



Track: The Power Connection: Electric Generation for Gas Utilities

Unit #4: Electricity Delivery Mechanisms

Presentation Outline

- Electrical Transmission
- Grid Infrastructure
- Additional Management Strategies
- Modern Grid Advancements
- Interconnection Independencies
- Balancing the Grid



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Electric Transmission & Distribution

Moving electricity is much like any other type of product delivery.

To move electricity long distances, it must be modified or **“packaged”** in a way that is easily transportable in large amounts.

In a complex network, it may need to go through **several stops** along its journey to reach a destination area.

To deliver to customers, it must be **“unpacked”** to a form that allows for easy use and distribution.



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Electric Transmission & Distribution

Transmission – Movement of electrical power over long distances. Electricity transmission networks consist of high-voltage transmission lines that interconnect various regions and demand centers.

- Designed to minimize power loss over long distances.

Distribution – Delivery of electrical power to individual customers via a localized grid. Distribution networks convert high-voltage energy from transmission networks to lower voltages that can be more readily used.

- Designed to make customer connection and use easy.



Source: U.S. Department of Energy (Nov 2023): How It Works: Electric Transmission and Protective Measures
https://www.energy.gov/sites/default/files/2023-11/FINAL_CESER%20Electricity%20Grid%20Backgrounder_508.pdf



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Electric Transmission & Distribution

Electricity is “packaged” for transmission by converting to high-voltage AC power.

Why high voltage?

- More power sent over a smaller conductor (line).
- Lower energy losses to resistive heat in lines over long distances.

Why AC over DC?

- Easier conversion between voltages.
- Existing infrastructure supports it.
- Safer for switching (reduced arcing).



AC power transmission is the backbone of our energy grid.

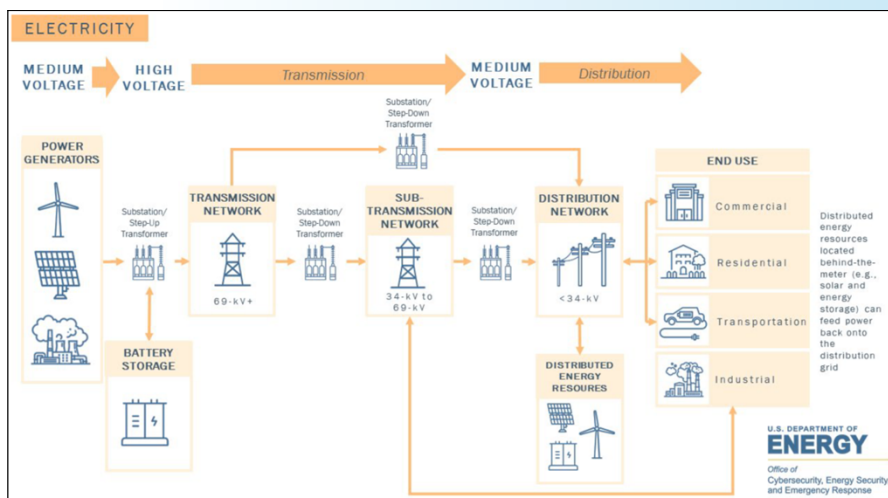
High Voltage Direct Current (HVDC) transmission has become more practical with technological advancements in recent years and is used for some newer infrastructure.



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Electric Transmission & Distribution



Source: U.S. Department of Energy (Nov 2023): How It Works: Electric Transmission & Distribution and Protective Measures
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Lines & Voltages

Transmission Lines:

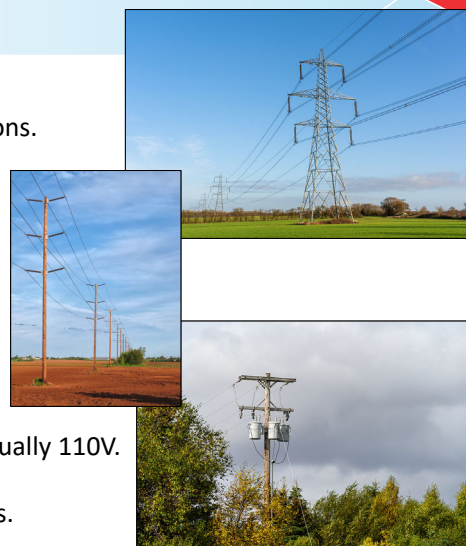
- From power sources to substations and between substations.
- Usually operate between 69kV and 735 kV.
- Large, robust structures and uninsulated lines.

Distribution Lines:

- From distribution substations to localized transformers.
- Usually operate at voltages below 34kV.

End-User Connections:

- From localized transformers to end-users.
- Usually operate at voltages below 1kV.
 - Homes are usually supplied 220V, and plug loads are usually 110V.
- Lines can be closer to each other.
- Smaller, less robust structures with robustly insulated lines.



Source: U.S. Department of Energy (Nov 2023): How It Works: Electric Transmission & Distribution and Protective Measures
https://www.energy.gov/sites/default/files/2023-11/FINAL_CESER%20Electricity%20Grid%20Backgrounder_508.pdf



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Lines & Voltages

High-voltage lines (transmission) are rarely buried due to:

- Cost over long distances.
- Heat dissipation needs when carrying large amounts of power.
- Difficulty of maintenance underground.
- The need for separate high-voltage lines to be kept far apart.

Low-voltage lines (distribution) are more regularly buried due to:

- Proximity to the public and associated hazards.
- Lower heat generation when carrying smaller amounts of power.
- The ability for lower-voltage lines to be buried together.



