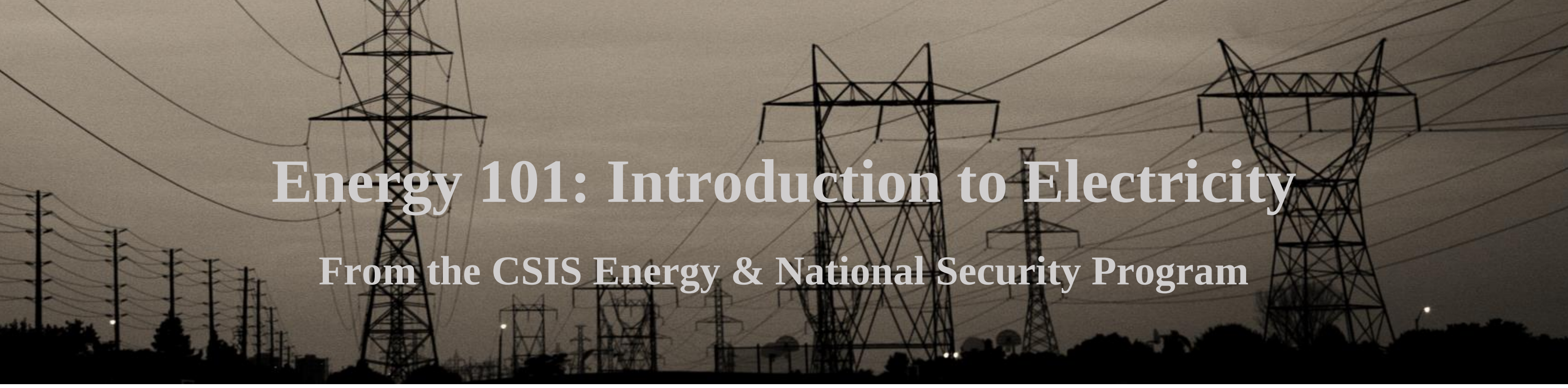

Energy 101: Introduction to Electricity

From the CSIS Energy & National Security Program

By Michelle Melton

Background

Electricity is an integral part of life in modern society and is a key input in economic growth. Its ubiquity can obscure the sector's financial, technical, and regulatory complexity. This complexity is compounded by the diversity of regulatory and market forms around the world.

Electricity is a secondary source of energy, which means it is produced via the conversion of other sources of energy into electrical power. This conversion happens in most cases via a generator that converts mechanical energy into electrical energy. In the case of fossil fuels, electricity is generated through the combustion of coal, oil, or natural gas, which creates pressure to turn a turbine that generates electrical energy. (See Coal 101, Oil 101, and Natural Gas 101 for more information on these fuel sources.) The generation process is similar for most renewable resources: wind, hydropower, biomass, tidal, geothermal, and nuclear all generate electrical energy from turbines. (See Renewable Energy 101 for more information on these fuel sources.) In the case of photovoltaic solar, energy is directly converted from the source (i.e., solar power) into electrical energy. For all of these sources, energy is lost in the conversion processes (energy is also lost during transmission and distribution). For example, a coal plant typically has a conversion rate (also called a "heat rate") of about 35 percent; the rate is about 45 percent for natural gas combined cycle plants, 33 percent for nuclear plants, 26 percent for wind turbines, 12 percent for PV solar, and 90 percent for hydropower facilities. Batteries, fuel cells, and thermoelectric generators can also produce electricity via other processes.

Electric power flows over a grid, a complex network comprising power lines that connect consumers to power plants. The electricity grid consists of three distinct services: generation, consisting of power plants that generate electricity; transmission, consisting of high-voltage power lines that carry electricity over long distances; and distribution, where power is transmitted at lower voltages and over smaller distances to individual end users (industrial, commercial, and residential customers). Transmission and distribution are analogous to an airplane trip. The part of the transit spent on the flight is transmission, while the taxi ride from the airport to the final destination is distribution.

