

THE ELECTRICAL GRID

A NONTECHNICAL GUIDE

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INTRODUCTION TO THE ELECTRIC GRID

The electrical grid, also known as the power grid, is an impressive feat of engineering and management that has played a crucial role in the development and growth of most nations. After Thomas Edison's invention of the lightbulb in 1879 and the subsequent construction of the first centralized power plant on Pearl Street in New York's financial district, the utilities industry has continually expanded in size, load, and complexity. The electrical grid is one of the largest machines ever built. In the United States, the grid spans thousands of miles, connects millions of people, and has been essential in providing reliable access to electricity for homes, businesses, and industries across the country. The National Academy of Engineering (NAE) ranked electrification, which includes the development of the electrical grid, as the greatest engineering achievement of the 20th century. The ranking was based on the overall impact of these achievements on the quality of life, economic development, and the welfare of societies.

The power grid is an interconnected network of power generation, transmission, and distribution systems that deliver electricity from power plants to homes, businesses, and other consumers across the United States. The primary purpose of the grid is to provide a reliable and efficient supply of electric power to meet the energy demands of the country. The United States (U.S.) power grid is one of the largest and most extensive power networks in the world, spanning the entire continent and providing electricity to urban, suburban, and rural areas alike. The grid's sheer size and complexity are a testament to the ingenuity and persistence of the engineers, planners, and workers who built and continue to maintain it. Despite its size and complexity, the U.S. electrical grid maintains a high level of reliability, ensuring that the vast majority of customers have access to electricity when they need it. While occasional outages and disruptions do occur, the grid's overall stability is a remarkable achievement, given the challenges of managing such a vast and intricate system.

The U.S. electrical grid has been a significant driver of economic growth and development. By providing reliable and affordable electricity, the grid has enabled the growth of industries, businesses, and communities across the country. Moreover, the grid supports an enormous number of jobs in the energy sector, from power plant operators and line workers to engineers and researchers.

and pricing. Additionally, grid operators engage in long-term resource planning, assessing future electricity needs and working with stakeholders to ensure the grid's capacity to meet those needs.

Some examples of balancing authorities and grid operators in the United States include ISOs and RTOs, such as the California Independent System Operator (CAISO), PJM Interconnection, the New York Independent System Operator (NYISO), and the Midcontinent Independent System Operator (MISO). Figure 1.3 shows the U.S.-based RTOs and ISOs.

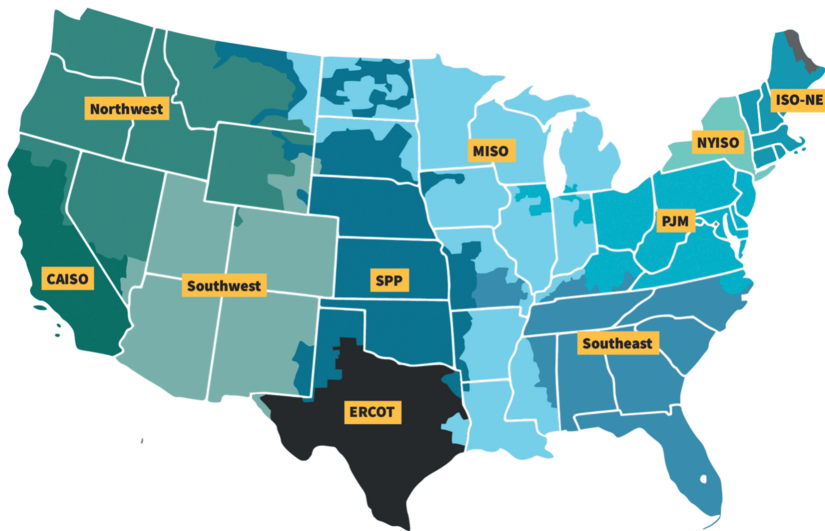


Figure 1.3. U.S. RTOs and ISOs Source: <https://www.ferc.gov/power-sales-and-markets/rtos-and-isos>

U.S. Utilities Organization

The organization of utilities in the United States is complex, as it involves a mix of private and public entities, and it varies from state to state. The three most common type of utilities that consumers interact with are Investor-Owned Utilities (IOUs), Public Power or Municipals, and Rural Electric Cooperatives (RECs).

