Continental Divide. The station consists of two reservoirs separated by about 1,260 feet (380 m) in elevation.

1985 *Pumped storage faculty in France*
The Grand'Maison Dam on the Eau d'Olle, a tributary of the Romanche River, produces the upper reservoir for a pumped-storage hydroelectric facility. With an installed capacity of 1,800 MW, it is the largest hydroelectric power station in France.

mid-1980s *Subsidy tariffs for electricity from renewables*
A policy is introduced to set fixed subsidy tariffs for the purchase by utilities of electricity from renewable electricity providers (especially in North America and Europe).

1986 *Guri (Raul Leoni) power plant in Venezuela*
First power generated at Guri (Raul Leoni) power plant, Venezuela, at the time the second largest hydroelectric plant in the world at 10,300 megawatts installed capacity.

1987 *Soviets launch two nuclear-powered spacecraft*
The Soviet Union launches two TOPAZ nuclear reactors in satellites. Developed for long-term space use, the TOPAZ unit is cooled by liquid metal, uses a high-temperature moderator containing hydrogen and highly enriched fuel, and produces electricity using a thermionic converter. One reactor operates for six months, the other for a year. The program will be canceled by Mikhail Gorbachev in 1988.

1988 *Wave energy to produce electricity*
Pelamis Wave Power Ltd. forms in Edinburgh, Scotland. The Pelamis machine is an attenuating wave energy converter comprised of a series of semisubmerged cylindrical sections linked by hinged joints. As waves pass along the length of the machine, the sections move relative to one another. The wave-induced motion of the sections is resisted by hydraulic cylinders which pump high-pressure oil through hydraulic motors via smoothing hydraulic accumulators. The hydraulic motors drive electrical generators to produce electricity.

1989 *Largest hydroelectric plant in Russia*
The Sayano-Shushenskaya hydroelectric plant in the Republic of Khakassia, Russia, begins operation. The 6,400 MW facility is the largest in Russia and one of the largest in the world. It sells most of its electricity to one client, metals giant Russian Aluminium.

1990 *Stromeinspeisungsgesetz passed in Germany*
The German Parliament passes Stromeinspeisungsgesetz (law on feeding electricity from renewable resources into the public grid). It specifies that renewable generators have the right to connect to the grid, and how they are paid for their generation based on a percentage of the retail price of electricity. Wind energy generation is paid 90% of the full retail rate; hydro, 75%; biomass, 75%. The law creates a boom in the renewable energy market in the 1990s.

1993 *First grid-supported photovoltaic system*
Pacific Gas and Electric installs the first grid-supported photovoltaic system in Kerman, California. The 500-kilowatt system is the first "distributed power" PV installation.

1994 *Pumped storage facility in China*
The Guangdong Pumped Storage Power Station in Guangzhou, Guangdong Province, China begins operation as the largest pumped storage facility in China. It has eight 300 MW units.

late 1990s *Green certificate trading is introduced*

Green certificate trading is introduced in Europe, the United States, and Australia. Generators of electricity from renewable resources receive a certificate for a predetermined unit of energy produced. These certificates have a market value, thus providing a financial incentive for the use of renewable energy.

2001 *Rolling blackouts in California*

Millions of people in California experience a new energy phenomenon known as a "rolling blackout." This is a planned series of temporary, controlled power outages intended to prevent heavy demand from disabling the state's electrical grid. Californians are faced with a combination of increased energy prices and reduced, uncertain supply.

2001 *Enron goes bankrupt*

Enron, an energy services corporation, files for Chapter 11 bankruptcy. It had become the seventh-largest U.S. company by buying electricity from generators and selling it to consumers, and was praised in the business media as the model for a new type of energy company. In reality Enron had been losing vast amounts of money and disguising the losses by false reports and accounting tricks.

2002 *Energy Policy Act of 2002*

The U.S. Energy Policy Act is signed. It reforms the Public Utility Holding Company Act and many other laws dealing with the electric utility industry. It also authorizes a production tax credit of 1.5 cents per kilowatt hour for wind-generated electricity.

2002 *Belgium phases out nuclear power*

At a time when more than 50% of its electricity comes from nuclear power, Belgium makes a decision to completely phase out nuclear power over the next 25 years.