Electricity is a commodity, but unlike most commodities, it is anchored to and embodied in a physical system, the electrical grid. This unique property of the commodity means two things: first and most important, due to the electrical properties of the grid, supply and demand must be in balance on the grid at all times; second, any entity wishing to either supply or procure energy in the form of electricity must be physically connected to the grid. These two attributes of the electricity system are essential for understanding the commercial, economic, policy, and regulatory issues in the sector.

Electric Utilities and Market Structure

Companies that engage in any of the three grid services—generation, transmission, and distribution—are often called "utilities." There is significant variation among utilities in terms of the services they provide, their ownership structures, how they are regulated, and the market conditions in which they operate.

Historically, all three parts of the electricity sector were considered a natural monopoly. A natural monopoly is a market condition in which it is more efficient to have one firm provide a service (in this case, electricity) than to have multiple firms provide that service. Because of the need for redundant, high-cost infrastructure, it has historically been considered costlier to have multiple firms provide generation, transmission, and distribution than if one company was granted a monopoly. In other words, it would be inefficient to have two, three, or four sets of electrical wires connecting a home or business to the broader electricity system; likewise, it would be inefficient to build two sets of transmission lines when one will suffice. Utilities have therefore historically been granted a monopoly over these services in exchange for the promise to serve all customers within a given territory. Regulators, generally through a public utilities commission or another government body, set terms of service and conditions on the monopoly provider to ensure that they receive a fair return on their investments and do not abuse their monopoly status. Regulators generally must preapprove utility investment plans, oversee the rates that they can charge customers, and set other terms of service, such as reliability standards.

In some parts of the world, this monopoly model still prevails and one utility is responsible for generation, transmission, and distribution within a given service territory. This model—referred to as a “vertically integrated utility”—exists in some regions of the United States and Canada, and many parts of the developing world. For example, Hydro Quebec, a utility in Quebec, Canada, owns and operates generation, transmission, and distribution in the province, with a few exceptions.

In the 1970s and 1980s, economists, industrial customers, and regulators began to question whether having one utility provide generation, transmission, and distribution was in fact the most efficient model for the sector, and whether new technology had transformed generation in a way that it was no longer a natural monopoly. Although transmission and distribution were still considered natural monopolies, it became clear that the barriers to market entry were considerably lower for generation, and generation appeared to be a market in which costs could be brought down through the forces of market competition. In places where this argument took hold, including parts of the United States, much of Europe, and some additional economies (such as Australia, the Philippines, and Chile), over the course of several decades, regulators experimented with and eventually created wholesale electricity generation markets, where prices for generation were deregulated and subjected to competitive market forces. However, in these new markets, vertically integrated utilities were considered to have an unfair advantage, because they were the sole buyer of electricity and also a seller. Consequently these markets were “unbundled”—that is, utilities were broken apart into separate commercial entities responsible for generation on the one side and transmission and distribution on the other. The result was the creation of many generation-only entities, often referred to as independent power producers or merchant generators. In these wholesale markets, the market sets the prices for generation, while an independent system operator (ISO) or regional transmission operator (RTO) forecasts demand, oversees and operates the market auction, and schedules and plans transmission. To prevent companies from giving their own affiliates preferential treatment, regulators oversee transactions that could otherwise result in abuse of market power. In regions with wholesale power markets, generation prices are set by the market and passed through to consumers, while transmission and distribution rates are by and large still set and approved by regulators (in the United States, transmission rates are set through regional tariffs overseen by the federal regulator and distribution rates are set by state regulators). In the United States, with the exception of Texas, federal regulators oversee wholesale energy markets to ensure just and reasonable rates.

