Grid
FUNDAMENTALS

LEARNING MANUAL

FEBRUARY 2025

Course Topics

Day One

Day Two

> The Western Electricity Coordinating Council (WECC) is a non-profit corporation that exists to ensure a reliable Bulk Electric System in the geographic area known as the Western Interconnection.

TIMELINE

ORIGINS OF THE WORD "ELECTRICITY"

Ancient cultures from around the world are thought to have explored the primitive properties of electrical energy during the first millennium BCE. Greek philosopher Thales of Miletus makes a series of observations about the static properties of amber, which is “elektron” in Greek. Amber, the fossilized resin of a now extinct coniferous tree, was valuable in ancient times.

A PIONEERING ELECTRICAL MACHINE

The first machine for producing static electricity is created, it was the first electrostatic generator.

Wellcome Images, a website operated by Wellcome Trust, a global charitable foundation based in the UK

THE KITE EXPERIMENT

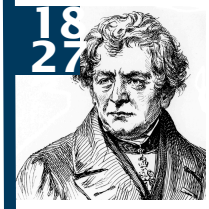
Benjamin Franklin reports he collected electric charges from thunderstorm clouds through a wet string from a kite fitted with a metal spike to prove static electricity and lightning are the same thing.

Benjamin Franklin Drawing Electricity from the Sky, by Benjamin West. Oil on slate. Circa 1816

BREAKTHROUGHS IN ELECTROMAGNETISM

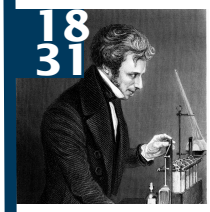
Danish scientist Hans Oersted experimentally discovers, while giving a lecture, that the current in a wire can affect the orientation of a magnetized needle.

Creative Commons



OHM'S LAW

German physicist Georg Simon Ohm details his theory of electricity in Die Galvanische Kette, Mathematisch Bearbeitet. The book also offers an understanding of “Ohm’s Law.”



THE FATHER OF GENERATION

In 1821, on the heels of Oersted and Ampère’s findings, British physicist and chemist Michael Faraday—another self-taught scientist (who was born in poverty)—invents two devices to produce electromagnetic rotation, resulting in the conversion of electrical energy into mechanical energy by electromagnetic means.

AC GENERATORS EMERGE

The Ganz Company, best known for its manufacture of tramcars in Hungary, patents and begins to use alternating current (AC) generators in small commercial installations in Budapest.

Public Domain

TIMELINE

1879 THE FIRST CENTRAL POWER STATION

George Roe, a Canadian broker living in San Francisco, incorporates California Electric Light Co.—a company that eventually grew into Pacific Gas & Electric Co.

The California Electric Light Co. Incorporated.

1880 A HYDRO PIONEER

Michigan's Grand Rapids Electric Light & Power Co. acquires a 16-light brush generator, installs it in the factory of the Wolverine Chair and Furniture Co., and begins generating power.

Wolverine Chair & Furniture Company

1882 THE VALUE OF PEARL STREET

Pearl Street Station becomes the first commercial central power plant in the United States. It was located at 255–257 Pearl Street in the Financial District of Manhattan, New York City, just south of Fulton Street.

United States Library of Congress's Prints and Photographs division under the digital ID cph.3b39873
Thomas Edison and his original dynamo, Edison Works, Orange, N.J., U.S.

1884 THE AC TRANSFORMER

Lucien Gaulard and John Dixon Gibbs build an AC power plant using a rudimentary transformer, which allows for voltage to stay constant despite additional load being added.

Deutsches Museum

1888 THE TESLA AC POLYPHASE SYSTEM

Nikola Tesla demonstrates the first AC electrical system. His AC system includes all units needed for electricity production and use: generator, transformers, transmission system, motor (used in appliances) and lights. George Westinghouse, the head of Westinghouse Electric Company, buys the patent rights to the AC system.

1889 A HYDRO AND TRANSMISSION FEAT

According to the Oregon History Project, in 1889, the Willamette Falls Electric Company successfully transmitted DC power from a hydropower plant in Oregon City across 14 miles to Portland.

Oregon History Project
Westinghouse dynamos at Willamette Falls Electric's Station A.

1895 A COMPLETE AC SYSTEM

Power generated from the Jaruga hydroelectric plant is transmitted to the city of Šibenik in Croatia, where six power transformers supply a large number of street lamps. It is one of the first complete multiphase AC systems.

Hrvatska pošta
A stamp commemorating the 100th anniversary of the Jaruga power plant.

TIMELINE

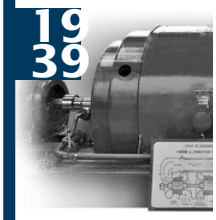
1907 THE BIRTH OF AN ELECTRIC UTILITY

By 1907, Samuel Insull had acquired 20 other utility companies and renamed his firm "Commonwealth Edison." The firm endures today as an Exelon Corp. subsidiary that serves Chicago and Northern Illinois.

Public Domain
A portrait of Samuel Insull, president of the Commonwealth Edison Co. in 1910.

1927 THE WORLD'S FIRST POWER POOL

The world's first continuing power pool is formed when three utilities—Philadelphia Electric Company (now PECO), Pennsylvania Power and Light (now PPL), and Public Service Enterprise Group (now PSE&G) came together.



1939 THE FIRST COMMERCIAL GAS TURBINE

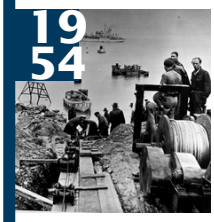
The world's first successful electricity-generating gas turbine goes into commercial operation at a municipal power station in Neuchâtel, Switzerland.

ASME
Brown Boveri in Baden's gas turbine.

1954 FIRST PRACTICAL SOLAR CELL

Researchers at Bell Laboratories demonstrate the first practical silicon solar cell. The finding is a major breakthrough in solar cell technology's history.

The Porticus Mission
The original Bell Solar Battery (photovoltaic panel) is used in an early test in 1955 in Americus, GA.



1954 THE AGE OF HVDC BEGINS

The first commercial high voltage direct current (HVDC) transmission link, a 20-MW, 100-kV installation between Swedish mainland and the island of Gotland in the Baltic Sea, is commissioned.

The electricity was sent through a 96km subsea cable between Vastervik and Ygne.

1955 NUCLEAR POWERS A TOWN

On July 17, 1955, Arco, Idaho, population 1,000, becomes the first town powered by a nuclear power plant, the experimental boiling water reactor BORAX-III.

INL/DOE

1959 LARGE-SCALE GAS POWER

According to the Oxford Institute for Energy Studies (OIES), the modern history of natural gas in Europe began in 1959, with the discovery of the Groningen field in the Netherlands.

TIMELINE

RELIABILITY WORRIES AND THE CREATION OF NERC

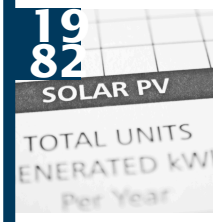
The New York Blackout of 1965 prompts the power industry to create a voluntary, utility-managed reliability organization, the North American Electric Reliability Council (NERC).

DeGolyer Library, Southern Methodist University

THE AGE OF GIANT WIND BEGINS

The town of Boone, NC, dedicates a 140-foot-tall wind turbine atop Howard's Knob, as part of a program by NASA and the U.S. Department of Energy to develop wind power as a renewable energy source in response to the 1970s OPEC oil embargo.

Wikimedia Commons

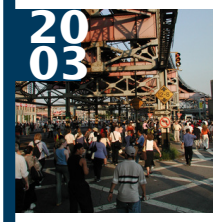


A SOLAR PV MARKER

The first 1-MW solar photovoltaic (PV) park is built by Arco Solar at Lugo near Hesperia, California.

WHOLESALE GENERATION COMPETITION BEGINS

U.S. Congress enacts the Energy Policy Act of 1992, which introduces wholesale generation competition and assigns the authority of the bulk transmission system to the Federal Energy Regulatory Commission (FERC).



A TRANSFORMING BLACKOUT

A surge of electricity to western New York and Canada touches off a series of power failures and enforced blackouts that leaves parts of at least eight states in the Northeast and the Midwest without electricity.

ENERGY POLICY ACT

FERC certifies an Electric Reliability Organization—the ERO (NERC); NERC may delegate authority to Regional Entities; e.g., WECC.

THE CARBON CAPTURE ERA BEGINS

The first large-scale coal-fired power unit fitted with carbon capture and storage technology is switched on at Boundary Dam, Saskatchewan.

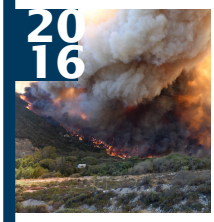
POWER Magazine

TIMELINE

THE PARIS AGREEMENT

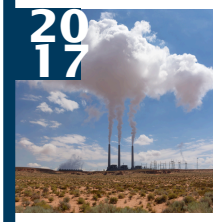
The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. It entered into force on 4 November 2016. The agreement covers climate change mitigation, adaptation, and finance.

United Nations Framework Convention on Climate Change



THE BLUE CUT FIRE

Southern California fire that spread through a transmission corridor, including three of Southern California Edison's 500-kV lines and two of Los Angeles Department of Water and Power's 287-kV lines.



REPEAL OF THE CLEAN POWER PLAN

In March, the Environmental Protection Agency announced its intent to repeal the Clean Power Plan under the Trump administration. The Clean Power Plan was originally introduced by the Obama administration.

CALIFORNIA WILDFIRES

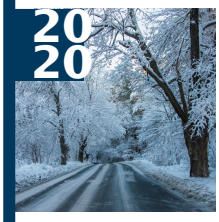
Reoccurring wildfires in California result in prolonged power outages and highlight the challenges the Western-Interconnection faces in maintaining a reliable electricity supply in the face of natural disasters.

