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How Does the U.S. Power Grid Work?

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Abstract

A vast network of power plants, transmission lines, and distribution centers together make up the U.S. electric grid. The grid constantly balances the supply and demand for the energy that powers everything from industry to household appliances. Out of sight for most, the grid usually only comes to public attention due to large-scale failures, such as the blackouts that struck Texas in early 2021. Extreme weather events influenced by climate change and vulnerability to cyberattacks have raised concerns about the grid's reliability. Emissions from electricity generation are a substantial driver of climate change, and there is an urgent need to transition away from fossil fuel–based power. But a June 2022 Supreme Court ruling constrained the ability of the Environmental Protection Agency (EPA) to regulate emissions from power plants, which means the grid could continue to rely on fossil fuels. Meanwhile, the rise of renewable energy and so-called distributed generation, or the ability of individual homes and businesses to produce their own power, has placed the traditional grid under increasing pressure. It is losing customers at the same time that its aging infrastructure requires a major and expensive overhaul. A sweeping infrastructure law passed in late 2021 provides about $65 billion for grid improvements, and the Joe Biden administration has started working with states to accelerate upgrades.

Keywords: *US, Power grid, Demand, Supply, Distribution*

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Background to the Study

How does the grid work?

The U.S. electric grid dates back to 1882, the year that Thomas Edison unveiled the country's first power plant at the Pearl Street Station in lower Manhattan. While the grid has expanded from Edison's original fifty-nine customers to hundreds of millions of users, for decades its basic structure has remained much the same. According to the U.S. Energy Information Administration (EIA), fossil fuel–based power plants burning coal, oil, or natural gas create about 60 percent of the nation's power, while nuclear power accounts for nearly 20 percent. Electricity is sent across long distances using high-voltage transmission lines, and local facilities known as substations convert that high-voltage power to a lower voltage (a process called "stepping down") and distribute it to nearby homes and businesses. Taken together, the grid has been called the largest machine in the world, comprising eleven thousand power plants, three thousand utilities, and more than two million miles of power lines. In practice, however, there are three separate U.S. grids, or self-contained interconnections of power production and transmission. These are the Eastern, Western, and Texas interconnections. Due to the high costs of constructing all of this infrastructure, electricity transmission and distribution is considered a "natural monopoly," meaning that only a company large enough to control an entire market will generally be able to afford the necessary investments. As a result, most energy utilities are granted monopoly control over a local market with the mandate to provide low-cost, reliable energy as a public good. To enforce this mandate, utilities are either publicly owned or, more commonly, heavily regulated by state regulatory commissions that set the prices utilities are permitted to charge consumers.

How Does Greening the Grid Factor into U.S. Climate Goals?

Decarbonizing the grid, or generating energy from renewable sources instead of fossil fuels, is central to President Biden's climate goals, particularly his pledges to halve U.S. emissions from its 2005 level by 2030 and achieve a carbon-free power sector by 2035. About a quarter of U.S. greenhouse gas emissions come from burning fossil fuels for electricity. The power sector relies mainly on coal and natural gas to produce electricity. Burning these fossil fuels releases greenhouse gases, which trap heat and warm the planet.

Cutting emissions through electrification, which includes the transition to electric vehicles, will require a clean, reliable energy grid. Already, renewable energy production is growing rapidly. Solar, wind, and other renewable energy sources generated 20 percent of U.S. electricity in 2021, according to the EIA, and that share is expected to double by 2050. But to fully phase out fossil fuels, experts say a range of policies will be needed: this includes subsidizing research and development (R&D) for clean energy production and storage; and putting a price on emissions, such as a carbon tax.

How are Renewable Energy Sources Affecting the Grid?

