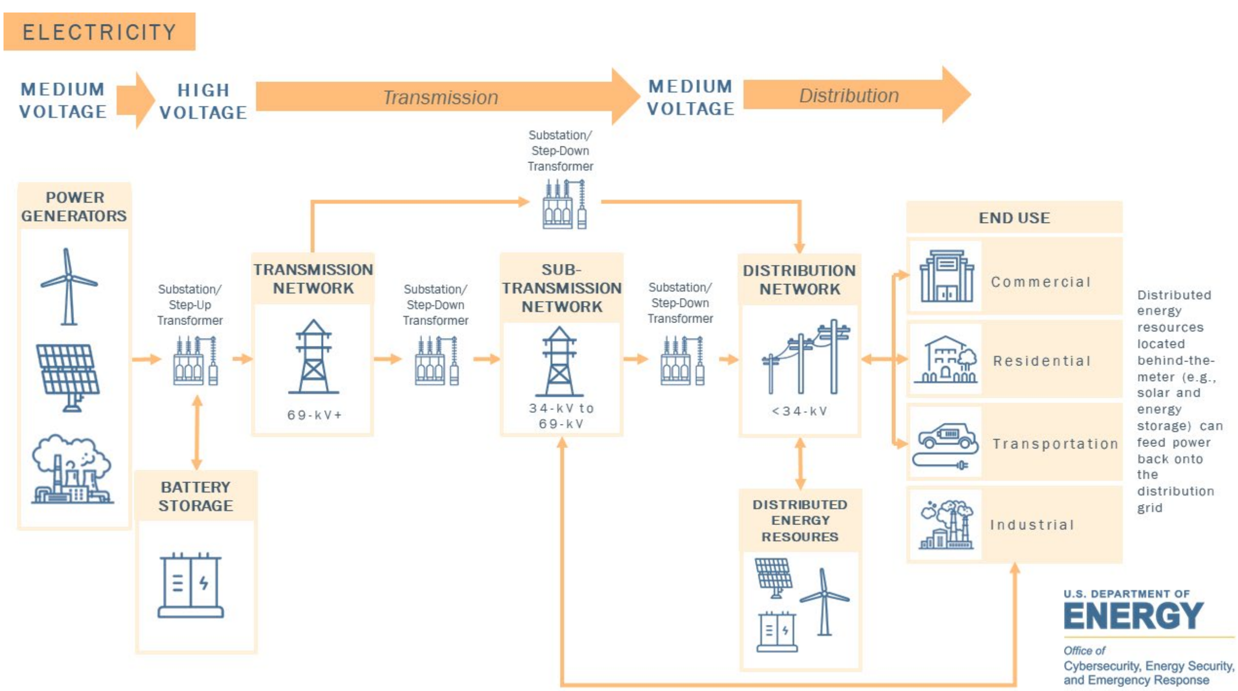
How It Works: Electric Transmission & Distribution and Protective Measures

The electricity supply chain consists of three primary segments: generation, where electricity is produced; transmission, which moves power over long distances via high-voltage power lines; and distribution, which moves power over shorter distances to end users (homes, businesses, industrial sites, etc.) via lower voltage lines. Exhibit 1 provides an overview of this supply chain. The focus of this primer is on the transmission and distribution segments: the power lines, substations, and other infrastructure needed to move power from generation sources to end users. Although most power flowing on the transmission and distribution grid originates at large power generators, power is sometimes also supplied back to the grid by end users via Distributed Energy Resources (DER)—small, modular, energy generation and storage technologies that provide electric capacity at end-user sites (e.g., rooftop solar panels).

Exhibit 1. U.S. Electric System Overview



Source: U.S. Department of Energy

Substations

Substations serve as critical nodes connecting generation, transmission, and distribution networks. While substations are used for several distinct system functions, most utilize electric power transformers to adjust voltage to match varied voltage requirements along the supply chain. A substation generally contains transformers, protective equipment (relays and circuit breakers), switches for controlling high-voltage connections, distribution feeders, electronic instrumentation to monitor system performance and record data, and fire-fighting equipment.

