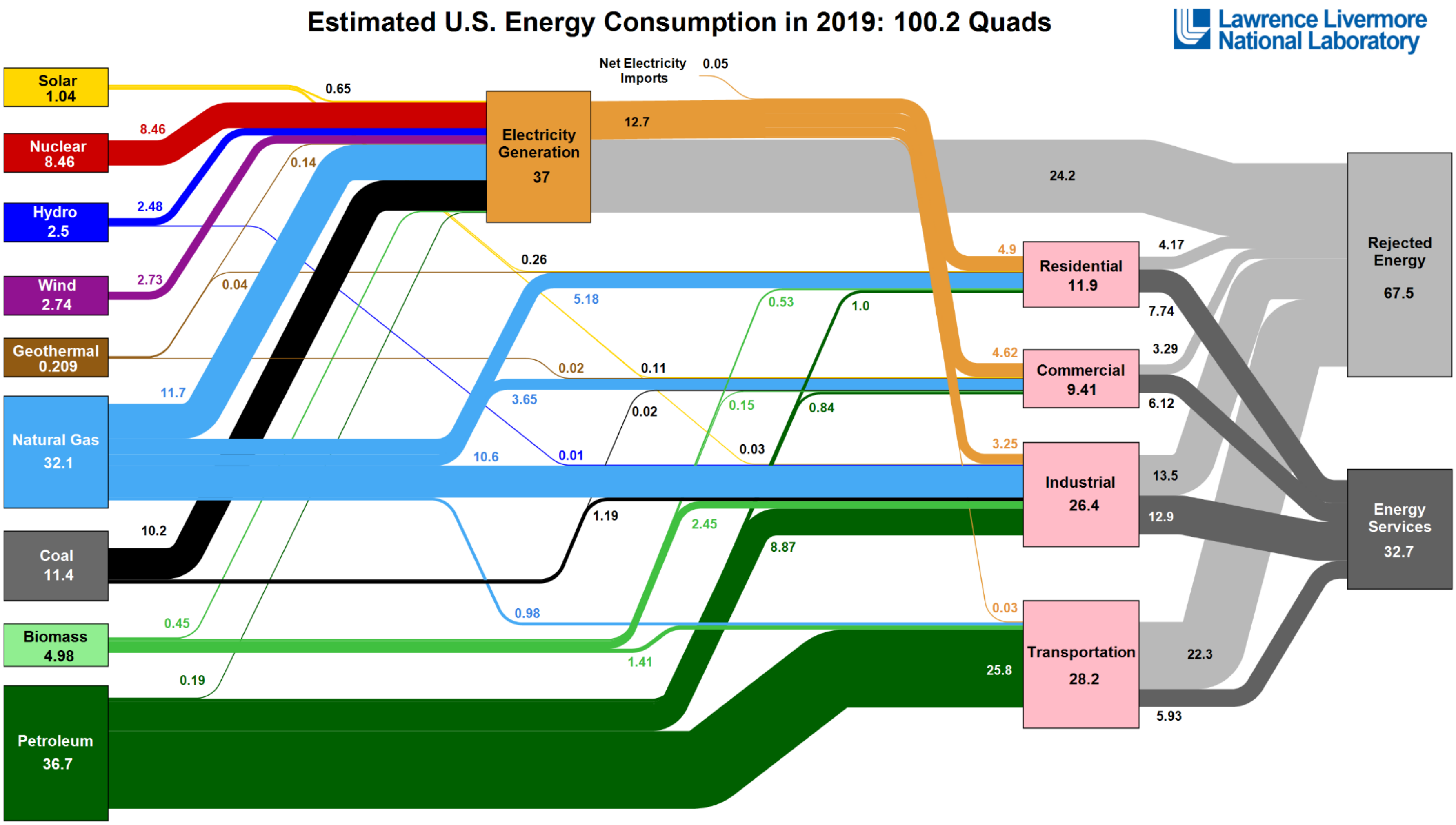
SECTION 1: OVERVIEW OF THE ELECTRICAL GRID