IOUs are private corporations that provide utility services and are owned by investors who buy shares of stock. They serve about 72% of U.S. electricity customers and often provide services in several states (sometimes adjacent but not always), although some are smaller and operate in a single state or part of a state. IOUs are usually monopolies and thus regulated by state Public Utility Commissions (PUCs) or Public Service Commissions (PSCs), which approve their

There are two types of solar power-based electrical generation in the U.S.: photovoltaic (PV) and concentrated solar power systems (CSP). CSP use lenses or mirrors and solar tracking systems to focus a large area of sunlight into a small beam to produce high-temperature heat, which can also be used to generate electricity, while PV (solar panels) convert sunlight directly into electricity. In 2021, about 4% of U.S. electricity came from solar power, which was up from 3.2% the previous year, and is forecasted to continue to increase. The growth of solar power in the U.S. can be attributed to various factors, such as declining costs of solar panels and equipment, favorable government policies and incentives, and increased public awareness of the benefits of solar power incentives. Federal, state, and local government policies have played an important role in the growth of solar power in the U.S. Incentives like the Investment Tax Credit, which offers tax credits for solar installations, and state-level net metering policies, which allow homeowners to sell excess solar-generated electricity back to the grid, have encouraged solar power adoption.

Photovoltaic panels are made up of a semiconductor material, typically silicon. When sunlight hits the solar cell, the energy from the absorbed light is transferred to the semiconductor. The energy absorbed from the light excites electrons in the semiconductor, promoting them from a state of low energy (the “valence band”) to a state of higher energy (the “conduction band”). This leaves behind “holes” where the electrons were. The movement of these electrons and holes creates an electron-hole pair. The photovoltaic cell is designed so that the excited electrons are naturally pushed towards one side of the cell. This is achieved through a built-in electric field that’s typically formed by joining p-type (positive) and n-type (negative) semiconductor materials. The electron-hole pairs are separated by this electric field, preventing them from recombining. When the cell is connected in a circuit with an external load (like a lightbulb), the electrons can travel from the negative layer of the semiconductor, through the external circuit, doing electrical work (like lighting the bulb), and then recombining with the holes in the positive layer as an electric current. By placing large numbers of these cells in series (a solar panel), we can generate enough electric current and voltage to contribute to the electric grid.

CSP systems generate electricity by using mirrors or lenses to concentrate a large area of sunlight onto a small area. The concentrated light is then used as a heat source for a conventional power plant. A CSP power plant system includes many mirrors or lenses, known as heliostats, which track the sun and reflect and concentrate the sunlight onto a specific point. This point can be a receiver located on a central tower or it can be a pipe containing a heat-transfer fluid. The concentrated sunlight heats up the receiver. Depending on the specific system, the receiver might be a fluid (like molten salt or synthetic oil) or a solid (like a ceramic material). The heat absorbed by the receiver can reach extremely high temperatures, often in excess of 750 degrees Fahrenheit (400 degrees Celsius) and even higher depending on system design. The heat is then used to generate steam, which drives a conventional steam turbine that generates electricity. Some

Primary and Secondary Distribution

From the substation, electricity undergoes a series of voltage reductions and distribution stages, traveling through primary lines, transformers, and service drops, until it's finally delivered to household appliances at a safe and usable voltage. Throughout this journey, various pieces of equipment ensure the safe, reliable, and efficient delivery of power.

The transition point from the transmission system described in Chapter 3 to the distribution network is the substation. Substations are intermediary points in the power grid that transform electricity from higher transmission voltages to lower distribution voltages. They contain transformers and various switchgear.