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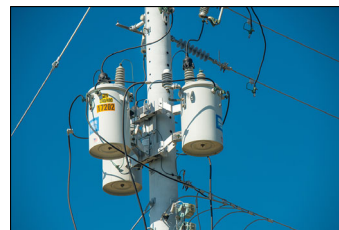
Transformers

Transformers convert power from one voltage to another, “stepping” it up or down. They can also convert three phase power to one phase for delivery.

Transformers work through the relationship between electric charges and magnetic fields.

- A change in direction of an electric charge creates a magnetic field.
- A change in direction of a magnetic field can induce an electric charge in a conductor.

A transformer harnesses the change in direction of charge of AC power to induce magnetic fields in a material, which in turn can be converted back to AC power in a separate circuit.



Source: <https://www.arcgis.com/apps/mapviewer/index.html?panel=gallery&layers=d4090758322c4d32a4cd002ffaa0aa12>
https://www.energy.gov/sites/default/files/2023-11/FINAL_CESER%20Electricity%20Grid%20Backgrounder_508.pdf



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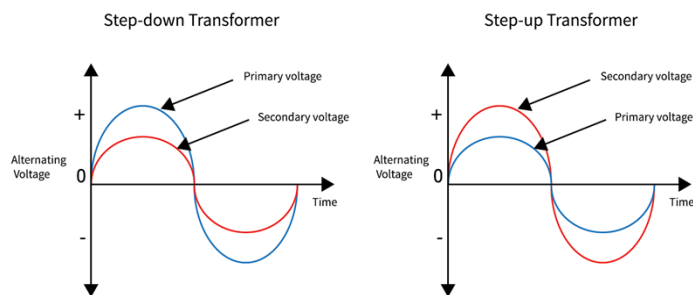
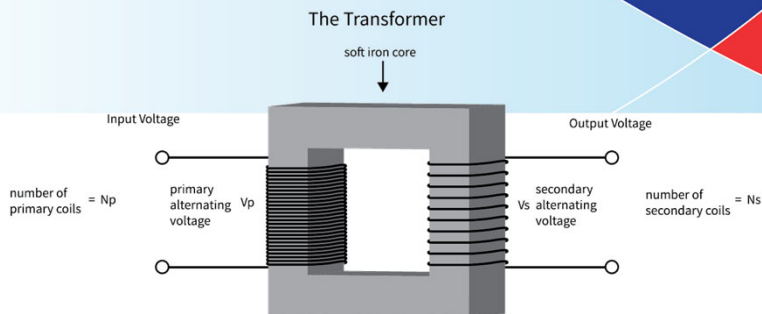
Transformers

Power = Voltage x Current

$$P = V \times I$$

$$P = V \uparrow \times I \downarrow$$

$$P = V \downarrow \times I \uparrow$$

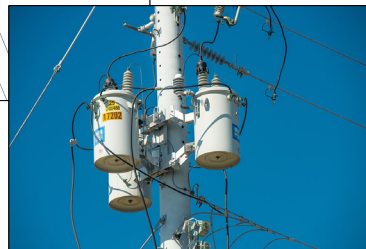
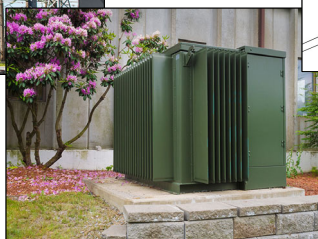


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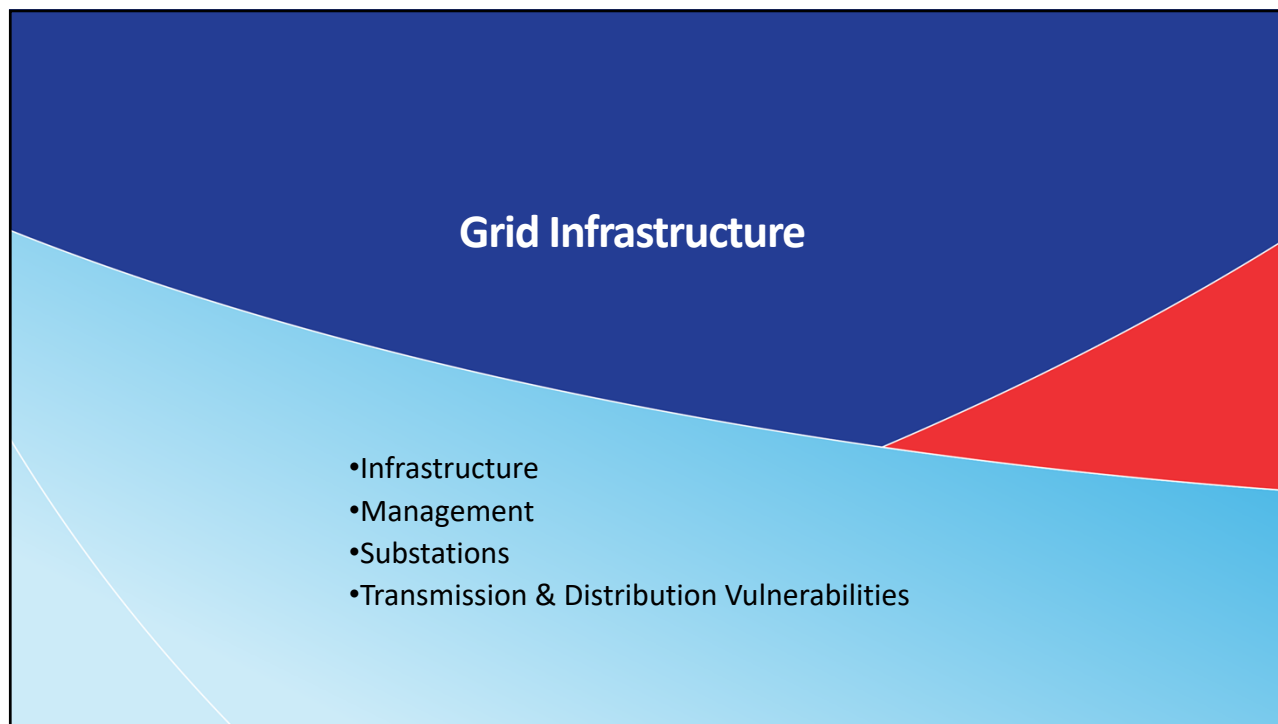
Transformers