2003 *Blackouts strike North America, Europe*

A blackout strikes over 50 million people in the northeast United States and the province of Ontario. The failure of a generator and the loss of key transmission lines due to tree contact and overloads combine to shut down 263 power plants with 531 generating units.

In the same year, a widespread, serious power outage affects most of Italy and part of Switzerland near Geneva. About 56 million people lose power for up to 18 hours.

2003 *First offshore tidal energy turbine*

England's Marine Current Turbines Ltd. installs the world's first offshore tidal energy turbine, about 1.5 kilometers offshore from Lynmouth in the Bristol Channel of the Irish Sea. The prototype has a single 11-meter-long rotor blade capable of producing 300 kilowatts of electricity.

2008 *First wave farm*

The Aguçadoura Wave Farm begins operation as the world's first wave farm, located 5 km (3 mi) offshore near Póvoa de

Wave energy Heavy surf striking the beach at Aguçadoura, Portugal. This site was chosen for the location of the world's first wave farm (2008); i.e., an ocean facility able to convert the energy of wave motion to electricity. (Francisco Caravana/Dreamstime)

Varzim north of Porto in Portugal. The farm uses three Pelamis wave energy converters to convert the motion of the ocean surface waves into electricity, totaling 2.25 MW in total installed capacity. Another 28 machines are planned to generate 22.5 MW for the state-run power company Energias de Portugal. However, the wave farm ceases operation two months after start-up due to technical problems.

2008 *First grid-connected offshore tidal energy*

England's Marine Current Turbines Ltd. (MCT) installs the world's first large-scale, grid-connected commercial tidal stream generator in the Strangford Narrows between Strangford and Portaferry in Northern Ireland. It generates 1.2 MW for as much as 18 to 20 hours per day. Strangford Lough is also the site of one of the first known tide mills in the world, dating to the year 787.

2009 *Huge power tower in Spain*

Abengoa Solar of Spain commences commercial operation of the Planta Solar 20 (PS20) power plant near Seville, in Andalucía. It is the world's largest commercial concentrating solar power tower. The facility has 1,255 heliostats covering 150,000 m^2 to generate 20 MW of power. This was preceded (2007) by the development nearby of Planta Solar 10 (PS10), Europe's first commercial concentrating solar power tower.

2009 *EU bans incandescent bulbs*

The European Union ends the sale of frosted incandescent bulbs, which represents the first step in a general plan to remove all incandescent bulbs from the market in member nations. This is part of a worldwide movement to phase out the traditional incandescent bulb, the dominant type of household lighting since the late nineteenth century, in favor of more energy-efficient formats such as compact fluorescent lamps (CFLs).

2009 *Hydropower for aluminum production in Iceland*

The Kárahnjúkar Hydropower Plant, a 690 megawatt hydroelectric power plant in eastern Iceland, is designed to produce power for Alcoa's Fjardaál aluminum smelter 75 km (47 mi) to the east. It is the largest concrete-face, rock-filled embankment dam in Europe.

2009 *First integrated solar combined cycle system*

One of the world's first commercial integrated solar combined cycle power systems (ISCCS) begins operation near Yazd, Iran. The plant has two 159 MW gas turbines, a 132 MW steam turbine, and a 17 MW solar parabolic collector plant. Heat from the solar system is used to augment steam generation from natural gas.

2010 *World's largest tidal power installation.*

The Sihwa Lake Tidal Power Station in Gyeonggi Province, South Korea, comes on line as world's largest tidal power installation. The facility's 254 MW surpasses the 240 MW Rance Tidal Power Station which held the title of world's largest for 45 years.

2011 *First grid-scale flywheel-based storage plant*

The world's first grid-scale flywheel-based storage plant is connected to the grid in Stephentown, New York. Beacon Power Corp. operates the 20 MW facility with 200 high-speed Beacon flywheels to provide frequency regulation services to the New York Independent System Operator (NYISO).