Transmission Networks

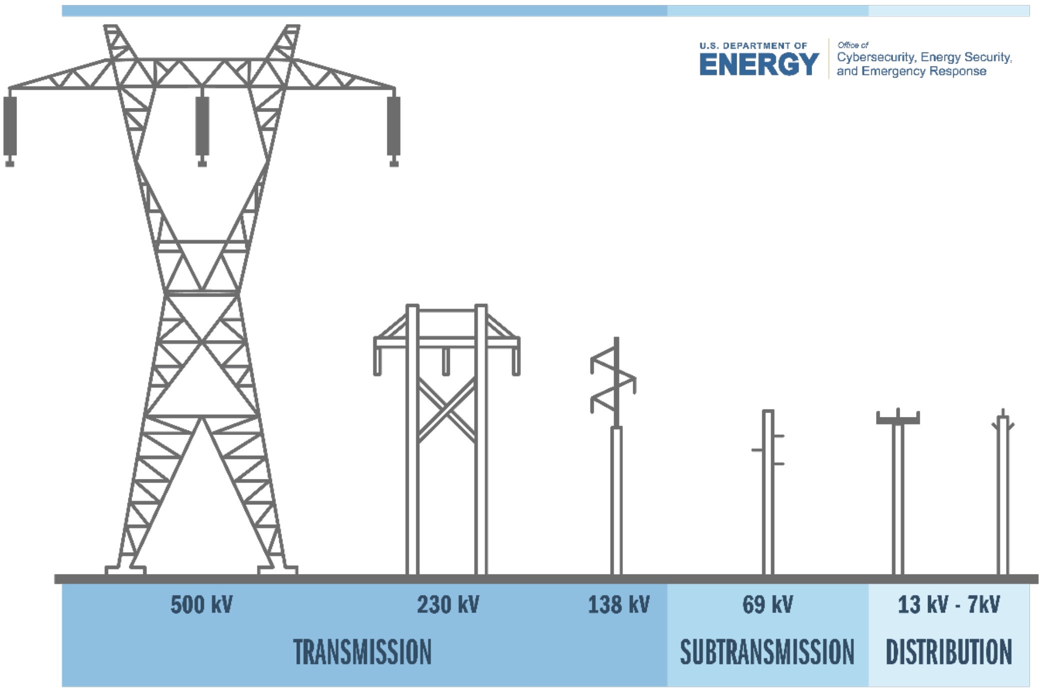
Electricity transmission networks consist of high-voltage transmission lines that interconnect various regions and demand centers. In some areas, individual utilities operate their own transmission networks. In other parts of the country, coordination, control, and monitoring of single-state or multi-state electric grids are managed by independent entities, known as Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs). Individual investor-owned utilities (IOUs) are regulated by state public utility commissions (PUCs), while RTOs and ISOs are regulated by the Federal Energy Regulatory Commission (FERC) but may also be subject to state regulation.

Electricity transmission networks are designed to minimize power loss over long distances by transmitting power at high voltage. Power plants generally produce electricity at low voltages (5–34.5 kilovolts (kV)). “Step up” substations are used to increase the voltage of generated power to allow for transmission over long distances. Typical transmission voltages include 115 kV, 138 kV, 230 kV, 345 kV, 500 kV, and 765 kV. Sub-transmission networks, used to transmit power over shorter distances, use 34 kV, 46 kV, or 69 kV. Before reaching the distribution network, “step down” substations are needed to reduce voltage. Transmission networks consist of various infrastructure components, including steel superstructures, high -voltage conductor cables, and high-voltage substations. The size of the steel superstructures depends on the power rating of the transmission lines being supported (See Exhibit 2).

Did You Know?

Transmission lines are rated both by voltage and by power capacity. The voltage rating specifies the maximum amount of voltage the line can withstand before failure and is typically used to describe individual system components. A transmission line’s power capacity, by contrast, specifies the maximum steady state power (current) the system is able to maintain under given conditions and is typically used to describe a connected system that depends on individual components. Power ratings can be expressed in terms of electric current (measured in units of amps) or power-carrying capacity (measured in units of megawatts (MW) or mega-volt amps (MVA).