Transformers come in many shapes and sizes and are distributed all along the grid.:



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Grid

Grid – “An electrical grid is an interconnected network for electricity delivery from producers to consumers. Electrical grids consist of power stations, electrical substations to step voltage up or down, electric power transmission to carry power over long distances, and finally electric power distribution to customers.”

– Wikipedia

Components

Power Plant/Station – A facility or location that generates electricity.

Electrical Substations – Stations that perform electrical grid-supporting functions in support of electrical transmission, distribution, collection, conversion, and switching.

Transmission Lines – High-voltage power lines that carry electricity over long distances.

Distribution Lines – Lower-voltage power lines that carry electricity over short distances to customers.

Meter – Devices that connect end-user to distribution lines and report on electrical usage for the purposes of monitoring and billing.



Source: https://en.wikipedia.org/wiki/Electrical_grid
<https://en.wikipedia.org/wiki/Substation>



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Grid Infrastructure

The electrical grid has many different physical and non-physical components:

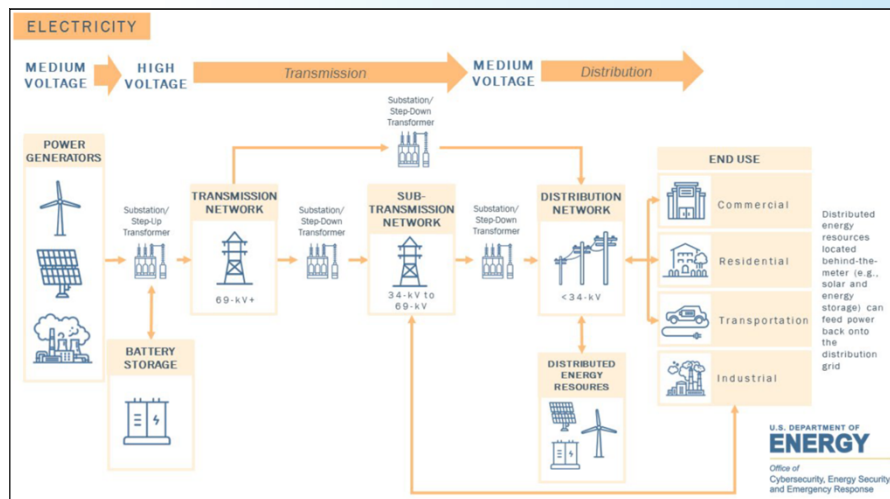
- Power Plants
- Transmission & Distribution Lines
- Substations
- Energy Storage
- Control Systems & Software
- Sensors
- Communication Infrastructure
- Meters
- Operation, Support, and Maintenance Staff
- More!



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Grid Infrastructure



Source: U.S. Department of Energy (Nov 2023): How It Works: Electric Transmission & Distribution and Protective Measures
https://www.energy.gov/sites/default/files/2023-11/FINAL_CESER%20Electricity%20Grid%20Background%20508.pdf



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Grid Management

The electrical grid must be actively managed to maintain operation. Management activities include:

- **Monitoring & Control:** Using **SCADA** (Supervisory Control and Data Acquisition) **Systems**, staff can monitor grid conditions and make appropriate changes.
- **Load Balancing:** Grid staff must monitor loads customers put on the grid in real time and manage energy sources and corrective equipment in response.
- **Preventative Maintenance:** Grid infrastructure is extensive and complex. Preventative maintenance plans must be executed on an ongoing basis to prevent failures.
- **Repair Activities:** When failures do occur, plans, equipment, and staff must all be available to respond at a moment's notice.
- **Disaster Response:** Disaster response contingencies must be in place to restore service in a quick, safe, and organized manner.



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Substations

Substations are locations that perform electrical grid-supporting functions in support of electrical transmission, distribution, collection, conversion, and switching.

Step-Up Transmission Substation: Uses step-up transformers to increase voltage for transmission.

Step-Down Transmission Substation: Uses step-down transformers to decrease voltage for more local transmission to distribution substations.

Distribution Substation: Uses step-down transformers to decrease voltage for distribution. These may be above or below ground.

Source: OSHA: <https://www.osha.gov/etools/electric-power/illustrated-glossary/sub-station>

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Substations

Substation functions can include:

- *Change voltage from one level to another*
- *Regulate voltage to compensate for system voltage changes*
- *Switch transmission and distribution circuits into and out of the grid system*
- *Measure electric power qualities flowing in the circuits*
- *Connect communication signals to the circuits*
- *Eliminate lightning and other electrical surges from the system*
- *Connect electric generation plants to the system*
- *Make interconnections between the electric systems of more than one utility*
- *Control reactive kilovolt-amperes supplied to and the flow of reactive kilovolt-amperes in the circuits*

- OSHA



Source: OSHA: <https://www.osha.gov/etools/electric-power/illustrated-glossary/sub-station>



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Substations

Substations may or may not be staffed depending on the purpose and complexity. Substations host equipment such as:

- Electrical lines
- Transformers
- Switchgear, circuit breakers, fuses, and disconnect switches
- Sensors
- Meters
- Control panels
- Lightning arrestors
- Frequency changers
- Capacitors



Source: OSHA: <https://www.osha.gov/etools/electric-power/illustrated-glossary/sub-station>



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Substations

Electrical **switchgear** at substations helps control, protect, and isolate equipment and portions of the grid. This general term includes components such as:

- Switches
- Circuit breakers
- Fuses
- Lightning arrestors
- Control panels
- Transformers
- And more.