In addition to a diversity of electricity market structures around the world, utility ownership varies widely as well. Some utilities are government owned and operated, either wholly or in part, either at the municipal, state, regional, or national level. Examples include Austin Energy, Power and Water Corporation of the Northern Territory Government of Australia, Karnataka Power Corporation in India, Saskatchewan Power Corporation in Canada, the Electricity Generating Authority of Thailand, the U.S. Bonneville Power Administration, and China’s State Grid. Others are independently run while the government is the primary or sole shareholder, as in the case of Brazil’s Electrobras (Latin America’s biggest power utility). Still others are cooperatives, where the utility’s users and workers own the utility. Finally, many utilities are publicly listed companies responsible to private shareholders (called investor-owned utilities, or IOUs). In the United States, IOUs serve approximately 70 percent of electricity demand. Even within a single jurisdiction, there may be multiple ownership types; for example, in California, there are IOUs, municipally owned utilities, and rural electric cooperatives, in addition to merchant generators and transmission utilities. In many cases, ownership type and service provided dictate how and by whom the utility is regulated.

Electricity Prices

Electricity is an essential input for nearly all economic activities, making electricity prices an important component of a region or country's economic competitiveness. In addition, the cost of electricity is an important element of any household's monthly expenses. Electricity prices are therefore economically—and politically—important, giving regulators a mandate to keep electricity prices reasonable and competitive. Because transmission and distribution (and in many places, generation) are authorized monopolies, competitive market forces have a more limited role in setting prices than in many other industries. What the exact role of the market is in setting prices varies depending on the market structure. In vertically integrated markets, regulators generally set rates through an administrative rate-setting process (details on the U.S. process appear here); in wholesale markets, rates reflect the auction price. Setting reasonable and appropriate electricity rates, where regulators have the authority to do so, or overseeing just and reasonable rates, in jurisdictions where they do not, is an essential regulatory task. The definition of "reasonable," "appropriate," and "fair" in rate-setting are often contentious. Who gets to define these terms and the arguments they use to support their claims are at the heart of electricity policy and regulation.

The actual cost of producing electricity is determined by many factors. Overall, the price reflects the cost of building, financing, operating, and maintaining power plants. But while some of these factors are steady over time, other factors also impact the price of electricity, including input fuel prices, weather conditions, and regulations. As with other commodities, the price of electricity varies according to supply and demand conditions. There is seasonal variation in electricity prices; during hotter and colder times of the year, when demand is higher, the cost of electricity is also higher because more supply, often using more expensive fuel sources, must be brought online and is generally less efficient and costlier to operate. The cost of generating electricity also changes over the course of the day; as people use less electricity in the late evening and early morning hours (when most people are asleep), costs are low, while costs rise as people consume more electricity in the afternoon and into the early evening. These price fluctuations cannot be smoothed out by storage, and therefore any fluctuation must be addressed by either curtailing demand or increasing supply. The former, called demand response, has been deployed in some markets. The far more common way that grid operators and regulators ensure load balance is to increase supply. Excess generation is actually held idle and available on stand-by, in case it is needed to meet peak demand in the day or in the season. These "peaker" plants are generally the most expensive power, but because there is no storage and because the cost of disruption is so costly, customers must pay to have resources available that are called upon for only a few hours of the year.

Not all customers necessarily bear the costs of electricity equally. Inequality in rates can be intentional or inadvertent. This can reflect how rates are set or the physical constraints of the grid. In "congested" areas of the grid—that is, there is limited ability to bring power in and out of the area due to voltage or capacity constraints—customers pay a premium. In New York City, for example, there are only so many high-power voltage lines carrying generation into the city, while demand continues to grow; the city can therefore be described as "congested" as load grows but supply is constrained. In addition, different types of customers (e.g., residential, industrial, commercial, or agricultural) typically pay different rates. In some countries, cross-subsidization—the practice of charging one customer group higher prices in order to lower the prices of another customer group—is evident. This cross-subsidization may occur among many different kinds of customer classes, such as from richer customers to poorer customers (or vice versa), from residential customers to industrial customers (or among any combination of customer classes), or from grid users in one region to grid users in another area (e.g., from rural to urban consumers). For example, power delivered to rural electricity customers in India is, in many cases, subsidized by surcharges on Indian industrial users. In some parts of the world, electricity prices are subsidized from other funds (e.g., general budget revenues or a specific tax) rather than by rates of another customer class.

