CHAPTER TWO

Electric Power Generation and Distribution

Power plants electrified the United States, and eventually the rest of the modern world, in only a century and a half. Although other types of energy are used around the world, electricity is the most versatile form for widespread distribution. The role of electric power plants is to generate electric current for distribution through a transmission grid.¹ The historical developments that led to the modern power generation and distribution system are outlined in the following section.² We then review the equations of electrodynamics, discuss the principles of electric power generation, and describe the system that has been developed to distribute electric power.

2.1 HISTORICAL DEVELOPMENT OF ELECTRIC POWER

People first used muscle energy to gather food and build shelters. Muscle energy was used to grind grain with stones, chop wood with hand axes, and propel oar-powered ships. In many instances in history, conquered people became slaves and provided muscle energy for their conquerors.

Stones, axes, and oars are examples of tools that were developed to make muscle energy more effective. Water wheels and windmills replaced muscle power for grinding grain as long ago as 100 B.C.E. Wind and sails replaced muscle energy and oar-powered ships. Early power stations were driven by wind and flowing water, and were built where wind and flowing water were available.

Furnaces use heat to smelt ore. Ore is rock that contains metals such as copper, tin, iron, and uranium. Heat from fire frees the metal atoms and allows them to be collected in a purified state. Copper and tin were the first metals smelted, and they could be combined to form bronze.
STEAM-GENERATED POWER

Heat and water were combined to generate steam, and steam engines were developed to convert thermal energy to mechanical energy. Early steam engines drove a piston that was placed between condensing steam and air, as illustrated in Figure 2-1. When steam condenses, it occupies less volume and creates a partial vacuum. The air on the other side of the piston expands and can push the piston. By alternately injecting steam and letting it condense, the piston can be made to move in an oscillating linear motion.

English inventor Thomas Newcomen invented the steam engine in 1705 and built the first practical steam engine in 1712. Newcomen's steam engine was used to pump water from flooded coal mines. Steam condensation was induced in Newcomen's steam engine by spraying cold water into the chamber containing steam. The resulting condensation created the partial vacuum that allowed air to push the piston. A weight attached to the rod used gravity to pull the piston back as steam once again entered the left-hand chamber, as shown in Figure 2-1.

Scottish engineer James Watt improved the efficiency of the steam engine by introducing the use of a separate vessel for collecting and condensing the expelled steam. Watt's assistant, William Murdock, developed a gear system design in 1781 that enabled the steam engine to produce circular motion. The ability to produce circular motion made it possible for steam engines to provide the power needed to turn wheels. Steam engines could be placed on platforms attached to wheels to provide power for transportation. Thus was born the technology needed to develop steam-driven locomotives, paddle wheel boats, and ships with steam-driven propellers. Furthermore, steam engines did not have to be built near a particular fuel source. It was no longer necessary to build manufacturing facilities near

![Figure 2-1. Schematic of a simple steam engine.](image)
sources of wind or water, which were formerly used to provide power. Manufacturers had the freedom to build their manufacturing facilities in locations that optimized the success of their enterprise. If they chose, they could build near coal mines to minimize fuel costs, or near markets to minimize the cost of distributing their products.

Steam-generated power was an environmentally dirty source of power. Burning biomass, such as wood, or fossil fuel, such as coal, typically produced the heat needed to generate steam. Biomass and fossil fuels were also used in the home. Attempts to meet energy demand by burning primarily wood in sixteenth-century Britain led to deforestation and the search for a new fuel source [Nef, 1977]. Fossil fuel in the form of coal became the fuel of choice in Britain and other industrialized nations. Coal gas, which is primarily methane, was burned in nineteenth-century homes.

The demand for energy had grown considerably by the nineteenth century. Energy for cooking food and heating and lighting homes was provided by burning wood, oil, or candles. The oil was obtained from such sources as surface seepages or whale blubber. Steam-generated power plants could only serve consumers in the immediate vicinity of the power plant. A source of power was needed that could be transmitted to distant consumers.

By 1882, Thomas Edison was operating a power plant in New York City. Edison's plant generated direct current electricity at a voltage of 110 V. Nations around the world soon adopted the use of electricity. By 1889, a megawatt electric power station was operating in London, England. Industries began to switch from generating their own power to buying power from a power generating company. But a fundamental inefficiency was present in Edison's approach to electric power generation. The inefficiency was not removed until the battle of currents was fought and won.