Switchgear allows workers to disconnect portions of the grid for maintenance, protects the grid by isolating faults



By Novoklimov - Own work, CC BY 4.0,
<https://commons.wikimedia.org/w/index.php?curid=157627995>



Source: Wikipedia: <https://en.wikipedia.org/wiki/Switchgear>



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Transmission & Distribution Vulnerabilities

Electrical transmission and distribution is complex and easily interrupted. To support the near-constant level of service expected and needed by end-users, the system must be built robustly and protected against **environmental, human, and virtual threats**.

Environmental vulnerabilities include:

- Damage from natural disasters like hurricanes, wildfires, and earthquakes.
- Damage and wear caused by weather including rain, wind, and lightning.
- Damage from animals through nesting, touching, and gnawing.
- Damage from plants like vines, trees, and brush.
- Degradation of materials from rust, rot, and sun exposure.
- Natural aging of materials over time.



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Transmission & Distribution Vulnerabilities

Human vulnerabilities include:

- Both unintentional and intentional damage from vandalism and sabotage.
- Damage from accidents such as car crashes or construction accidents.
- Equipment failures due to faulty materials or construction.

Virtual vulnerabilities include:

- Cyber vandalism and sabotage.
- Data security breaches.
- Faulty software and code.



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Additional Management Strategies

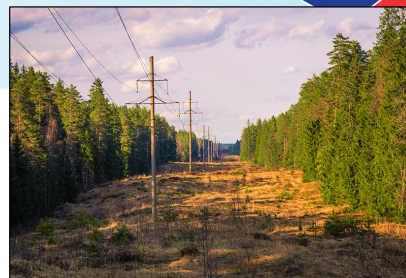
Vegetation Management

Vegetation such as trees, vines, and shrubs can be a danger to electrical infrastructure. Branches can fall on and short power lines, trees can topple power poles, vines can cause add weight to lines, and shrubs can grow into ground equipment.

Vegetation management is an important part of prevention and maintenance.

- Trees are removed entirely from transmission lines.
- Trees are trimmed around local distribution lines, and dead or dying trees removed.
- Regular inspections are carried out equipment and poles both manually and remotely.

ROW or “**Right of Way**” is a utility’s ability to manage areas around their transmission and distribution infrastructure.



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Automated Distribution

The advancement of communication, computer, and sensor equipment over the last few decades has allowed grid operators to include more automation in their grid management strategies. **Automated distribution** allows utilities to:

- Quickly detect and locate disruptions.
- Automatically isolate issues and re-route power.
- Automatically respond to issues or facilitate manual responses.
- Better monitor equipment to predict failure.
- Manage some sites remotely.



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Asset Inspection

Regular asset inspection is important for grid operators to ensure their infrastructure is reliable, resilient, safe, cost-effective, and compliant. This is done through:

- Visual inspections and drone imagery.
- Testing through thermal imaging, ultrasonic testing, etc.
- Satellite imagery and LiDAR (Light Detection and Ranging) equipment.
- Remote monitoring through sensors and automation.

Poles must be replaced as they rust and rot, lines must be replaced when damaged, transformers must be replaced as they age...



Source: U.S. Department of Energy: How It Works: Electric Transmission & Distribution and Protective Measures
https://www.energy.gov/sites/default/files/2023-11/FINAL_CESER%20Electricity%20Grid%20Backgrounder_508.pdf



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Grid Hardening

Grid hardening is the term for activities that make transmission and distribution more resistant to failure from hazards. Methods include:

- **Undergrounding** – Burying lines to protect from threats.
- **Structural Upgrading** – Upgrading poles to stronger materials.
- **Dead-End Transmission Towers** – Towers in line with and at the end of straight line runs built to stop a domino effect if a tower or set of towers is compromised.
- **Breakaway Service Connectors** – Disconnect points that break from a service meter if a line is pulled by something like a falling branch, preventing damage to the meter equipment.
- **Physical Security** – Fencing, barriers, cameras, obscured sightlines into substations, etc.
- **Flood Protection** – Elevated platforms, floodwalls near water, preservation of natural flood barriers, stormwater pumps, relocating out of flood-prone areas.
- **Fire Protection**



Source: U.S. Department of Energy: How It Works: Electric Transmission & Distribution and Protective Measures
https://www.energy.gov/sites/default/files/2023-11/FINAL_CESER%20Electricity%20Grid%20Backgrounder_508.pdf



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Fire Protection

Fire protection includes both measures to protect grid equipment from fires and prevent grid equipment from starting fires. Measures include:

- Fire resistant steel poles.
- Composite crossarms.
- Covered conductors.
- Pretreating assets near active wildfires with fire-retardant coatings or wrapping in fire retardant sheaths.
- Line-break protection systems to automatically de-energize broken lines.
- Reconductoring older lines to increase capacity and update to stronger materials.