RENEWABLE GENERATION ACCOUNTS FOR A THIRD OF GLOBAL POWER CAPACITY

The International Renewable Energy Agency's annual statistics reveal that renewable energy accounted for a third of global power capacity. Globally, total renewable electricity generation capacity reached 2,351 GW, with hydropower accounting for almost half of that total, while wind and solar energy accounted for most of the remainder.

CYBERATTACK HITS ELECTRICAL SYSTEMS SERVING LOS ANGELES AND SALT LAKE

Both Los Angeles and Salt Lake electrical systems were affected by a distributed-denial-of-service attack. The attack luckily did not cause any outages or affect electrical delivery, however it did cause interruptions throughout the systems.

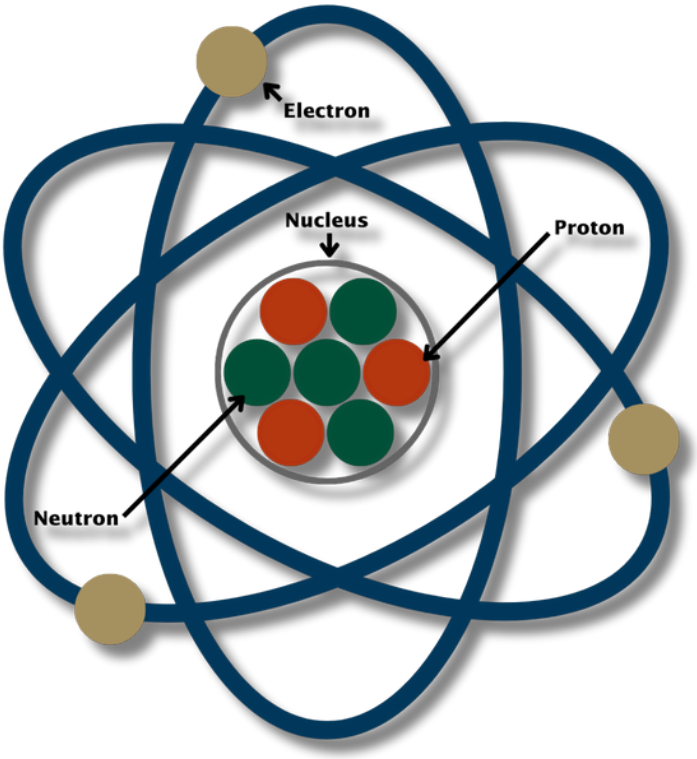


EXTREME WINTER CONDITIONS

Extreme weather conditions experienced by the Midwest and South Central states contributed to power outages affecting millions of electricity customers throughout the region. NERC and FERC produce stronger mandatory electric reliability standards, specifically regarding winter conditions.

Electricity Basics

What is Electricity?

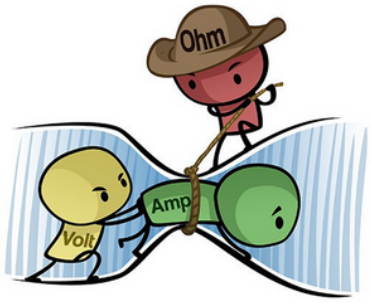


Electricity

Flow of electrons in a circuit.

Electricity is created in three ways:

- Electromagnetic conversion,
- Chemical reaction, and
- Solid-state conversion



Voltage

Measure of electrical pressure. "How far will the spark jump?" Measured in Volts (V).

Current

Movement of charge through a conductor. "Think gallons per second." Measured in Amps (I).

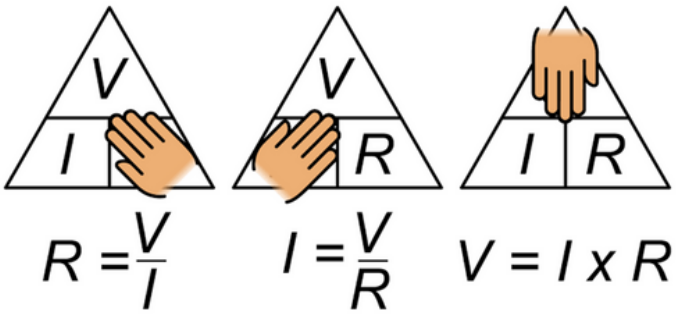
Resistance

Provides resistance to the circuit. Opposes the Current. Measured in Ohms (Ω).

Ohm's Law

Voltage (V) = Current (I) x Resistance(R). V = I x R

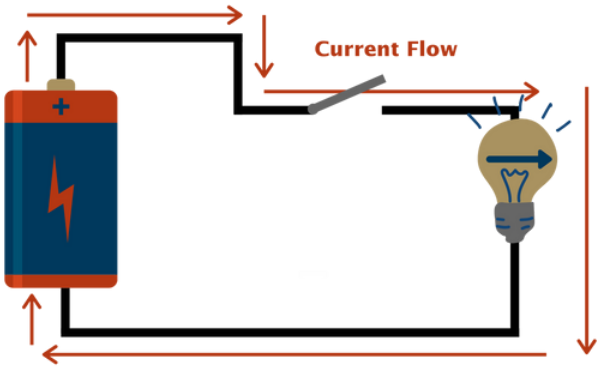
They are all tied together!



Electricity Basics

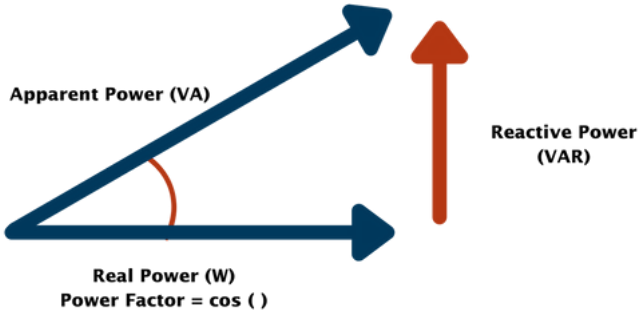
Circuit

Closed path through which electricity flows.



Short Circuit

Electrical circuit that allows a current to travel along an unintended path with very low or no impedance.



Power

The rate at which work is being performed. Measured in Watts (w). A watt is an instantaneous value. It is the power being used at any given time.

Power = Voltage x Current.

Energy

The sum of power delivered over a period. Measured in kilowatt hours (kWH) for the power grid.

Kilowatt hours = Kilowatts x Time (in hours).

Real Power

Does the work. Does the heating, lighting, and turning of motors. Measured in watts.

Reactive Power

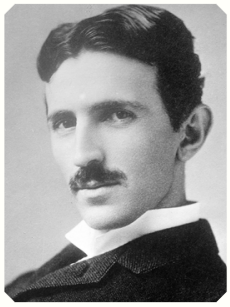
Sometimes called imaginary power. Supports the magnetic and electric fields required for AC systems to function.

Measured in Volt-Amperes-Reactive (VAR).

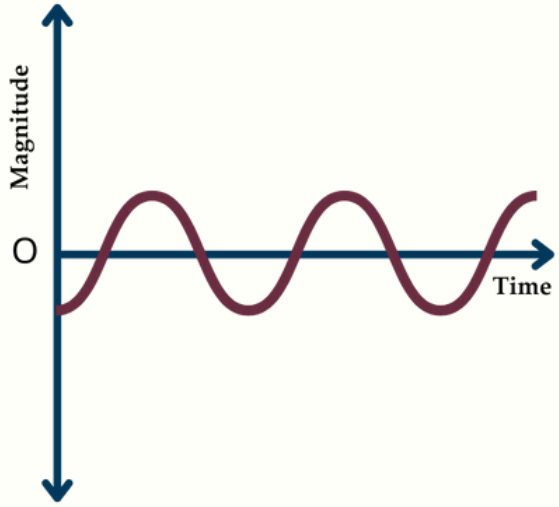
Electricity Basics

Alternating Current (AC)

Current flows back and forth.



Nikola Tesla



Alternating Current

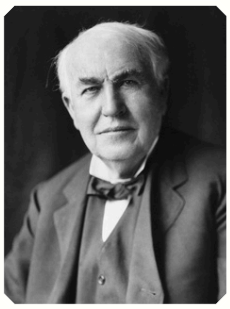
Generator

Appliances

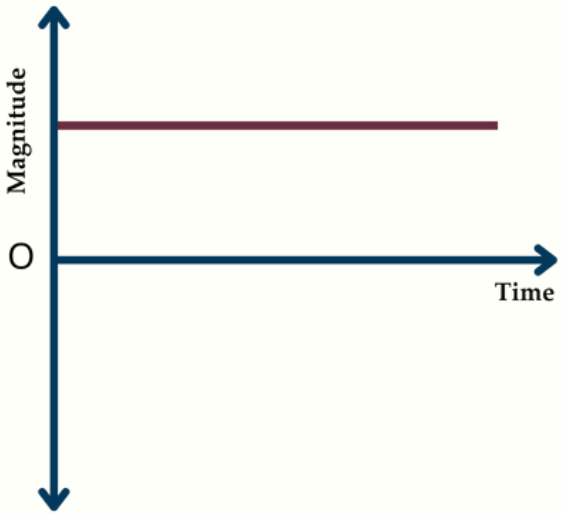
Radio Signals

Direct Current (DC)

Current only flows in one direction.