Within the substation, step-down transformers reduce the high transmission voltage (often tens or hundreds of thousands of volts) to a lower voltage suitable for distribution (usually in the range of a few thousand volts). Once the voltage has been stepped down, the electricity is sent out on distribution lines. The primary distribution lines, also called “feeders,” carry the stepped-down voltage, typically between 2.4kV and 35kV. They are the main lines running through neighborhoods or commercial areas.

Before electricity enters homes, the voltage must be reduced further. This is the job of the pole-mounted (or sometimes ground-mounted) distribution transformers commonly seen in residential areas. The output from distribution transformers goes to secondary circuits, which are typically rated at 120 V/240 V in the U.S. for residential areas. The service drop is the final stretch of electrical line that connects the secondary circuit to individual homes.

Before entering the home, the service line connects to an electricity meter. This device measures the amount of electricity consumed, which the utility uses to calculate the customer's bill. Inside the home, the electricity first encounters the main electrical panel or breaker box. Circuit breakers and fuses are safety devices that interrupt power if there's an overload or fault. They ensure that the current flowing in household circuits stays within safe limits.

From the panel, individual circuits branch out to various parts of the home, delivering electricity to outlets, lights, and appliances. Each circuit typically has its own breaker in the panel. Once the electricity reaches the outlets, it's ready to be used by various devices and appliances in the home, like refrigerators, TVs, lightbulbs, and computers.

Phases

North America, like much of the world, predominantly uses single-phase power for residential applications and three-phase power for commercial and industrial applications. Three-phase power is created by the system generator due to the way its coils are arranged and how the rotor moves within these coils. Due to the

are typically reviewed and approved by a regulatory body such as a Public Utility Commission (PUC) to ensure that they are fair and reasonable. The CIS keeps track of all this information and applies the correct rate to customers based on the amount and time of their consumption in a billing period.

Work Management System

A work management system (WMS) is used by utility companies to manage and coordinate the process of maintenance, repairs, installations, inspections, and other field service activities. These systems can help utilities increase efficiency, improve customer service, and ensure that important field service work is completed in a timely and effective manner. They are particularly important for utilities due to the large number of physical assets they manage and the critical nature of their services. Most WMSs today extend their capabilities to mobile devices. This enables field workers in utility companies to access, update, and manage work orders and other relevant information while on-the-go. They can also capture images, record notes, and even access schematics or maps as needed.

WMSs are used to handle tasks ranging from routine maintenance to emergency repairs and they often integrate with other systems like a Geographic Information System (GIS), Customer Information System (CIS), and Enterprise Asset Management (EAM) to manage all aspects of field service work. These systems enable the creation, assignment, tracking, and completion of work orders. A work order can include all necessary information such as what work needs to be done, where it needs to happen (associated with a premise or asset ID), what materials or equipment are required, and any other pertinent details.

WMSs often include tools for scheduling field service work and dispatching personnel. This can include automated scheduling and routing based on factors like skill sets, location, and availability of field service workers. They can track the condition and maintenance history of infrastructure assets, which aids in planning preventive maintenance, managing asset lifecycles, and budgeting for replacements. Integration with GIS enables utilities to visualize work orders spatially, and often in real time, which aids in efficient routing and location of assets. Many modern systems also include reporting and analytics tools to help managers track productivity, identify trends or problems, and make data-driven decisions about their field service operations.

Advanced

Advanced OT systems are newer technologies being deployed by utilities to achieve new functionality and better operate the grid in the modern environment of distributed energy resources and increased data from grid monitoring and control devices. This list includes the AMI, MDMS, DR, ADMS, and DERMS.