THE BATTLE OF CURRENTS

The origin of power generation and distribution is a story of the battle of currents, a battle between two titans of business: Thomas Edison and George Westinghouse. The motivation for their confrontation can be reduced to a single, fundamental issue: how to electrify America.

Edison invented the first practical incandescent lamp and was a proponent of electrical power distribution by direct electric current. He displayed his direct current technology at New York City's Pearl Street Station in 1882. One major problem with direct current is that it cannot be transmitted very far without significant degradation.
Unlike Edison, Westinghouse was a proponent of alternating electric current because it can be transmitted over much greater distances than direct electric current. Alternating current could be generated at low voltages, transformed to high voltages for transmission through power lines, and then reduced to lower voltages for delivery to the consumer. Nikolai Tesla (1857–1943), a Serbian-American scientist and inventor who was known for his work with magnetism, worked with Westinghouse to develop alternating current technology. Westinghouse displayed his technology at the 1893 Chicago World’s Fair. It was the first time one of the world’s great events was illuminated at night, and it showcased the potential of alternating current electricity.

The first large-scale power plant was built at Niagara Falls near Buffalo, New York, in the 1890s. The power plant at Niagara Falls began transmitting power to Buffalo, less than 30 kilometers (20 miles) away, in 1896. The transmission technology used alternating current. The superiority of alternating current technology gave Westinghouse a victory in the battle of currents and Westinghouse became the father of the modern power industry. Westinghouse’s success was not based on better business acumen, but on the selection of better technology. The physical principles that led to the adoption of alternating current technology are discussed in the following paragraphs.

A chronology of milestones in the development of electrical power is presented in Table 2-1 [after Brennan, et al., 1996, page 22; and Aubrech, 1995, Chapter 6]. The milestones refer to the United States, which was the worldwide leader in the development of an electric power industry.

**GROWTH OF THE ELECTRIC POWER INDUSTRY**

The power industry started out as a set of independently owned power companies. Because of the large amounts of money needed to build an efficient and comprehensive electric power infrastructure, the growth of the power industry required the consolidation of the smaller power companies into a set of fewer but larger power companies. The larger, regulated power-generating companies became public utilities that could afford to build regional electric power transmission grids. The ability to function more effectively at larger scales is an example of an economy of scale. Utility companies were able to generate and distribute more power at lower cost by building larger power plants and transmission grids.

The *load* on a utility is the demand for electrical power. Utilities need to have power plants that can meet three types of loads: base load, intermediate
Table 2-1
Early milestones in the history of the electric power industry in the United States

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Comment</th>
</tr>
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<tbody>
<tr>
<td>1882</td>
<td>Pearl Street Station, New York</td>
<td>Edison launches the “age of electricity” with his DC power station</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Westinghouse displays AC power to the world</td>
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<tr>
<td>1893</td>
<td>Chicago World’s Fair</td>
<td></td>
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<tr>
<td>1898</td>
<td>Fledgling electric power industry seeks monopoly rights as regulated utility</td>
<td>Chicago Edison’s Samuel Insull leads industry to choose regulation over “debilitating competition”</td>
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<tr>
<td>1907</td>
<td>States begin to regulate utilities</td>
<td>Wisconsin and New York are first to pass legislation</td>
</tr>
<tr>
<td>1920</td>
<td>Federal government begins to regulate utilities</td>
<td>Federal Power Commission formed</td>
</tr>
</tbody>
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or cycling load, and peak load. The base load is the minimum baseline demand that must be met in a 24-hour day. Intermediate load is the demand that is required for several hours each day and tends to increase or decrease slowly. Peak load is the maximum demand that must be met in a 24-hour day.

Electric power for small towns and rural communities was an expensive extension of the power transmission grid that required special support. The federal government of the United States provided this support when it created the Tennessee Valley Authority (TVA) and Rural Electric Associations (REA).

**STATUS OF ELECTRIC POWER GENERATION**

The first commercial-scale power plants were hydroelectric plants. The primary energy source (the energy that is used to operate an electricity-generating power plant) for a hydroelectric plant is flowing water. Today, most electricity is generated by one of the following primary energy sources: coal, natural gas, oil, or nuclear power. Table 2-2 presents the consumption of primary energy in the year 1999 as a percentage of total primary energy consumption in the world for a selection of primary energy types. The table is based on statistics maintained at a website by the Energy Information Administration (EIA), United States Department of Energy. The statistics should be considered approximate. They are quoted here because the EIA is a standard source of energy information that is