Source: U.S. Department of Energy: How It Works: Electric Transmission & Distribution and Protective Measures
https://www.energy.gov/sites/default/files/2023-11/FINAL_CESER%20Electricity%20Grid%20Backgrounder_508.pdf



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Modern Grid Advancements

- Smart Grids
- Modern Delivery Systems
- Grid Modeling
- Energy Storage Investments

Smart Grids

Smart grid is the term that describes an electrical grid that integrates advanced communication technology and sensors to improve on system efficiency, reliability, and operation. The key component of a smart grid is two-way communication of system components, allowing both utilities and users to use real-time information to inform their decisions. Some other key elements are:

- **Smart meters** – Meters that can provide both users and grid operators detailed information on usage remotely.
- **Sensors and automation** – These allow the grid to be remotely monitored and automatically adjusted.
- **Demand response** – These are strategies that can encourage customers to load-shift in response to grid demand.



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Demand Response

Demand Response can prevent the need to run costly peaking plants and prevent brown-outs where service becomes unreliable.

Direct Load Control example – A utility can enroll a large pool of customers in a program where air conditioners are cycled on and off in coordinated batches during peak energy use times, preventing spikes in grid usage.

Time-Based Rates example – A utility can implement time-of-use pricing, critical peak pricing, or real-time pricing to push customers to shift their energy loads to off-peak periods.

Source: U.S. Department of Energy: <https://www.energy.gov/oe/demand-response>

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Modern Grid Delivery

Smart meters allow customers to interact more effectively with the electricity grid they rely on. Customers can see real time usage and potentially additional information such as:

- Current electricity rates in flexible rate structures and real-time cost of operating appliances.
- Their own energy usage patterns throughout each day, week, and season.
- Connected appliance information.
- Recommended energy savings strategies and their real impact.
 - Ex: The actual impact turning your specific thermostat in your specific building up or down by one degree based on past events, and the larger impact it has on hotter days.



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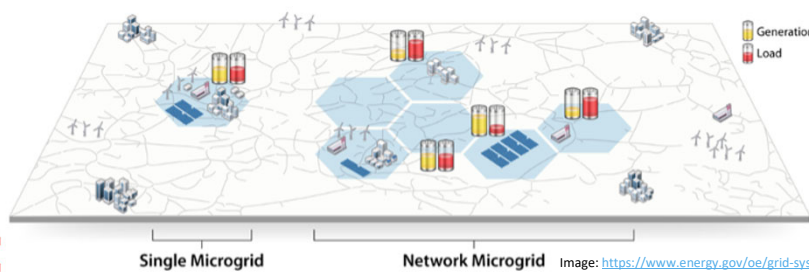
Microgrids

*"A **microgrid** is a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to operate in grid-connected or island mode.*

Advanced microgrids enable local power generation assets—including traditional generators, renewables, and storage—to keep the local grid running even when the larger grid experiences interruptions or, for remote areas, where there is no connection to the larger grid. In addition, advanced microgrids allow local assets to work together to save costs, extend duration of energy supplies, and produce revenue via market participation."

Source: [Microgrids | Grid Modernization | NREL](#)

- NREL



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Accurate Grid Modeling

Grid modeling is important for utilities to understand how their grid operates in both real and hypothetical scenarios. This allows operators to analyze historical events and trends, predict future events and trends, and stress-test without risking grid infrastructure. Modeling can incorporate:

- **Big data** – Historical and real-time data collected from across the industry.
- **Advanced mathematical theory** – Use mathematics to support models in new ways.
- **High-performance computing** - Model complex systems in ways impossible to do with traditional computing resources.



Source: U.S. Department of Energy: <https://www.energy.gov/oe/advanced-grid-modeling>



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Energy Storage Investments

Energy storage is a relatively new component of energy grids, and is under rapid development and implementation. Investing in energy storage gives electrical grids flexibility in **production** and **use**. It fills a key gap between the two and is critical for:

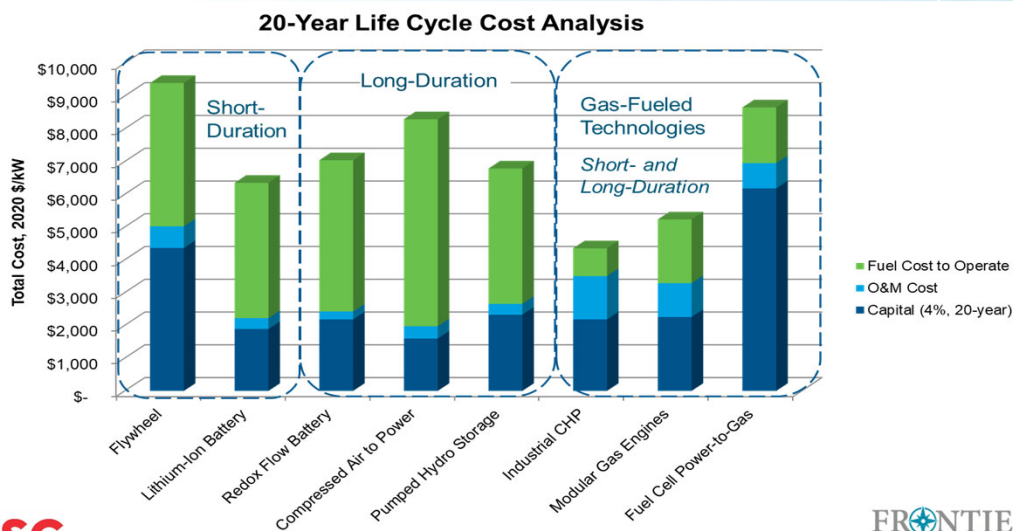
- Reducing energy losses.
- Reducing energy costs by shifting peak loads to periods of low demand when generation is cheaper.
- Ensuring grid stability during unexpected events.
- More effectively integrating intermittent power sources, such as wind and solar, into the grid.



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Electric Storage Investments



Source: Energy Storage Comparison Analysis with Gas-Fueled Technologies, ICF, September 2020

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Interconnection Interdependencies

- Regional
- State & Province

Regional Interconnections

North America has two major and three minor AC power grids. These are called **Interconnections**. All utilities in each interconnection are electrically tied together and operate their grids at a synchronized 60Hz frequency.