Thomas Edison



Direct Current

Solar Panels

Batteries

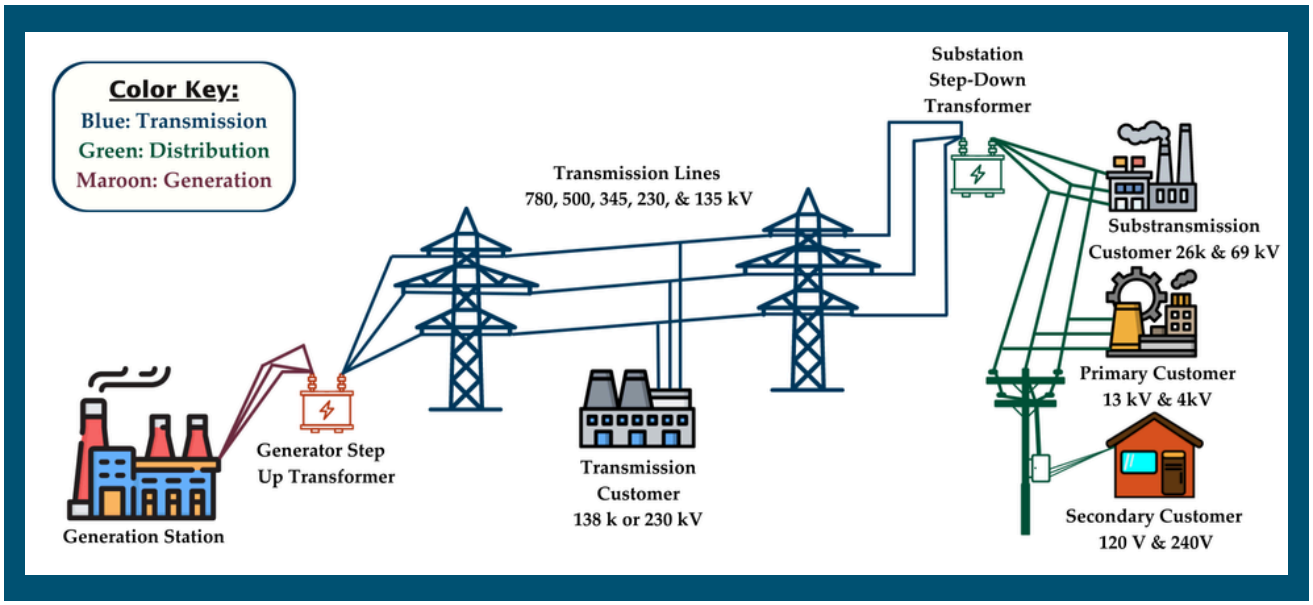
Charging Devices

Interconnected Power System

The Largest Machine Ever Built

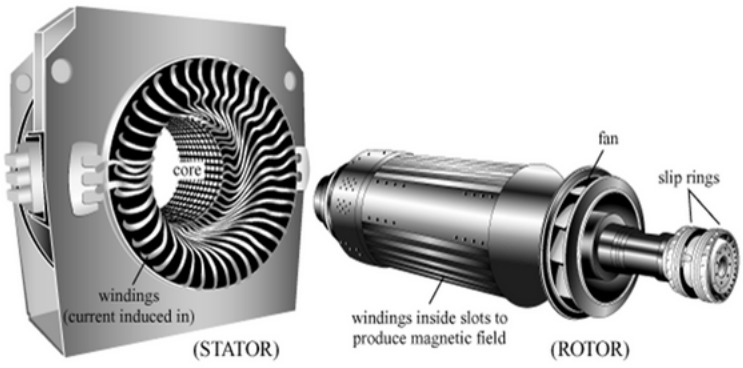
The Smithsonian Magazine called the North American power grid the largest machine ever built.

The Electrical System Structure



Generator

A generator is a machine by which mechanical energy is changed to electrical energy.

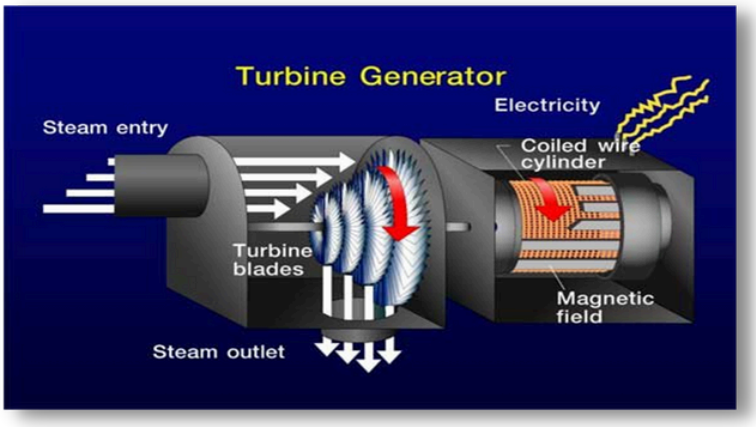


Combined Cycle
Steam Generation

https://youtu.be/D406Liwm1Jc?si=plAvNPvMFY_kRGGc

Interconnected Power System

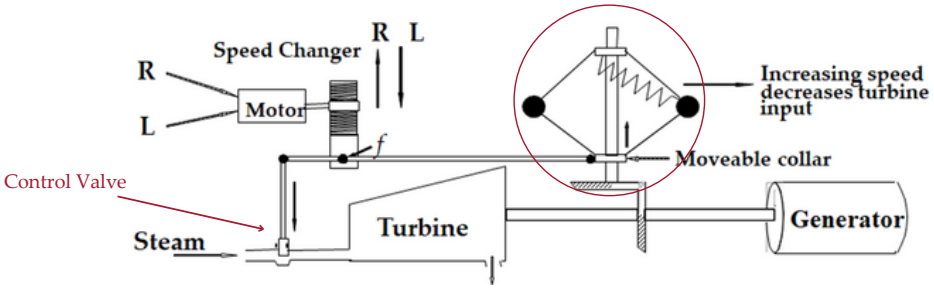
Basic Generation



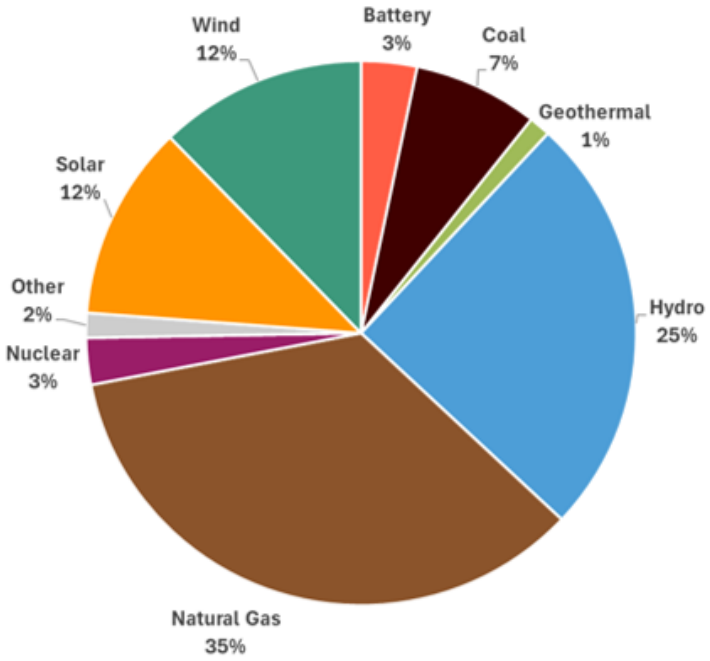
How to Build a DC Motor

https://www.youtube.com/watch?v=4bzpq56ew-s

Turbine Governor Controls



2023 Total Installed Capacity (299.5 GW)



Interconnected Power System

Thermal Fuel Sources

Coal

Natural Gas Combustion

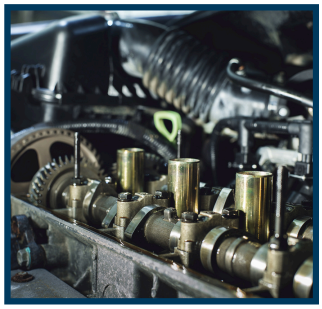
Combined Cycle

Geothermal

Nuclear

Solar Thermal

Other Fuel Sources



Internal Combustion

Wind

Solar Photovoltaic

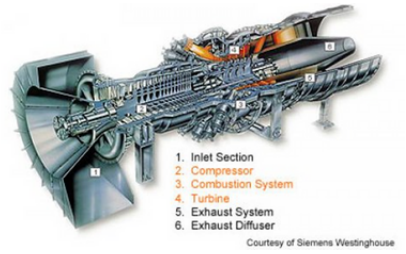
Battery

Hydroelectric

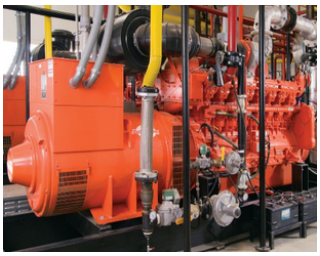
Energy 101: Solar PV

https://youtu.be/0elhlcPVtKE?feature=shared

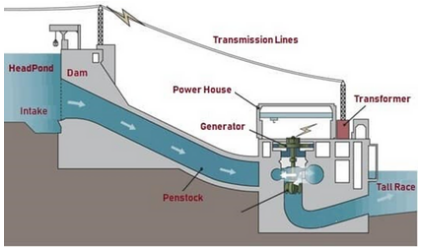
Interconnected Power System



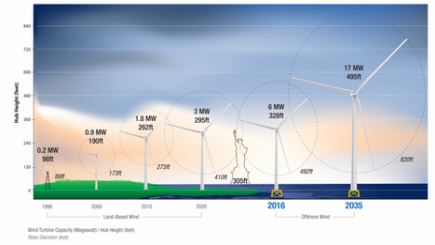
Combustion Turbine



Internal Combustion



Hydroelectric Power Generation

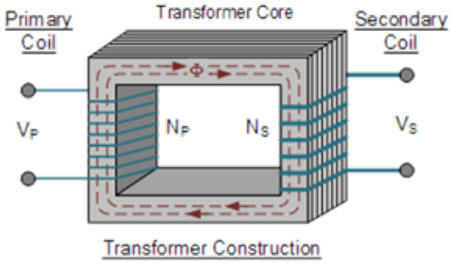


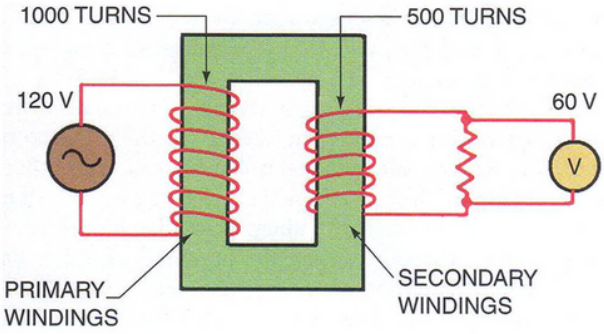
Wind Generation

Solar Generation

Transformers

Changes from high voltage to low voltage
Enables high-voltage transmission of power
Works only with AC power