Exhibit 2. Electric Power Line Structures by Type



Source: U.S. Department of Energy. A non-exhaustive representation of the types of equipment involved in electricity transmission and distribution.

Distribution

The power distribution system is the final stage in the delivery of electric power to individual customers. Distribution grids are managed by IOUs, Public Power Utilities (municipals), and Cooperatives (co-ops) that operate both inter- and intra-state. IOUs are typically regulated by state PUCs. Municipal and co-op utilities are not traditionally regulated by PUCs, but by local government bodies or elected utility boards. Distribution systems, typically rated below 34 kV, can tie directly into high-voltage transmission networks or be fed by sub-transmission networks via “step down” substations. Distribution circuits, also known as express feeders or distribution main feeders, carry low-voltage power from the distribution substations to transformers closer to customer sites that further reduce the voltage and feed power to secondary circuits that serve residential and commercial customers.

Threats to Electric Transmission & Distribution Infrastructure

Damage to transmission and distribution networks can result in customer power outages, ranging from localized neighborhood outages to widespread, multi-state events. Power outages can impact economic activity and disrupt critical infrastructure and essential services, such as hospitals and water treatment plants.

Threats to electric transmission and distribution infrastructure include natural/environmental threats, such as hurricanes, thunderstorms, winter storms (ice and/or snow), extreme heat, droughts, wildfires, floods, sea-level rise, earthquakes, geomagnetic (solar) storms, and contact with wildlife and vegetation; and human threats, such as vandalism or cyber attacks.

Individual utilities and transmission line operators manage threats to the electric grid to maintain and improve system reliability through both hardening measures that reduce the vulnerability of infrastructure to threats, and through maintenance and mitigation measures that improve the ability of operators to identify and respond to disruptions. Grid operators use risk assessments to enable cost-effective design and deployment of risk management solutions and technologies to enhance reliability,

The North American Electric Reliability Corporation (NERC) and state PUCs are responsible for planning, implementing, and enforcing operational reliability standards for the grid. NERC is the Electric Reliability Organization (ERO) for North American bulk power system and is overseen by FERC and governmental authorities in Canada. NERC standards are designed to lower risks for all potential events through use of best practices and technologies that reduce/mitigate risk or enable adequate recovery time.

For investor-owned utilities, investments, including resiliency investments that go beyond the NERC standards, are assessed by state PUCs as part of the utility rate cases. Funding for energy resilience projects is also available from federal programs such as FEMA's Building Resilient Infrastructure Communities (BRIC) or Hazard Mitigation Grant Program (HGMP) funds and DOE's Bipartisan Infrastructure Law funds. For these opportunities, state energy and/or emergency officials will collaborate or coordinate with industry partners.

Operations and Maintenance

Routine maintenance can improve the ability of operators to identify and respond to disruptions, reducing outage durations by enabling faster repair and/or mitigation measures. A few examples are below.

Vegetation Management

During major storms, distribution lines and poles primarily fail due to fallen trees rather than the direct impact of wind. Utilities regularly conduct vegetation management for distribution systems including clearing overhang and removing dead or dying trees. Where possible, utilities may seek to expand the existing rights-of-way (ROW) for distribution infrastructure to allow for additional vegetation management. New remote sensing technologies, such as Light Detection and Ranging (LiDAR) can be used to enable more effective vegetation management.

Automated Distribution Management Systems

Utilization of smart grid remote sensors and fiber-optic communication technologies enables utilities to quickly detect and pinpoint disruptions and facilitate automatic or manual corrective actions, such as isolating damaged equipment to minimize the number of customers affected, or rerouting power to undamaged circuits and feeders. New technologies such as artificial intelligence, machine learning, and predictive modeling with real-time data can be used to identify both early warning signs of potential equipment failure, and downed wires.

Drones for Asset Inspection

The use of drones to inspect transmission and distribution infrastructure allows for safer and more frequent inspections, enhanced asset information, reduced operational costs and failure rates, and extended asset lifetimes. The use of drones to inspect infrastructure after storms and other disruptive events can speed up damage assessments and resource deployments, reducing restoration timelines.