Major Interconnections:

- Eastern Interconnection
- Western Interconnection

Minor Interconnections:

- Texas Interconnection
- Alaska Interconnections
- Quebec Interconnection



Image: [Learn More About Interconnections | Department of Energy](https://www.energy.gov/learn-more-about-interconnections)

Source: U.S. Department of Energy (Mar 2025): <https://www.energy.gov/learn-more-about-interconnections>



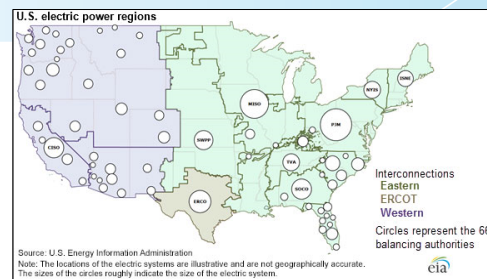
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State & Province Interconnections

The network structure of the interconnections helps:

- Maintain the reliability of the grid
- Allows generators to supply electricity to many load centers
- Provides redundancy



Source: U.S. Energy Information Administration
Note: The locations of the electric systems are illustrative and are not geographically accurate.
The sizes of the circles roughly indicate the size of the electric system.

A **balancing authority** ensures, in real time, that power system demand and supply are finely balanced. They also manage transfer of electricity in and out of their region and maintain reliability standards. In the US there are more than 60.

State and province interconnections allow individual states to regulate and manage their energy industries and grids separately from their neighbors, while being a part of a regional interconnection allows for grid stability, the buying and selling of power between states, and centralized management.



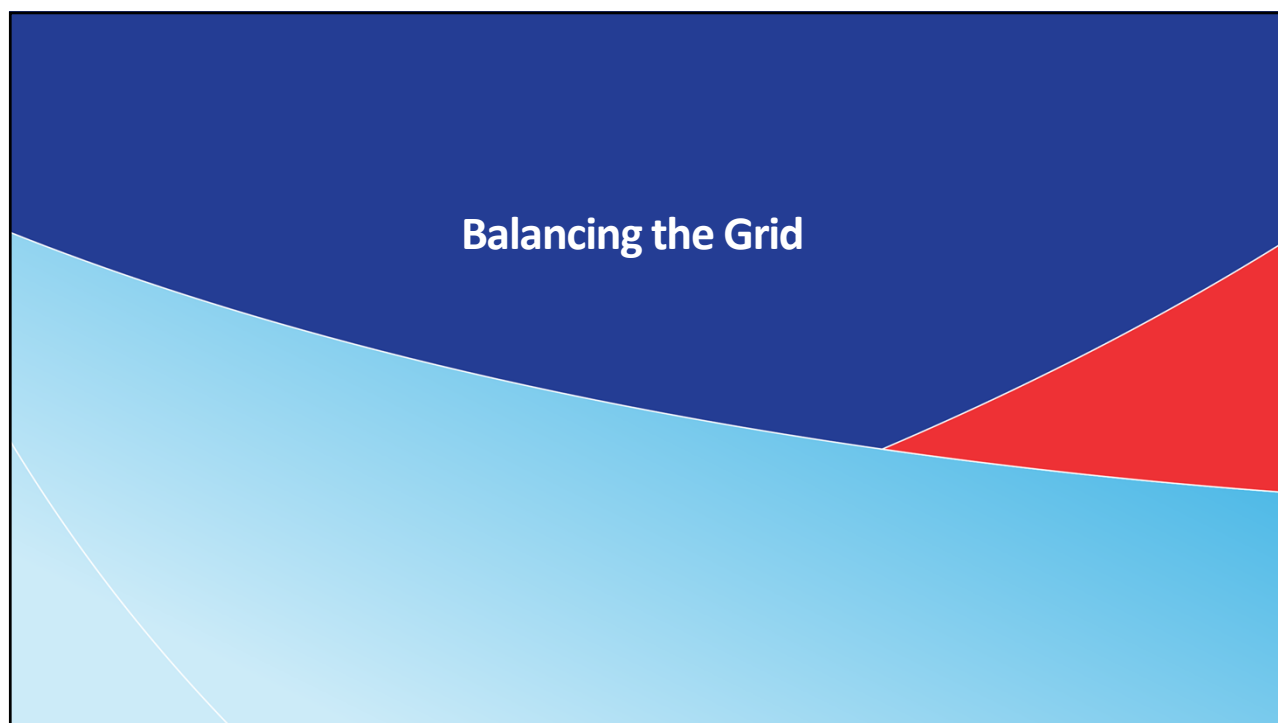
Source: Federal Energy Regulatory Commission (May 2023): <https://www.ferc.gov/electric-power-markets>

Source: U.S. Energy Information Administration (Apr 2024): <https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php>



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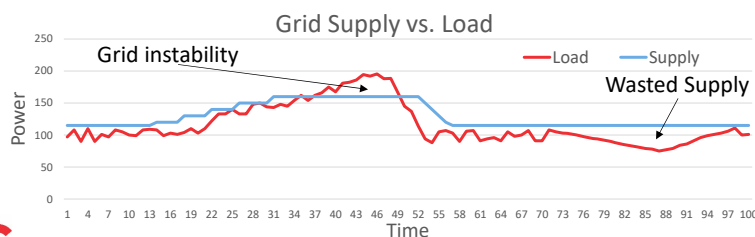


Grid Balancing

Grid balancing is the task of monitoring grid loads and ensuring electricity supply is matched appropriately. This is the task of the balancing authority.