Finally, electricity-pricing systems vary. Many residential customers, for example, pay flat rates, meaning customers pay a purely volumetric, set price for their electricity, regardless of the cost of generation. Another common rate structure, called "block rate," is a volumetric system in which each incremental block of electricity consumed is a different price. In some markets, however, prices are determined by short-term supply and demand, based on the location on the grid or the time of day. In U.S. wholesale electricity markets, wholesale prices reflect the differences of load generation, and physical limits of transmission in different areas (this is called locational marginal pricing, or LMP). At the retail and commercial level, regulators have begun to experiment with "time-variant" pricing, where customers may pay a different price depending on the time of year, or time of day, in an effort to better reflect the varying costs of generation. France, Italy, Oklahoma, parts of Illinois, and Ontario, Canada, all provide customers the option to pay rates that vary over time in some way. Examples of different time-varying rates include critical peak pricing, where customers pay higher prices during a few days of the year where wholesale prices are highest; time-of-use, where customers pay different fixed rates during different times of the day (for example, the price of electricity is higher in a three-hour window in the late-afternoon); and real-time pricing, where customers pay a rate linked to the hourly market price for electricity. These time-varying rates are meant to send a price signal to customers to align their consumption with the varying costs of electricity generation.

Policy Issues in the Electricity Sector

Many of the policy challenges are specific to the market or service territory; nonetheless, there are several challenges across all jurisdictions. At their core, all the policy issues represent an attempt by regulators to balance reliability, affordability, and environmental sustainability. Five important, ongoing, and overarching policy issues in the sector include 1) transmission; 2) how to ensure resource adequacy (that there will be enough power to meet demand); 3) traditional pollution control and decarbonization; 4) the rise of distributed energy resources and the future of the grid; and 5) access to electricity, which primarily affects the developing world.

Transmission

Expanding and improving the transmission network is necessary to ensure that electricity is moved efficiently from one place to another, and provides many benefits, such as improving reliability, connecting renewable energy resources, and accommodating changes in electricity demand. For example, growing demand in a particular area can result in transmission congestion and necessitate a new power line to help alleviate high local generation prices. In addition, new power plants and resources often wish to serve new load areas. New transmission, although costly up-front, can help bring power prices down over the long term. However, siting and financing new transmission can be challenging for many reasons. First, approval for new routes requires obtaining the right to the necessary land, which can be a long and contentious process, especially if local landowners do not want transmission on their property. Many people dislike transmission lines because of their aesthetic impacts on a landscape. In addition, how to finance transmission can also be a challenge, especially when transmission lines cross more than one jurisdiction. For example, a power line connecting generation in South Dakota to a load center in Chicago may pass through Iowa—but Iowa will not want to help pay for a line that primarily benefits producers in South Dakota and consumers in Illinois. While there are institutional mechanisms to address this issue in many places, transmission is nonetheless a politically challenging proposition almost everywhere.

Resource Adequacy

Electricity cannot currently be economically stored on a large scale, so it must be generated when it is ready to be consumed. In a market with a storable commodity, such as grain or oil, a supply shortage would send a price signal for producers, traders, and other holders of the commodity to release it onto the market. While other commodities—such as oil or grain—can be stockpiled during times of low prices for release during times of high demand, a shortage of electricity could destabilize the grid, causing outages, economic disruption, and damage to infrastructure. Because the costs of disruption are both economically and politically high, regulators often seek to have enough capacity available at all times to meet peak demand. In other words, because electricity cannot be stored, the price of generation must reflect the cost of all generation, even generation that is not needed except for several hours—or minutes—a year when demand is highest. In wholesale markets, short-term price signals alone have not necessarily resulted in adequate generating capacity.