2011 *China's first battery energy storage*

One of the world's largest battery energy storage facilities goes on line in Zhangbei, Hebei Province, China. The facility combines 140 MW of renewable energy generation (both wind and solar) with 36 MWh of energy storage in the form of iron-phosphate batteries. The project is a joint venture of BYD Company Limited and the State Grid Corporation of China (SGCC).

TOP TEN

Milestones in Electricity Markets

1. **Passage of PURPA (Public Utility Regulatory Policy Act; 1978)**
   PURPA let states obligate utilities to purchase energy from cogeneration and small renewables when their power was less expensive than avoided costs. The success of this program illustrated the feasibility of low-cost power supply from independent power producers (IPPs).

2. ***Markets for Power*** **(1982)**
   MIT professors Paul Joskow and Richard Schmalensee penned a report for the Department of Energy exploring ways to benefit from increased market forces in the power industry. Their work grew into the first comprehensive review of the technical, economic, and institutional features of the power industry. The work was eventually published as *Markets for Power: An Analysis of Electric Utility Deregulation* and—though it was quite measured on the subject of deregulation—the book became an influential road map for energy deregulators.

3. **U.K. Government Privatizes the Power Sector and Creates a Market (1989)**
   The Electricity Act of 1989 broke apart the U.K.'s Central Electricity Generating Board (CEGB), a state-owned monopoly operating the entire industry. The resulting private generating companies began selling into one of the first large centralized power markets. The outcome was initially judged more resource-efficient than its state-owned predecessor, but also suffered from large market power problems that required a major redesign.

4. **Order 888 and 888-A, Open Access Transmission Tariff (OATT) Reform (1996)**
   EPAct 1992 and mergers allowed the Federal Energy Regulatory Commission (FERC) to slowly open up transmission access to competitive generators until Order 888 required mandatory open access for all transmitting entities. Open access was America's alternative to vertical divesture and a major milestone for the development of U.S. competitive wholesale markets.

5. **California Energy Crisis (2000)**
   From May 2000 to July 2001, adverse fundamentals, poor market design, and market manipulation led to sustained price increases and the first market-induced blackouts ever. This crisis damaged confidence in retail electricity deregulation across the entire United States, if not the world.

6. **EU Directive Opening Markets (2003)**
   As early as 1996 the European Union began to develop an internal wholesale power market by creating common rules in its Directive 96/92/EC. Four years later it revisited and strengthened its market with Directive 2003/54/EC. In this last directive the EU created stronger safeguards against anticompetitive behavior, increased access to networks, and increased transparency.

7. **Birth of the Smart Grid (2005)**
   In 2005, researchers at the U.S. Pacific Northwest National Laboratory provided customers at a small utility in Washington State with a primitive version of price-controllable smart appliances. This was the first ever demonstration of the potential for a customer-centered, price-responsive smart grid and, though it was technologically unsophisticated, it was seen as a success.

8. **The Energy Policy Act (2005)**
   While known for reducing the barriers to utility mergers and establishing new tax incentives and loan guarantees, the third installment of the Energy Policy Act (EPAct) solidified wholesale competition as a national policy. EPAct provisions allowed FERC to reduce congestion and use transmission incentives to facilitate stronger competition.

9. **FERC Order 1000 (2011)**
   This sweeping order established regional transmission planning processes, clarified allowable cost allocation, and tied transmission planning to policy imperatives. While opposition to many specifics of the order means that its full impact is yet to be seen, the Order codifies the reality that good large-scale grid planning must be holistic, policy-consistent, and regional in nature.

10. **Grid Parity for Renewables and Shale Gas (2014–2020)**
    Renewable energy costs have reached unprecedented lows and are continuing to decline. Solar and wind resources increasingly compete with fossil fuels on a cost basis, especially when the price of carbon emissions is factored in. Meanwhile, shale gas is easing a shift away from coal-fired power and lowering the cost of integrating variable grid resources. These forces will continue the shift toward low-carbon, small-scale resources that will dramatically reshape the world's power sector.

    And an honorable mention for the issue of global climate change. Though not formally connected to electricity markets, it has generally been a complementary factor. Of course, climate change is also prompting an increasing reliance on emissions markets, such as those in the European Union and the northeastern United States.

—Peter Fox-Penner, Principal and Chairman, The Brattle Group