The increased use of renewable energy poses challenges for grid operators. For example, the variability of the wind and sunlight make forecasting the supply and demand of electricity more difficult. The increasing number of households installing their own energy sources also presents issues. In contrast with the grid's original, one-way economic model, decentralized forms of energy production known as “distributed generation” are on the rise. Solar power production, including from home installations, has grown exponentially over the past decade, reaching 126.1 gigawatts (GW) of total capacity in 2022 enough energy to power more than twenty-three million homes. The trend is expected to continue. For example, electric car and clean energy company Tesla sells battery systems and solar panels packaged together as an alternative to the traditional grid. Utilities worry that distributed generation threatens their viability, particularly through the policy of “net metering.” Under net metering, first adopted by Minnesota in 1983, regulators require that utilities buy any excess power back from solar users at the full retail rate of electricity. Utilities argue that by receiving the full retail price of electricity, those users effectively avoid paying for grid upkeep even though the vast majority of homes and businesses that use distributed generation still rely on the grid, using it at times when the sun isn't shining or the wind isn't blowing. Those customers should still have to contribute, utilities say. Utilities warn that as solar use spreads and they lose more customers, they will have to raise prices, which in turn will push more people to go “off grid” a process known in the industry as the “utility death spiral.” It is unclear how much costs have shifted so far; an analysis by the Rocky Mountain Institute, a nonpartisan energy research organization, estimated that utilities in the Northeastern United States could lose up to $15 billion by 2030 as customers switch to solar power.

This increasing pressure on the grid comes at a time when, as energy expert Brian Warshay points out, the U.S. economy is more dependent on reliable, affordable electricity than ever before. Rising prices would hurt consumers and businesses, while utilities that are unable to make the billions of dollars' worth of needed investments could suffer more power outages which are estimated to cost tens of billions of dollars annually. To make up for lost revenue, some utilities have imposed new fees or restrictions on solar users. Another option is for utilities to get into the renewable business themselves. The largest U.S. utility, North Carolina's Duke Energy, began integrating wind and solar into its network in 2007. Much of the increase in solar power capacity has been driven by utilities, rather than homeowners.

How is the Grid Regulated?

Historically, most utilities controlled everything from the power plant all the way to the household electrical outlet. In 1978, Congress passed legislation to partially deregulate the sector, allowing for non-utility power generators to enter the market. The 1992 Energy Policy Act allowed further deregulation, especially the separation of power generation (wholesale markets) from transmission and distribution (retail markets). The ostensible purpose of these efforts was to promote competition and lower energy prices. However, the 2000–2001 California energy crisis [PDF] raised questions about such restructurings after state reforms led to higher prices, energy shortages, and the near bankruptcy of major utilities. Today, oversight of the grid is the responsibility of a patchwork of federal and state authorities. The 2005 Energy Policy Act designated the Department of Energy's Federal Energy Regulatory Commission (FERC) as the primary authority over power generation and transmission across the United States. However, jurisdiction of local-level retail power distribution, which actually delivers that power to end users, remains in the hands of state and municipal governments. Due to growing concerns about climate change, the EPA has attempted to regulate greenhouse gas emissions from the grid. The 1970 Clean Air Act gave the agency authority to limit air pollution. Under the auspices of that law, the Barack Obama administration tried to implement sweeping standards for power plant emissions with its 2015 Clean Power Plan, part of a larger effort to move the power sector away from coal and gas and toward renewable sources of energy. But the plan faced court challenges and never took effect. In June 2022, the Supreme Court ruled that Congress had not granted the EPA the authority to impose sector-wide rules for power plant emissions, though the EPA can continue to regulate emissions from individual plants.

What is the Smart Grid?

The "smart grid" refers to a suite of technologies that allow for greater responsiveness in connecting power producers and consumers. According to the U.S. Department of Energy, which has made building a smart grid a national policy goal, it comprises "digital technology that allows for two-way communication between the utility and its customers," as well as sensing along transmission lines. A smart-grid system can increase reliability and reduce power outages. Special meters on houses and businesses and sensors along transmission lines can constantly monitor demand and supply, while mailbox-sized devices known as synchrophasors measure the flow of electricity through the grid in real time, allowing operators to foresee and avoid disruptions. Smart appliances can "talk" to the grid and shift electricity use to off-peak times, which eases the burden on the grid, ultimately lowering prices and helping to avoid blackouts. Decentralized "microgrids" can be paired with new battery technology to allow power to flow to communities even when severe weather or other outages afflict the broader power system. Since 2010, the Department of Energy has invested billions of dollars in smart-grid infrastructure, and by 2017, nearly half of U.S. electricity customers had smart meters installed. By 2020, more than one hundred million smart meters had been installed, according to the EIA, and the number is expected to grow.