Regulators have responded in different ways to address this challenge. In some regions, regulators have directed utilities to invest in energy efficiency to prevent the need to build additional generation. Regulators in vertically integrated regions can simply direct their utilities to build generation to meet projected demand through a resource adequacy plan. Some regulators work to build transmission connections to other markets to increase the amount of power they can draw on in times of need, although this option is not necessarily available to islands and isolated regions, and building new transmission is difficult. In regions with wholesale markets, regulators have attempted to create a price signal (often via capacity markets) that will incentivize the build-out of new generation. All of these options cost money that must ultimately be covered by ratepayers, so regulators try to balance the need for adequate supply with the desire to keep prices low.

Traditional Air Pollution Control and Decarbonization

Burning fossil fuels results in air pollution, and therefore the electric power sector is a significant source of pollution, including sulfur dioxide (which causes acid rain), nitrogen oxide (which contributes to ground-level ozone), particulate matter (which can contribute to serious health issues), and heavy metals like mercury (which pose grave hazards to human health). The power sector is also one of the largest sources of greenhouse gas emissions in both the United States (over 30 percent) and globally (25 percent). The extent of a given electric power system's air pollution depends a great deal on the fuels used to generate electricity as well as the technologies used at the source to control pollution.

Reducing air pollution from the electricity sector has been the focus of policy and regulatory attention for decades. While most agree on the need to reduce emissions, exactly how to reduce emissions and how to pay for the cost of reducing emissions have been points of contention. In the United States, the primary law regulating air pollution from power plants is the Clean Air Act (CAA). Through the CAA, the U.S. Environmental Protection Agency (EPA) sets pollution limits from power plants for a variety of pollutants. In August 2015, EPA set limits on carbon dioxide pollution from new and existing power plants for the first time. States and regional organizations in the United States are also working to reduce greenhouse gas emissions from the power sector. Other countries and regional bodies (i.e., the European Union) also have programs that target emissions from the electricity sector.

When it comes to decarbonizing the electricity sector, the broader challenge for regulators has been how to design policies that encourage new technologies, energy efficiency, and lower greenhouse gas emissions while strengthening the system's ability to withstand more frequent and severe weather events—all while not dramatically increasing the cost of power or jeopardizing the reliability of the electric grid. This is a particularly pressing challenge in developing economies, where there is an incentive to install the cheapest reliable power source available (usually coal) in order to meet growing demand.

There are many different policy instruments to support the goal of decarbonization, but all broadly aim to either increase the share of electricity generated from zero-emitting sources of energy or reduce consumption. All policies either implicitly or explicitly increase the relative cost of generation from polluting sources, or lower the cost of generation from zero-emitting sources, but the mechanism they use to do so varies. Tax credits, renewable portfolio standards, feed-in-tariffs, and net metering all incentivize the deployment of renewable energy. In some places, governments direct utilities to build non-polluting generation or subsidize it by providing low-cost financing and/or by agreeing to purchase power from the plant at a set, above-market price. Another method, aimed at reducing emissions, is to impose regulatory standards which require emission reductions from the power plant smoke stack, either through the deployment of technology that controls pollution from the point it enters the atmosphere, or by requiring polluting entities to hold permits to pollute (typically under a cap and trade regime). The European electricity sector and the power plants in several Northeastern U.S. states are both subject to a cap and trade system. Alternatively, governments can simply charge power plants for polluting, in terms of the absolute amount (dollar per ton; this is a carbon tax), or governments can mandate that the power plants meet an intensity standard (they can emit no more than X number of pounds per mWh).