Engineering

The engineering group is typically responsible for the design and analysis of both new additions to the system and necessary improvements to ensure safe and reliable operations. The engineering group also develops equipment specifications, standards, and requirements for the infrastructure components. The specific tasks and responsibilities can vary by utility, but generally include:

- Designing new components of the infrastructure, such as substations, transmission lines, or distribution networks.
- Specifying equipment and materials to be used in construction or upgrade projects.
- Assessing current and future demand to ensure the system can reliably meet the needs of its customers.
- Identifying areas of the grid that need reinforcement or expansion based on projected growth, aging infrastructure, or other factors.
- Project management of infrastructure projects from conception to completion, including budgeting, scheduling, and coordinating with contractors.
- Ensuring all engineering activities and designs meet local, state, and federal regulations and coordinating with regulatory bodies for approvals, inspections, or audits.

System Operations Center

Load management at a utility is typically performed by a team or department specializing in system operations and energy management. This group can be referred to by various names, but System Operations Center (SOC) is common. In the SOC, operators monitor the energy system in real time and make decisions to ensure a balance between supply and demand. They can dispatch generation resources, engage demand response programs, or curtail loads to manage the system load. Load forecasters are an offline group and predict energy demand using historical data and predictive modeling, considering variables like weather, economic activity, and customer behavior. Collaboration across various departments is critical for effective load management. For instance, the marketing department may help promote demand response programs, while IT specialists maintain the data systems that monitor loads and manage program participation. The integration of renewable energy sources and the increasing prevalence of smart grid technologies have made load management a more complex and technologically sophisticated field within utilities. New innovations in operating technology include ADMS and DERMS to reduce workload and at some utilities perform actions such as switching to protect the grid in real time.

to consumers, resulting in higher electricity rates. It is estimated that electric utilities in the U.S. spend more than \$100 billion annually to maintain aging infrastructure.

As infrastructure ages, its reliability diminishes. Outdated equipment and power lines become more prone to failures and outages. This not only disrupts the daily lives of consumers but also has severe consequences for industries relying on uninterrupted power supply, such as healthcare, manufacturing, and technology.

Aging infrastructure also poses safety risks to both utility workers and the general public. Equipment malfunctions, worn-out components, and outdated safety systems can lead to accidents, electrical fires, and electrocutions. Enhancing the safety of infrastructure is crucial to protect lives and property.

Transitioning to Renewables

Moving from traditional fossil fuels to renewable sources presents operational and investment challenges, especially with integrating intermittent DER sources like solar and wind. Intermittent sources cannot be guaranteed, and worst-case planning requires other sources to be available to fill gaps and avoid brownouts and blackouts that endanger citizens, commercial, and industrial users. In Australia, solar generation capability is so great that they need to actively curtail solar generation sources during the day. However, without matching storage capability, fossil fuels are still required to fill the energy needs during “shoulder” periods around the midday peak. Many of the technologies discussed in this book such as ADMS, DERMS, and grid edge processing are designed to manage the integration of DER sources into the grid. The technology that lags behind in the energy transition discussion is battery storage, and advances are needed before we can achieve the vision of an all-renewable future. Adoption of more distributed storage on the system, microgrids to provide more centralized power from DERs, and active load control are all potentially solutions to help manage the future distribution system. Renewables represented about a quarter of the energy supply in 2018, and continue to grow as shown in figure 10.1.

On the demand side, major incentives are currently in place to incentivize a change over to electric vehicles. In addition, the EPA and some states have either mandated cessation of new internal combustion engine (ICE) cars and trucks or raised emission standards to a level that no ICE engine could conceivably meet. The planning issue for utilities is that the scenario of eliminating all ICE engines is unlikely. For city and many suburban dwellers, an electric vehicle makes sense from a subsidized economic and lifestyle point of view. However, for a rural dweller with long-distance commutes and heavy towing needs, the benefits are currently outweighed by the realities of limited charging infrastructure and lower energy density in EVs, leading to reduced range. For example, with the largest available battery pack, a fully charged 2022 Ford F-150 Lightning electric truck has less energy onboard than a regular F-150 with four gallons of gas in its tank (MotorTrend, July 2022).