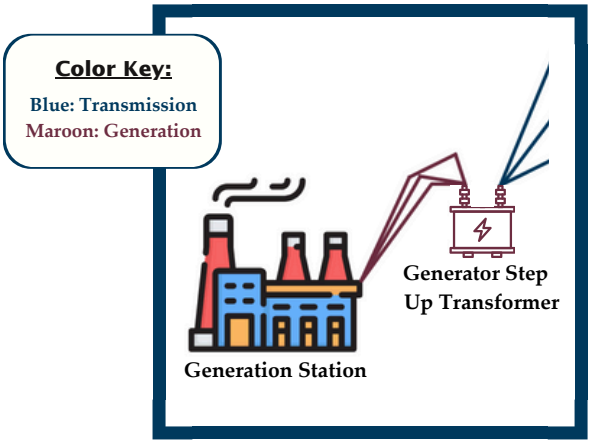
Instrument Transformers

- In high-voltage systems, direct measurement of voltage or current is not practical
- Instrument transformers scale down the values for use by meters and relays
- Current transformers (CT)
- Potential transformers (PT or VT)

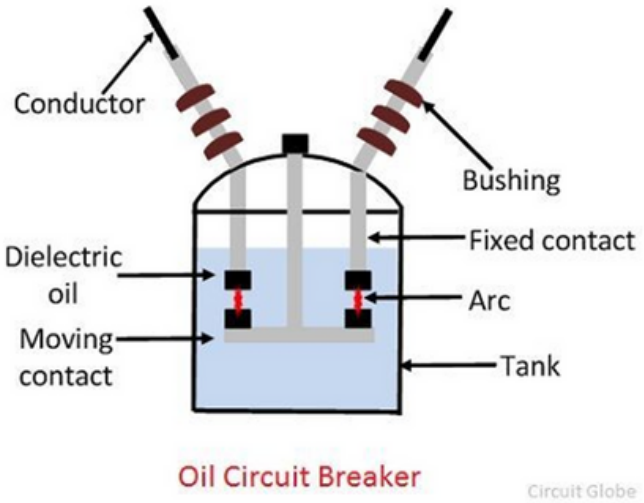
Interconnected Power System

Substation

Substations are junction points in the power system, often transforming voltages up or down through transformers.



Substation Equipment



Disconnect Switch

Disconnect Switches

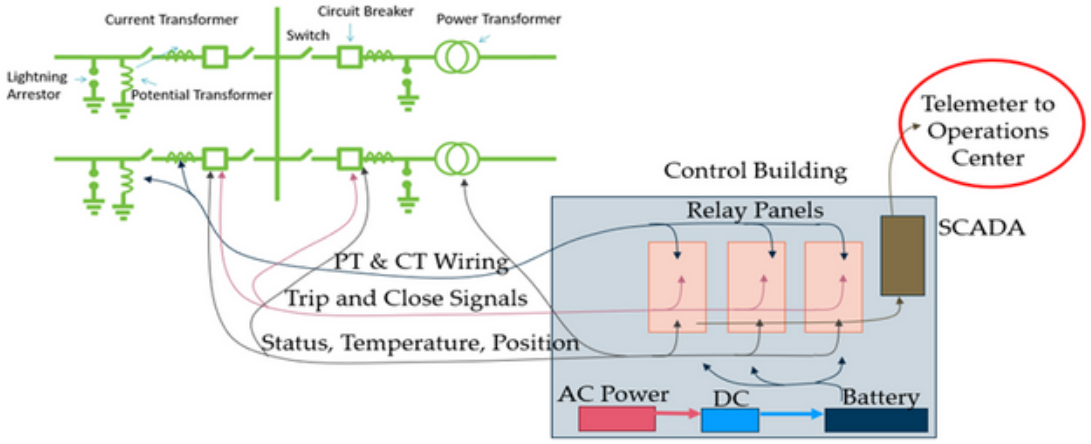
https://youtu.be/VrY_k_pdlCs?si=JZVNBkGfETCOp3NT

Interconnected Power System

Substation Equipment

Switchgear Cabinet

Control House



Substation Connections

Conductors

Conductors carry the electricity.
Big current requires big conductors.

Overhead Conductor

Underground Conductor

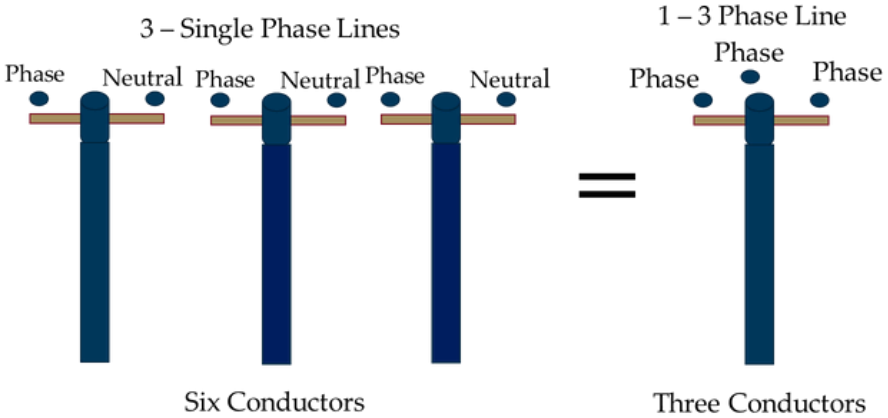
Interconnected Power System

Insulators

Insulation for voltage

Transmission Line Designs

Three-Phase Circuits



Hot Line Work

https://youtu.be/hA5wNMSNwGo?si=ico7riEsygUpP9uD

Interconnected Power System

Capacitors

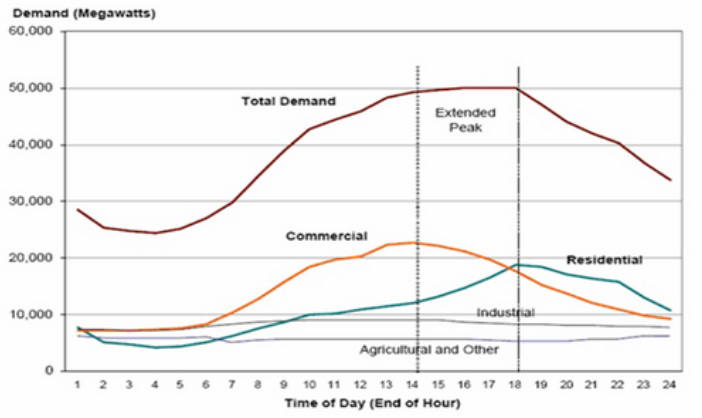
Distribution Switched Capacitor Bank

Substation Capacitor Bank

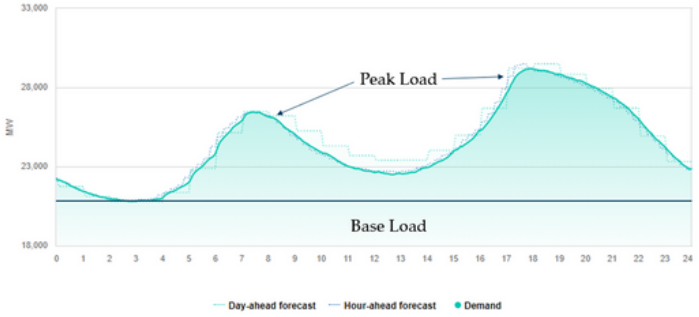
Load

An end-use device or customer that receives power from the electric system.

Load Varies by Customer Type



Base Load and Peak Load

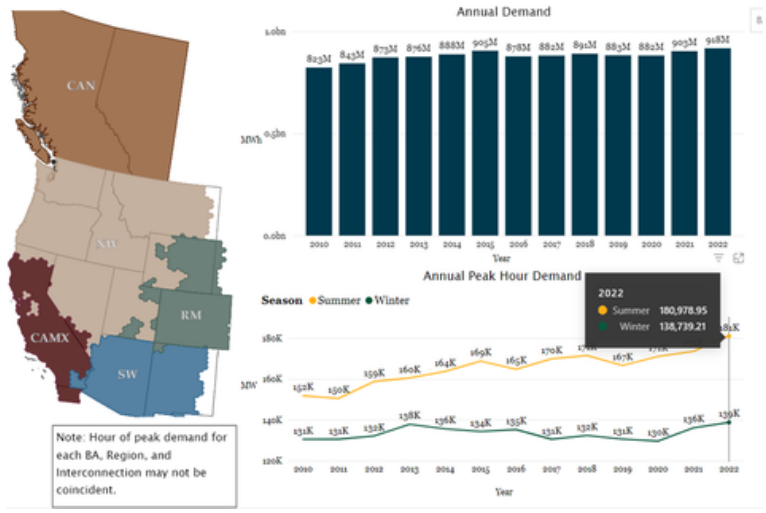


Interconnected Power System

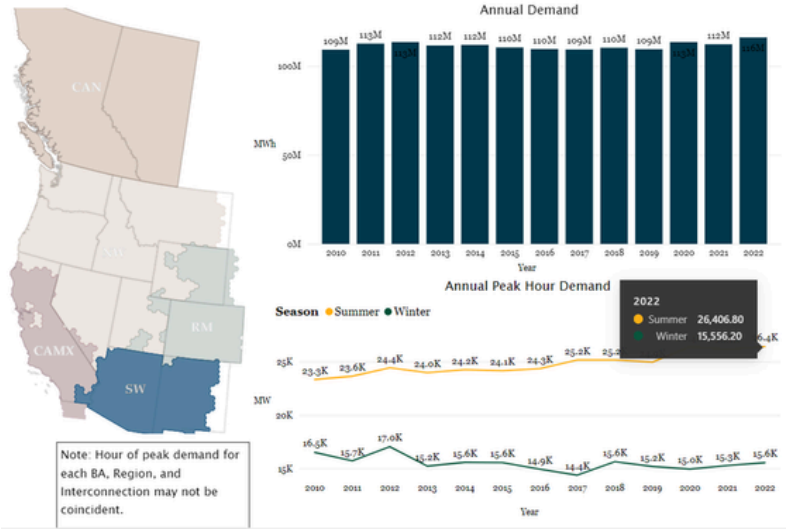
Load

Load can also vary by geographical location. The Western Interconnection is a summer-peaking interconnection. The Desert Southwest peaks in the summer and Alberta and British Columbia peak in the winter.