If supply drops below load, the grid becomes unstable, equipment can be damaged, and brown-outs or blackouts can occur.

Supply above the current load is wasted energy unless adequate energy storage is available.



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Source Generation Priorities

Balancing authorities **dispatch** grid resources to meet demand, prioritizing less costly generation sources. There are two phases to dispatch.

Day-Ahead Commitment: Future demand is modeled and power sources are committed 24 hours in advance to ensure availability. Dispatchable and non-dispatchable sources are characterized by their cost, startup time, availability, responsiveness, and maximum and minimum outputs, and an appropriate mix is selected.

Real-Time System Dispatch: Real-time loads are monitored and each resource committed in the day-ahead phase is operated in response with the goal of ensuring grid reliability and minimizing costs. Forecasted load may not match real-time loads, so continual adjustments must be made.

Reserves must be kept available should a generating source fall offline or demand peak unexpectedly.

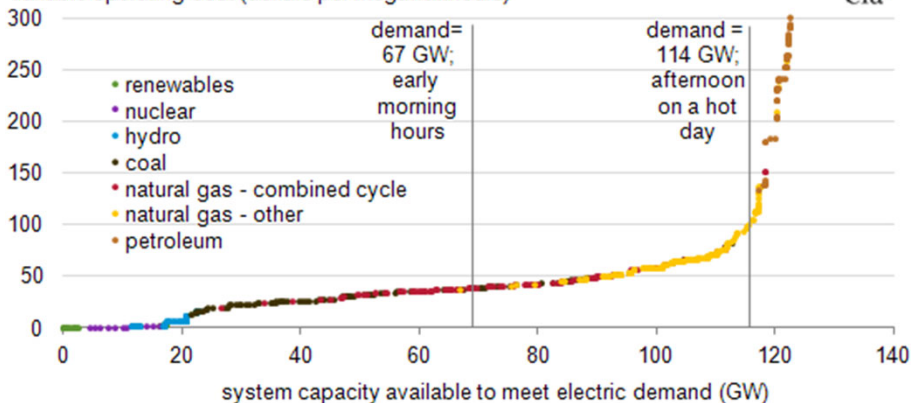


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Source Generation Priorities

Hypothetical dispatch curve for summer 2011
variable operating cost (dollars per megawatthours)



Source: U.S. Energy Information Administration: <https://www.eia.gov/todayinenergy/detail.php?id=7590>



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Grid Congestion & Constraints

Grid congestion happens when demand on the grid exceeds part of the grid's throughput capacity, or ability to transmit power from least-cost energy sources (its constraints).

- Consumers in a certain area may suddenly use more than the lines or substation connecting them are able to handle. This could be from rapid development in an area or another transmission route going offline and re-routing power through other routes.
- Distributed energy resources, like solar or wind, may temporarily exceed the capacity of the transmission lines or substations connecting them to the grid and its customers if other energy sources are also online.

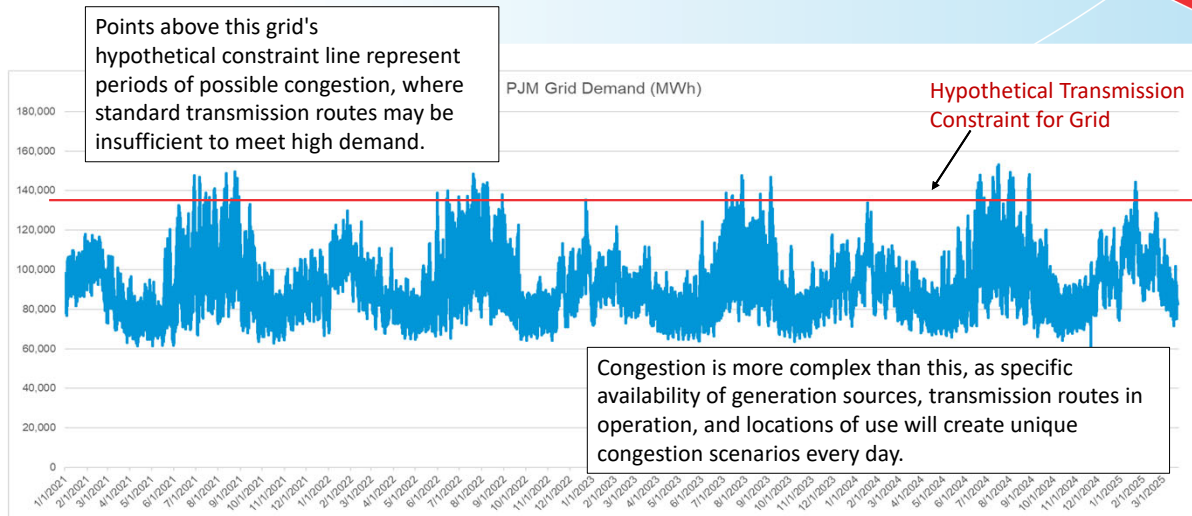
Grid congestion can decrease grid reliability and lead to energy waste. Additional power must be imported to an area and/or re-routed to keep up with demand, and stability can deteriorate. Upgraded infrastructure and redundancies, load management strategies, and smart technologies can help manage grid congestion.



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Grid Congestion & Constraints



Source: https://www.eia.gov/electricity/gridmonitor/dashboard/electric_overview/regional/REG-MIDA



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Grid Congestion & Constraints

Investments in new infrastructure can relieve grid congestion between local areas and even regions.