The Scope of the Future Grid

The electricity sector has long been designed around a few central tenants: that strong electricity demand growth would continue indefinitely, and that large, centralized generation, sent in unidirectional flows from producers to consumers, was the most efficient way to meet this demand. For most of the sector's history, economies of scale were believed to be the key driver for cost reductions: build a larger power plant, and the cost per kWh would decline. For policy, technology, and economic reasons, however, these three foundational assumptions have come into question in recent years. Increasingly, there is a question of whether the combination of intermittent renewable resources and local, distributed resources, such as rooftop solar or small, behind-the-meter batteries and/or electric vehicles, will upend the traditional grid model from both a commercial and a reliability perspective. From a commercial perspective, this question matters because utilities will make trillions of dollars' worth of investments in the coming years to modernize the grid—but these investments may be misguided if the grid looks more decentralized. In addition, the design and operation of a system heavily reliant on distributed resources is a different system than the one we have now. From a reliability perspective, this question matters because it is unclear whether the traditional grid, or a more distributed grid, will enhance resilience and reliability while lowering system costs. Regulators, policymakers, industry stakeholders, and others are engaging on a variety of specific policy issues that address these broader questions. The broad debate over net energy metering and how to adequately value distributed energy resources reflect the broader debate about the future of the grid and how and whether to incentivize distributed resources.

Access to Electricity

In the developing world, access to electricity is the primary and driving electricity policy issue. According to the World Bank, over one billion people—the vast majority of them rural residents of developing countries in South Asia and sub-Saharan Africa—do not have access to electricity. Because of the link between electricity and economic development, expanding energy access is a policy imperative in many developing countries. However, the barriers to expanding rural networks are high. Low population density makes extending networks to remote areas expensive; coupled with the fact that these residents often lack the capacity to pay for service, rural expansion is challenging. Compounding the problem in many of these developing economies is that the utility responsible for expanding access may not have the ability to obtain low-cost financing, either because of lack of creditworthiness or because of the uncertainty of achieving cost recovery. Because of the challenges of extending the traditional grid to rural residents, many have suggested that off-grid options such as microgrids and distributed generation are more viable solutions. Microgrids have been successfully implemented in many rural settings, but as of yet the policy and financing support is not in place to address the significant scale of the access problem. Others are skeptical about the long-term viability of microgrids as a solution to energy poverty on principle.

Quick Facts about Electricity

- Electricity is measured in watts (w) and watt-hours (Wh). Power is often measured in kilowatts (KW; 1,000 watts), megawatts (MW; 1 million watts), gigawatts (GW; 1 billion watts), and terawatts (TW; 1 trillion watts). A watt-hour is 1 watt supplied over the course of one hour. The amount of electricity used is measured in watt-hours.
- Globally, electricity demand is projected to grow 69 percent by 2040, from 21.6 trillion kWh in 2012 to 36.5 trillion kWh in 2040, but the vast majority of this growth will come from non-Organization for Economic Cooperation and Development (OECD) economies.
- In 2015, the United States generated 4,000 TWh of electricity in 2015. It was the second-largest generator in the world, behind China (which generated over 5,100 TWh in 2013).
- The average monthly electricity consumption for a U.S. home in 2014 was 911 kWh.
- The average residential price of electricity for U.S. consumers in February 2016 was 12.15 cents/kWh, but there is significant regional variation. The average residential price for European consumers was 20.8 cents Euro/kWh in 2014 (approximately 23 cents/kWh). Differences are explained by many factors.

About the CSIS Energy & National Security Program

The CSIS Energy and National Security Program is dedicated to understanding energy policy, markets, and technology. Through its collaboration with leaders in industry, government, academia, and nonprofits, the CSIS Energy and National Security Program helps illuminate the opportunities and challenges that we expect to confront policymakers and industry players in the coming years. To join our mailing list, contact energy@csis.org, or follow us on twitter @CSISEnergy. Our other Energy 101 fact sheets can be found here.

Michelle Melton is an associate fellow with the Energy and National Security Program at the Center for Strategic and International Studies (CSIS) in Washington, D.C.

This report is produced by the Center for Strategic and International Studies (CSIS), a private, tax-exempt institution focusing on international public policy issues. Its research is nonpartisan and nonproprietary. CSIS does not take specific policy positions. Accordingly, all views, positions, and conclusions expressed in this publication should be understood to be solely those of the author(s).