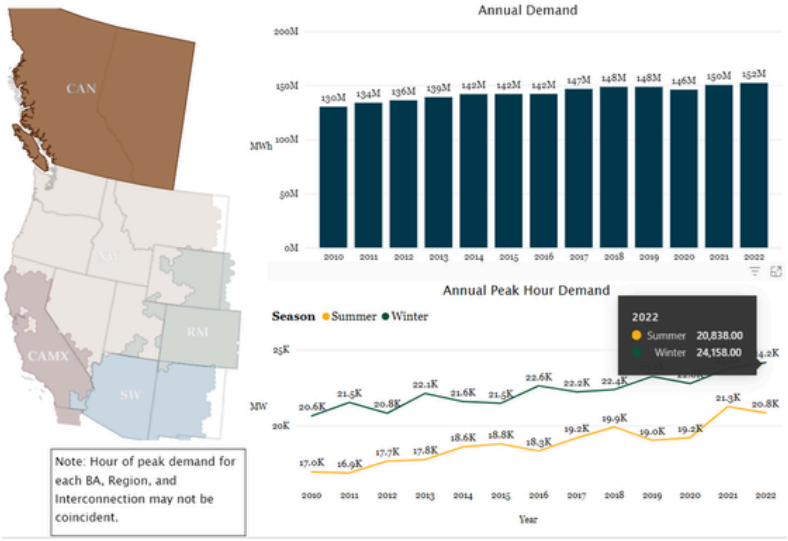
Western Interconnection



Southwest



Alberta/BC



Interconnected Power System

Forecasting Load

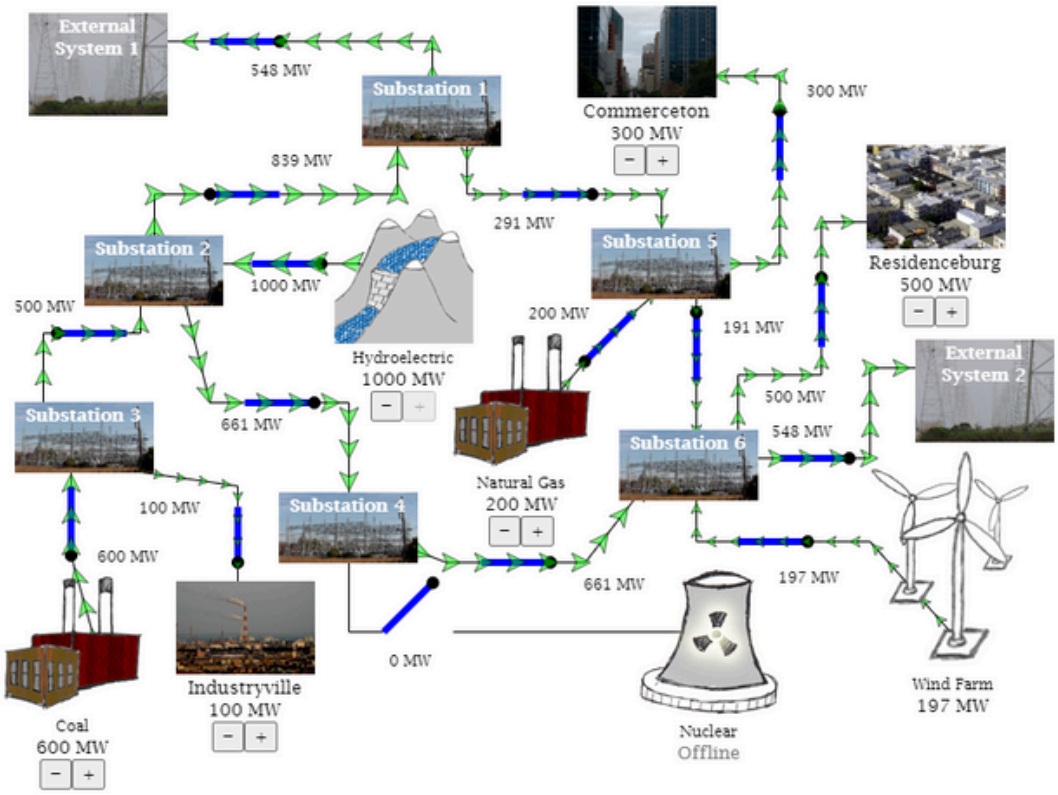
Load forecasting is a technique used by power or energy-providing companies to predict the power/energy needed to meet the demand and supply.

Forecast	Time	Use
Very Short	Seconds to Minutes	Generation, Distribution, Operations Analysis
Short	Minutes to Hours	Unit Commitment, Maintenance Scheduling
Medium	Days to Weeks	Seasonal Peaks
Long	Months to Years	Generation/Growth

Resources

Western Electricity Coordinating Council: www.wecc.org
North American Electric Reliability Corporation: www.nerc.com
U.S. Energy Information Administration: www.eia.gov

The Power Grid



The Cyber Resilient Energy Delivery Consortium (CREDC) Power Grid Tool
https://credc.mste.illinois.edu/applet/pg

Power System Operations

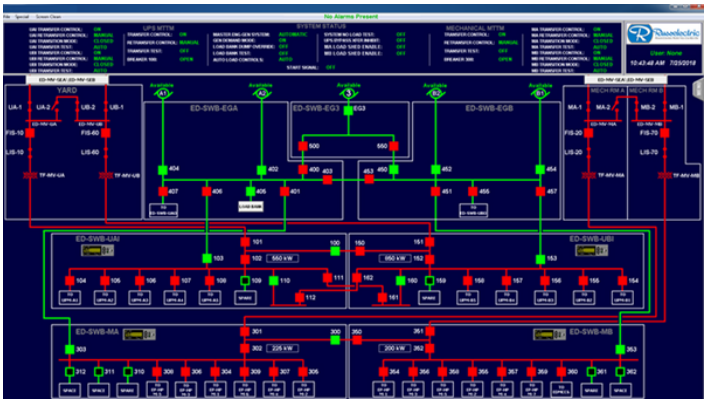
Transmission Operators

The entity responsible for the reliability of its "local" transmission system and operating or directing the operations of the transmission facilities.

Control Center

One or more facilities that hosts operating personnel that monitor and control the Bulk Electric System (BES) in real time to perform the reliability tasks (including their associated data centers) of:

1. Reliability Coordinator,
2. Balancing Authority,
3. Transmission Operator for transmission Facilities at two or more locations,
4. Generator Operator for generation Facilities at two or more locations.



SCADA

Supervisory Control and Data Acquisition.

System Operating Limits

- Thermal or Voltage Limits
- Load Limits—Protect transmission from too much flow.
- System Stability—Protects Generation from loss of synchronization.

Real-time Contingency Analysis (RTCA)

An evaluation of system conditions using Real-time data to assess existing (pre-Contingency) and potential (post-Contingency) operating conditions.

System Events and System Restoration

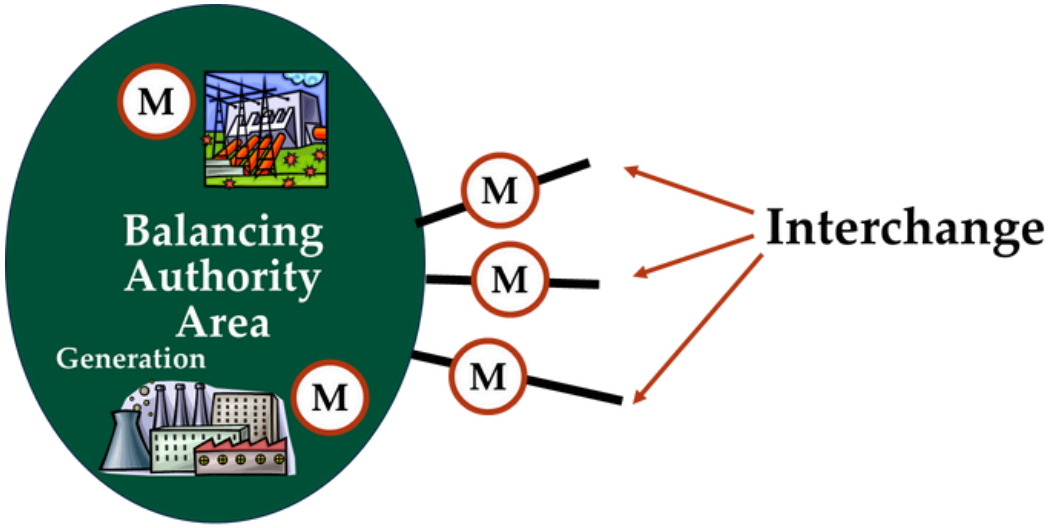
- When equipment trips,
- Congestion on the power system,
- Relays, Remedial Action Schemes (RAS), or operators, take action to prevent or mitigate equipment overloads,
- Field crews are dispatched to investigate/repair.