Advanced Metering Infrastructure (AMI)

AMI is an integrated system of smart meters, communications networks, and data management systems that enables bi-directional communication between utilities and customers. Smart meters can provide near-real-time visibility into customer outages and help utilities allocate resources and restoration activities more efficiently.

Grid Hardening Measures

System hardening refers to making transmission and distribution infrastructure less susceptible to damage or failure from hazards. Common hardening measures include:[1] [2] [3]

Undergrounding

Burying power lines protects lines from exposure to external threats including high winds and falling branches, wildfires, extreme heat or cold, icing, dirt/dust/salt accumulation, and animals; but may increase exposure to flooding, depending on location. Although undergrounding reduces outage frequency, when there is a disruption, outage duration may increase due to the additional time needed to identify problems, dig up, and then re-bury damaged equipment. Although widespread undergrounding of transmission and distribution infrastructure is costly, some utilities may bury lines serving critical infrastructure and select backbone circuits located in areas at high risk for high winds or wildfires.

Structural Upgrading

Upgrading poles and other structures to stronger materials may help them withstand storm impacts. Distribution poles can be upgraded from wood to steel and transmission structures can be upgraded from aluminum to galvanized steel lattice or concrete. Less expensive options include upgrading crossarm materials or adding guy wires, trusses, or other structural supports. Securing structures with guy wires may be required for transmission and distribution structures in flood-prone areas.

Dead-End Transmission Towers

High-voltage transmission lines are supported by structures, known as transmission towers. Suspension towers are typically used when the transmission line continues along a straight path. Dead-end towers (also called anchor towers or anchor pylons) are self-supporting structures made with heavier material than suspension towers. Dead-end towers are used at the end of a transmission line; where the transmission line turns at a large angle; on each side of a major crossing such as a large river, valley, or highway; and at intervals along straight segments to provide additional support. When weaker suspension towers are compromised or topple, the stronger dead-end structures can stop a domino effect that takes down multiple towers. Reducing the spacing between dead-end structures can limit the impacts of domino effect failures.

Breakaway Service Connectors

A breakaway service connector is designed to disconnect when the power line it is attached to is pulled by a falling limb or other debris. This avoids damage caused when a service wire is pulled down in a way that damages the meter receptable. Although the electric meter is typically owned by the utility, the meter receptables that attach the meter to the house are not owned by the utility, and a private electrician is needed to first make repairs, delaying service restoration.

Flood Protection

Water damage from flooding can have severe and long-term effects on electrical equipment, particularly electric substations. Saltwater damage can cause corrosion with prolonged exposure, and clean-up is particularly lengthy and labor-intensive. Flood protection at substations in low-lying or flood-prone areas can be enhanced by elevating substations on a raised platform, installing sheet pile floodwalls or other barriers to prevent water incursion, managing the environment to preserve natural barriers to flooding, installing storm-water pumps, installing submersible equipment, or simply re-locating assets outside of flood-prone areas.

Fire Protection

In some areas of the country, utilities are making investments to both protect grid equipment from wildfire damage and to prevent equipment from starting wildfires. Fire-protection measures may include installing fire resistant steel poles, composite crossarms, and covered conductors, or pre-treating assets near a wildfire with fire-retardant coatings or wrapping assets in fire-retardant sheaths. To protect assets from starting a fire, utilities may install line-break protection systems to automatically de-energize broken power lines or reconductor wires to increase transmission capacity, thus reducing the propensity for high loads and line sag.

Physical Security

Protection against human threats (e.g., trespassing, vandalism, sabotage, etc.) at substations can be strengthened through a layered security strategy and physical security protective measures such as upgrading fencing from typical chain-link to engineered perimeter barriers; installing cameras, intrusion detection systems, and other security equipment; and by installing ballistic shielding or obscuring sightlines into substations, making it more difficult to target critical substation components with gunfire.

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[1] https://www.oe.netl.doe.gov/docs/HR-Report-final-081710.pdf
[2] https://www.eei.org/issuesandpolicy/transmission/Documents/Value%20of%20Transmission%20-%20Resilience%202020.pdf
[3] https://www.tdworld.com/vegetation-management/article/20962556/hardening-the-system