What are the Grid's Vulnerabilities?

Extreme weather events, often exacerbated by climate change, are increasingly a top concern. Hurricanes, blizzards, floods, heat waves, wildfires, and even solar flares can overwhelm aging power lines. (The average age of power plants is over thirty years old, while power transformers are, on average, more than forty years old.) In addition, most of the grid infrastructure is built above ground, which is cheaper to construct but more vulnerable. Increased variability due to climate change will not only increase demand for energy, but also reduce the efficiency of its production and transmission.

The early 2021 power failures in Texas were a case in point. Temperatures in the state dropped to thirty-year lows, disabling multiple sources of power generation just as demand for heating surged. The result was widespread blackouts that left millions of people without power during a devastating winter storm; dozens of people died. The state is now rethinking its hands-off approach to energy regulation, which allows utilities to avoid winterizing their equipment. In California, meanwhile, rising temperatures contributed to rolling blackouts in the summer of 2020, the state's first such outages in nearly two decades.

The problem is that the energy grid was designed for a world that no longer exists, says CFR Senior Fellow Alice C. Hill, who was senior director for resilience policy on the National Security Council during the Obama administration. "All of these systems were built just on the assumption of a certain range of extremes," she says. "That was a safe way to build because our climate was stable." As climate change makes extreme weather events increasingly frequent and severe, "basing it on past patterns leaves you highly vulnerable," she adds. To prevent future disasters, utilities will need to harden grid infrastructure, Hill says. That could include burying power lines or making sure that aboveground poles are fire-resistant. The costs of inaction are high, she says, noting that the Texas blackouts are estimated to have cost the state $90 billion. Renewable energy sources have their own vulnerabilities: solar power production in Australia fell sharply during devastating wildfires in 2019 and 2020 as smoke and soot blocked out the sun. Additionally, the growing reliance of the grid on digital systems increases the possibility of cyberattacks. Recent reports from the U.S. Government Accountability Office warn that the grid's generation, transmission, and distribution systems are all increasingly vulnerable to cyber intrusions. Since the 1970s, grid operators have relied on electronic industrial control (IC) centers that are generally unsecured against malware such as the Stuxnet virus, which targeted Iranian nuclear facilities in 2010. In 2019, the U.S. grid was hit by a cyberattack for the first time, though it did not cause any power disruptions. In May 2021, a ransomware attack forced one of the largest oil pipelines in the United States to temporarily close down.

Conclusion/Recommendation

President Biden has proposed major investments in modernizing the U.S. energy grid. The bipartisan infrastructure law he signed in November 2021 includes $65 billion for grid modernization, including new transmission lines, smart grid and clean energy technologies, and cybersecurity. The Department of Energy launched an initiative in 2022 to collaborate with states and give them some of the funding from the law. However, Biden's plans could be complicated by the challenges of laying the new transmission lines, which aim to add renewable energy capacity to the grid as well as improve reliability by allowing grid operators to more effectively route power to where it's needed. Resistance from states and localities can delay projects for years or even kill them altogether. For example, it took fifteen years for the Trans West Express Transmission Project - a seven-hundred-mile line that will carry wind power from Wyoming to Arizona, California, and Nevada to receive permits. With such delays likely, experts say sweeping upgrades could remain out of reach for years. In addition, Biden has struggled to pass more ambitious climate legislation, and the June 2022 Supreme Court ruling could constrain further executive actions to reduce emissions.

Reference

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