Power System Operations

Balancing Authority (BA)

The responsible entity that integrates resource plans ahead of time, maintains load-interchange-generation balance within a BA Area, and supports interconnection frequency in real time.

BA Loads and Resources



Britain Peak Demand

https://youtu.be/sIDAvewWfrA?si=9M9X3EapKRU5G92y

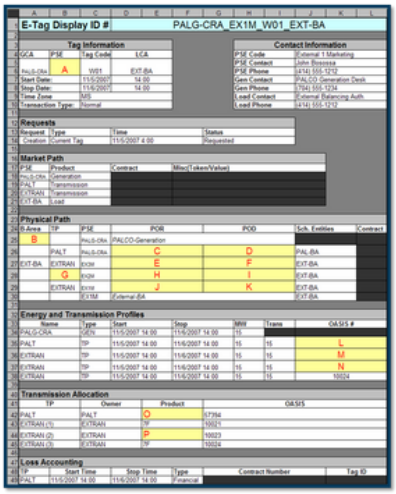
BA Load = Generation + (imports – exports)

BA Tools

- Scheduling,
- Load and Generation Balancing,
- Frequency Response.

Transaction Tagging (E-Tag)

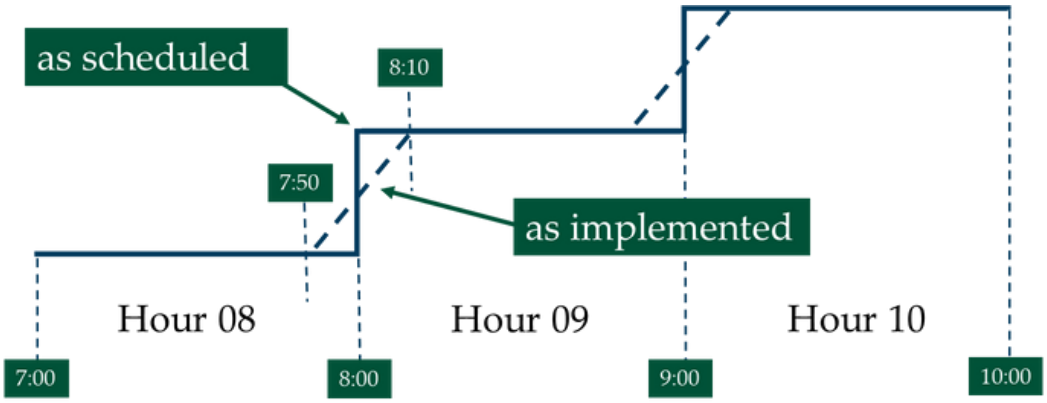
- Identifies each transaction.
- Identifies all parties and transmission arrangements.
- Facilitates timely schedule cuts if problems arise.



Power System Operations

Power Scheduling

In real time, hourly schedule changes are "ramped" to smooth out abrupt changes.



Common Power Schedule Types

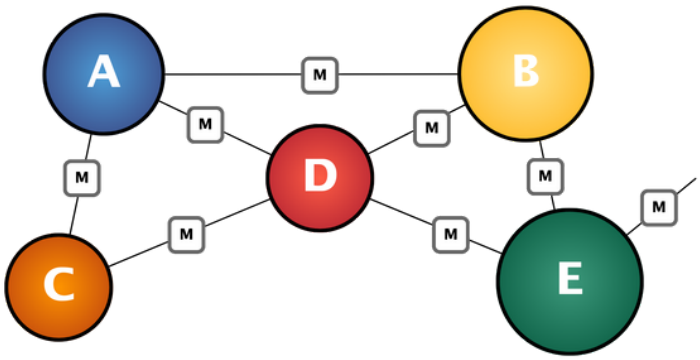
- Firm—Highest delivery priority, backed-up, system-wide resources treated like your own resource.
- Non-firm/Interruptible—Lowest priority, highest likelihood of being cut.

Scheduled vs. Unscheduled Flow

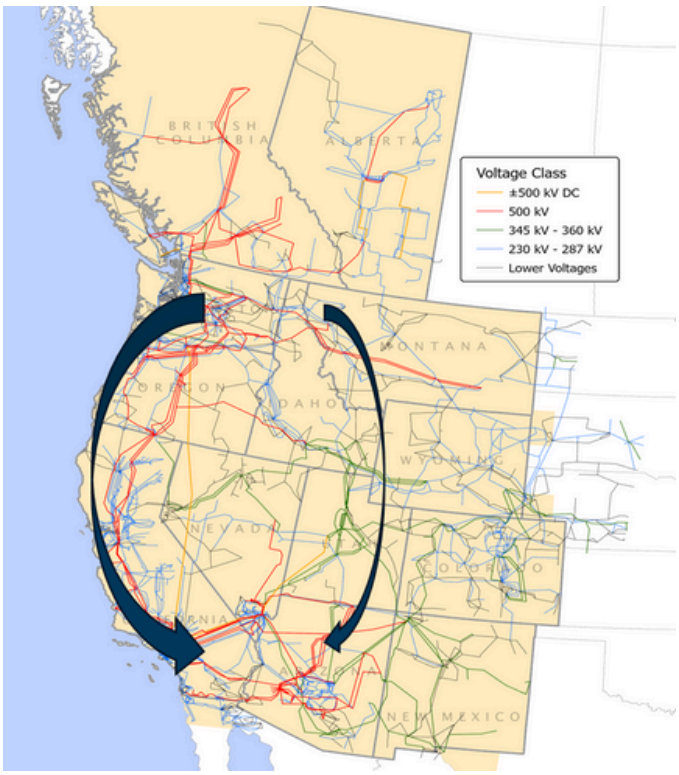
Scheduled Flow – Actual Flow

=

Unscheduled Flow



Unscheduled (Loop) Flow



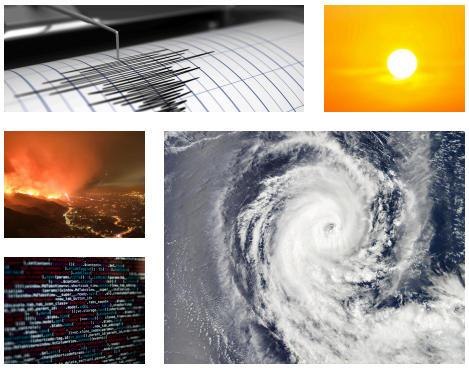
Power System Operations

Major Disturbance

Load shedding, trip of generation, full or partial blackout.

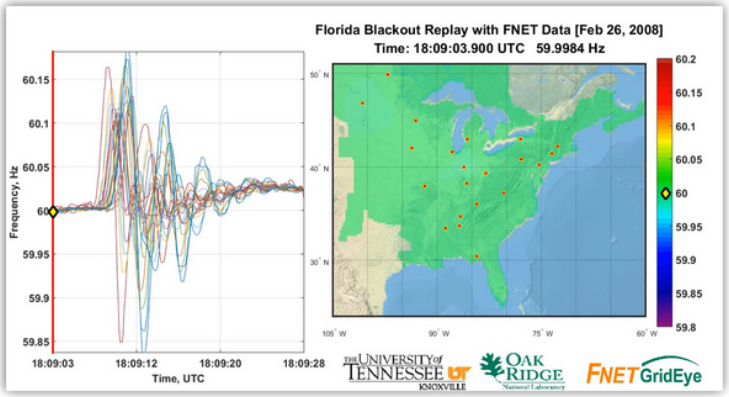
Causes:

Storms, earthquakes, fires, equipment malfunction, inadequate system, operating errors, sabotage, combination of events (“perfect storm”).



FNET/GridEye GPS

GPS-synchronized wide-area frequency measurement network. Measures the frequency, phase angle, and voltage of the power system.



Area Control Error (ACE)

Measures whether BA is properly generating its MW requirements.
Helps control interconnection frequency.

ACE Equation

$$ACE = (Actual - Scheduled) - (Bias \times (Actual - Scheduled))$$

Interchange — Frequency

Automatic Generation Control (AGC)

- Monitor generation and load balance using ACE
- Adjusts power output of generators.
- Ramps generation and load schedules.

Operating Reserves

That capability above firm system demand required to provide for regulation, load forecasting error, equipment forced and scheduled outages and local area protection. It consists of spinning and non-spinning reserve

Power System Operations

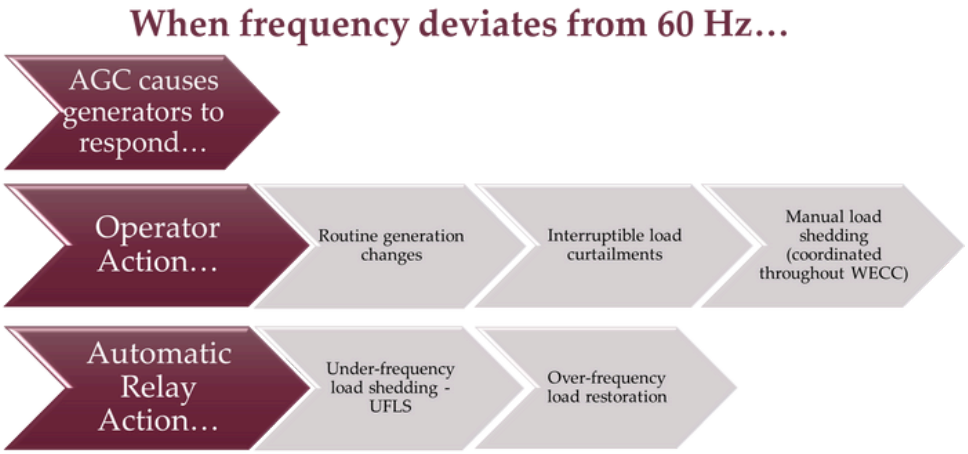
Reserve Sharing Group

A group whose members consist of two or more BAs that collectively maintain, allocate, and supply operating reserves required for each BA's use in recovering from contingencies within the group.