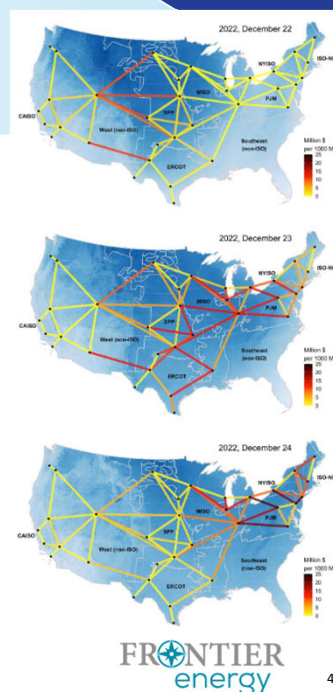
Better planning in locating power generation facilities, and investments in energy efficiency and demand-side management strategies can also help relieve congestion.

Source: Lawrence Berkeley National Laboratory (Millstein et al. 2022b and 2023)
https://www.energy.gov/sites/default/files/2023-12/National%20Transmission%20Needs%20Study%20-%20Final_2023.12.1.pdf



Transmission value between selected regional nodes moved east with cold surface temperatures during December 22–24, 2022 (Winter Storm Elliot)

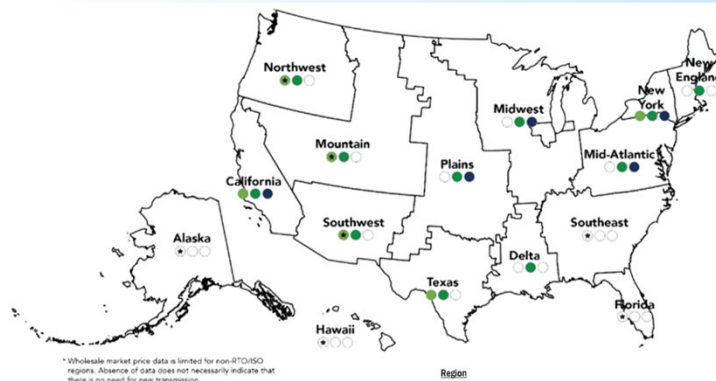
Note: Transmission value is measured in cumulative daily million USD of a hypothetical 1000 MW transmission link between two nodes. Darker blue background colors reflect colder surface temperatures.



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Grid Congestion & Constraints



Source: https://www.energy.gov/sites/default/files/2023-12/National%20Transmission%20Needs%20Study%20-%20Final_2023.12.1.pdf



Current Need	California	Northwest	Mountain	Southwest	Texas	Plains	Midwest	Delta	Southeast	Florida	Mid-Atlantic	New York	New England	Alaska	Hawaii
Alleviate congestion & unscheduled flows	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Alleviate transfer capacity limits between neighbors	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Deliver cost-effective generation to meet demand	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●



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Brownouts and Blackouts

Brownouts are when part of the grid loses the capacity or power to operate properly, usually for minutes or hours.

Blackouts are when part of the grid loses power entirely for a prolonged period.

Blackouts are usually caused by unexpected damage to the grid or insufficient capacity and are avoided at all costs.

Brownouts can happen unexpectedly but can also be used as a tool to prevent blackouts in extreme circumstances. If grid load approaches a point where it will surpass available supply and no other preventative measures can be implemented, a grid operator has the option to disconnect a portion of the grid, cutting off transmission there to preserve grid stability elsewhere. This is called **load shedding**.

If load will exceed capacity for a longer period, such as when a critical power supply source is offline due to damage, the location of the brownout can be periodically moved to minimize disruption to any one area. This is called a **rolling brownout**.



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Oversupply & Undersupply Events

Oversupply Event – When electricity generation exceeds demand. These waste energy and can cause grid instability. Examples might include:

- Low demand periods like sunny, mild weather days.
- High supply periods like sunny and windy days where renewables provide more energy than is needed.

Undersupply Event - When electricity demand exceeds generation. These cause grid instability, brownouts, blackouts, and increased operational costs. Examples might include:

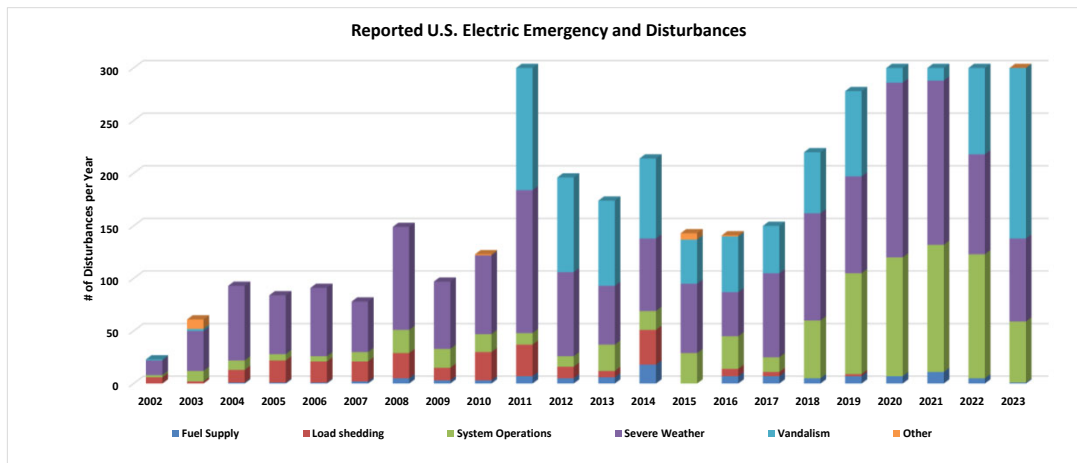
- Hot, sunny days when AC loads from customers are high.
- Power plant outages or transmission disruptions.



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Grid Outage History



OE-417 Electric Emergency and Disturbance Report



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Thank You

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course material is fresh in your mind



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