Energy Imbalance Market (EIM)

An EIM is a real-time energy supply market that offers electricity generation and transmission services.

Off-nominal Frequency Load Shedding

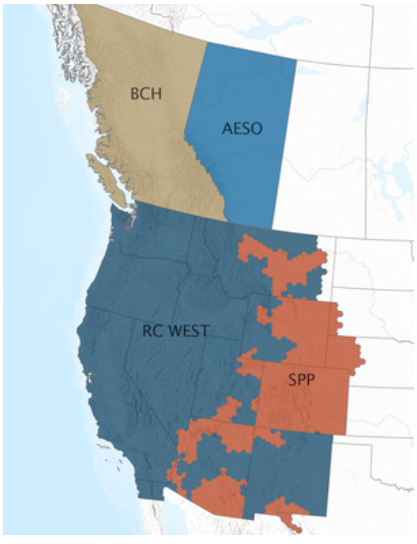


Underfrequency Load Shedding (UFLS)

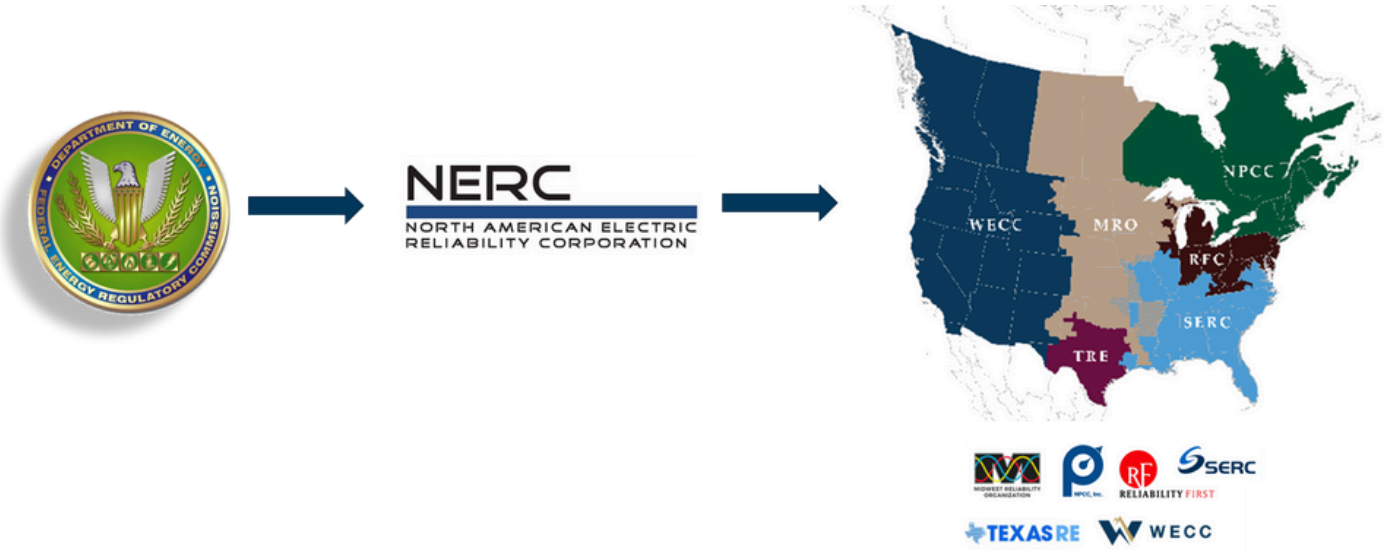
When frequency falls, UFLS helps frequency recover by dropping pre-planned blocks of load.

Reliability Coordinators (RC)

Entity with the highest level of authority who is responsible for the reliable operation of the BES, including the authority to prevent or mitigate emergency operating situations in next-day analysis and real-time operations. Four RCs operate in the Western Interconnection.



Regulation: Who, How, Why

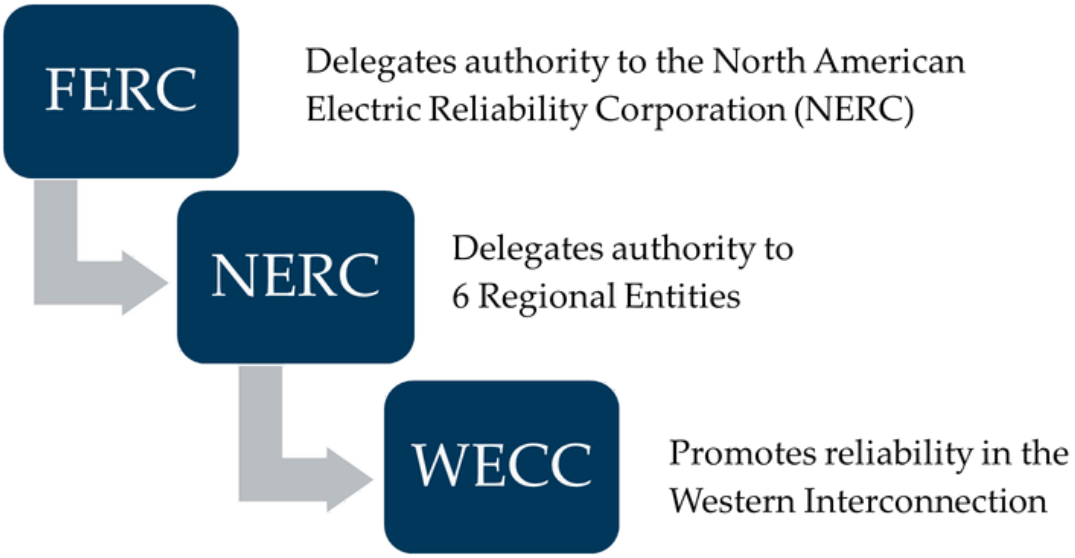


FERC

Federal Energy Regulatory Commission. Regulates the interstate transmission of electricity, natural gas, and oil.

NERC

North American Electric Reliability Corporation. Not-for-profit international regulatory authority whose mission is to ensure the effective and efficient reduction of risks to the reliability and security of the grid.

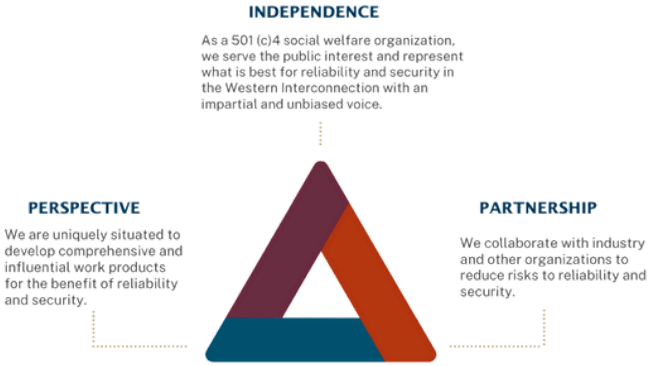


Regulation: Who, How, Why

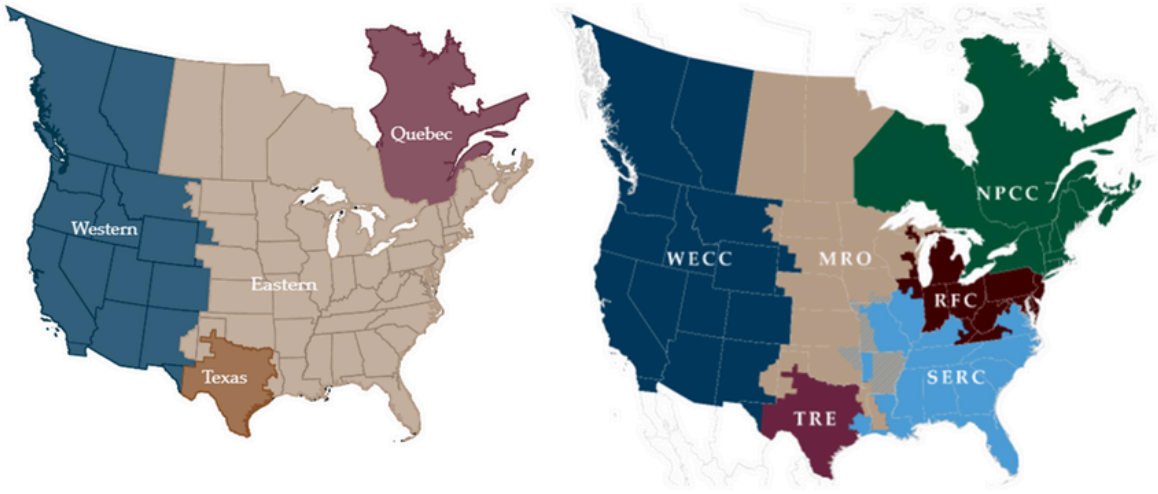
WECC

Western Electricity Coordinating Council. Designated as the Regional Entity (RE) for the Western Interconnection. Has responsibility to help create, monitor, and enforce reliability standards and promote activity that ensures reliability.

- Largest of the six Regional Entities
- Designated as the Regional Entity for the Western Interconnection
- Has responsibility to help create, monitor, and enforce reliability standards and promote activity that ensures reliability
- Service territory
  - Canada (Alberta and British Columbia)
  - Northern part of Baja California, Mexico
  - All or parts of the 14 Western states



Four Interconnections—Six Reliability Entities—One ERO



Regulation: Who, How, Why

2003—The Great Northeast Blackout

https://youtu.be/nd3teNgUq8E?si=B0dDv9riGRAbmS8x

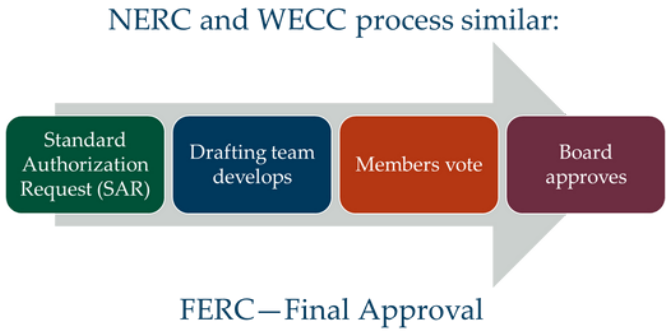
Federal Power Act of 2005

- Federal Power Act, Section 215 calls for enforceable standards
- Industry develops standards, approved by FERC
- FERC certifies an Electric Reliability Organization—the ERO (NERC)
- NERC may delegate authority to Regional Entities; e.g., WECC

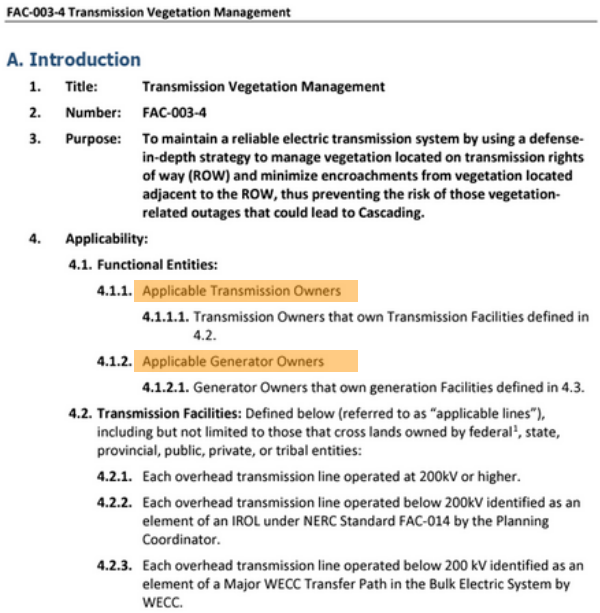
Regional Entities

The Electric Reliability Organization (ERO) Enterprise now encompasses six regional organizations of similar size and complexity. NERC provides industry-wide perspective and oversight, and the Regional Entities have unique features and activities that serve the needs of their regional constituents while ensuring that industry follows NERC Reliability Standards.

Standards Development



NERC Entity Functions



FAC-003-4 Transmission Vegetation Management

A. Introduction

1. **Title:** **Transmission Vegetation Management**
2. **Number:** **FAC-003-4**
3. **Purpose:** **To maintain a reliable electric transmission system by using a defense-in-depth strategy to manage vegetation located on transmission rights of way (ROW) and minimize encroachments from vegetation located adjacent to the ROW, thus preventing the risk of those vegetation-related outages that could lead to Cascading.**
4. **Applicability:**
   - **4.1. Functional Entities:**
     - **4.1.1.** Applicable Transmission Owners
       - **4.1.1.1.** Transmission Owners that own Transmission Facilities defined in 4.2.
     - **4.1.2.** Applicable Generator Owners
       - **4.1.2.1.** Generator Owners that own generation Facilities defined in 4.3.
   - **4.2. Transmission Facilities:** Defined below (referred to as "applicable lines"), including but not limited to those that cross lands owned by federal[1], state, provincial, public, private, or tribal entities:
     - **4.2.1.** Each overhead transmission line operated at 200kV or higher.
     - **4.2.2.** Each overhead transmission line operated below 200kV identified as an element of an IROL under NERC Standard FAC-014 by the Planning Coordinator.
     - **4.2.3.** Each overhead transmission line operated below 200 kV identified as an element of a Major WECC Transfer Path in the Bulk Electric System by WECC.

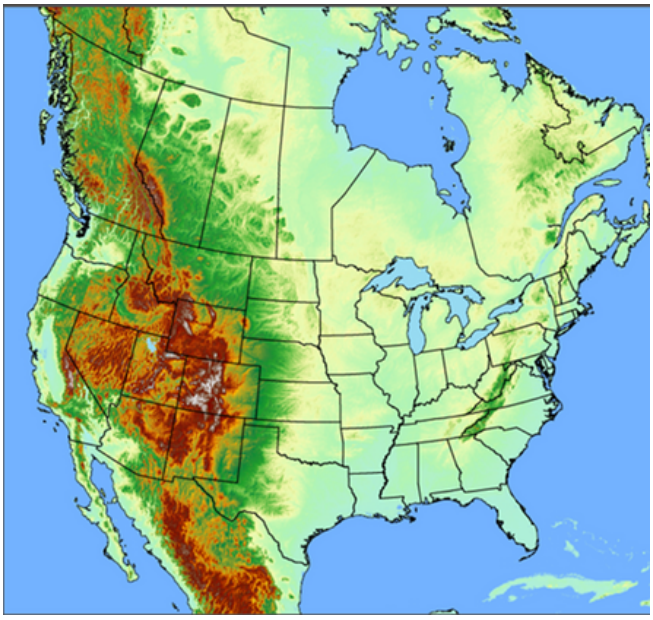
Standards Subject to Enforcement

Acronym	Title	# of Standards
BAL	Resource and Demand Balancing	9
CIP	Critical Infrastructure Protection	12
COM	Communications	2
EOP	Emergency Preparedness and Operations	6
FAC	Facilities Design, Connection, and Maintenance	9
INT	Interchange Reliability Operations and Coordination	4
IRO	Interconnection Reliability Operations and Coordination	13
MOD	Modeling, Data, and Analysis	14
NUC	Nuclear	2
PER	Personnel Performance, Training, and Qualifications	3
PRC	Protection and Control	23
TOP	Transmission Operations	6
TPL	Transmission Planning	2
VAR	Voltage and Reactive	3

Regulation: Who, How, Why

Western Interconnection is Different

- Unique geography
- Longer transmission lines
- Population centers are spread out
- Land uses
  - Nearly 87% of the Western Interconnection is public or protected land,
  - Compare that to just 27% in the combined Eastern, Texas, and Quebec interconnections



The Grid - 20 Years of Progress

https://vimeo.com/844974841/515b516d9c

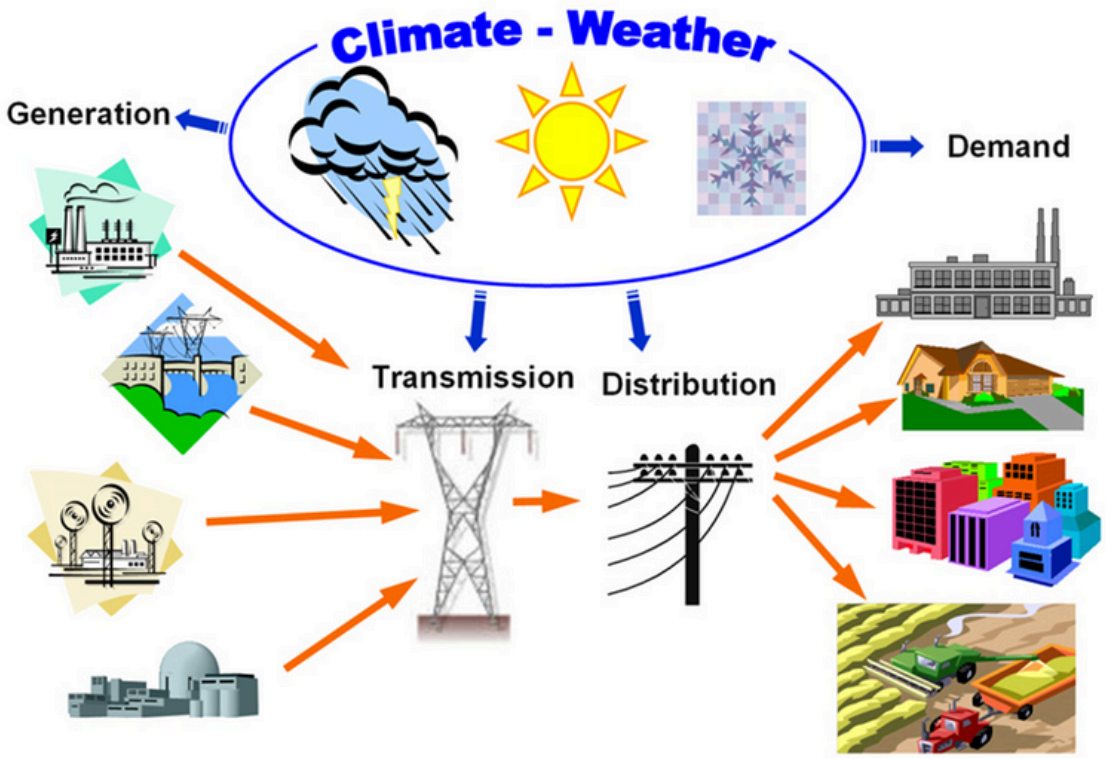
Extreme Natural Events

Environmental Impacts and the Grid

Wildfires	· Effect on electricity transmission and fuel sources for generation
Weather	· Effect on electricity transmission and fuel sources for generation

Extreme Natural Events

Weather Impacts



Notes

Notes

Grid
FUNDAMENTALS

SHARE YOUR FEEDBACK!

TAKE THE
SURVEY

https://www.surveymonkey.com/r/9KPDLHB