ESE 470 – Energy Distribution Systems

Flow of Energy in the US



https://flowcharts.llnl.gov/content/assets/images/energy/us/Energy_US_2019.png

Energy Distribution

- Energy ***distributed*** to end users in three primary forms:
  - ***Electricity***
  - ***Natural gas***
  - ***Petroleum products***

- Primary energy sources by sector:
  - Residential
    - Electricity – 41%
    - Natural gas – 44%
  - Commercial
    - Electricity – 52%
    - Natural Gas – 40%
  - Industrial
    - Electricity – 13%
    - Natural gas – 38%
    - Petroleum – 33%
  - Transportation
    - Petroleum – 92%

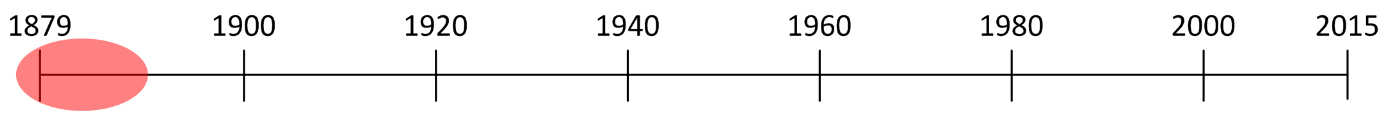
- In this course, we will focus on ***electrical energy distribution***
  - Specifically, the ***electrical transmission and distribution grid***

Energy Distribution and Conversion

- Bulk of distributed energy is ***converted to another form of energy*** by the consumer
  - Typically ***mechanical*** or ***thermal***
- Natural gas/petroleum
  - Energy stored in chemical form
  - No energy conversion prior to distribution
- Electricity
  - Generated by conversion from chemical and/or mechanical energy
  - Converted again by the consumer
- ***Energy conversion is inefficient***
  - Could conceivably distribute energy in desired form, e.g. shafts, pneumatic lines, etc. – terribly inefficient
- ***Conversion inefficiencies (substantial) outweighed by efficiency of distribution***

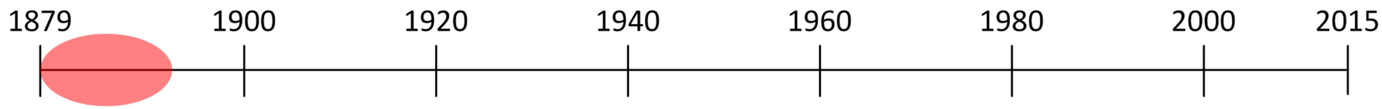
History of Electrical Power Distribution

History of Electrical Power Distribution



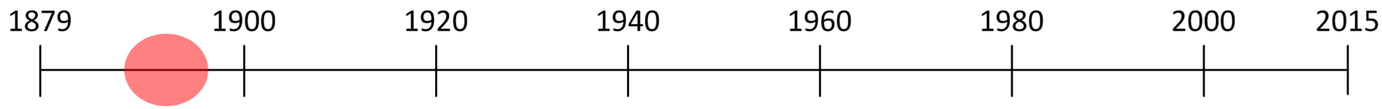
- **<u>1879</u>**
  - Edison develops the electric light
- **<u>1882</u>**
  - Edison launches General Electric with backing of J.P. Morgan
  - Opens Pearl Street Station in New York
    - Steam-driven DC generators
    - 30 kW, 110 V DC
    - 59 Customers
- **<u>1884</u>**
  - Frank Sprague develops a DC motor

History of Electrical Power Distribution



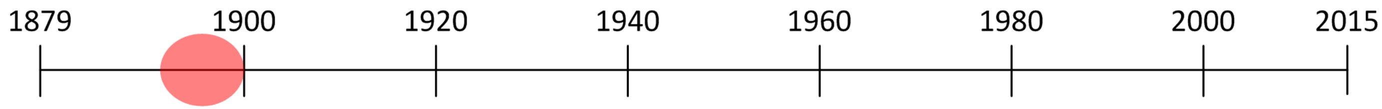
- **<u>1880s</u>**
  - War of Currents
    - Edison and DC power vs. Westinghouse/Tesla and AC power
- **<u>1880s</u>**
  - Tesla introduces AC induction motors/generators
- **<u>1885</u>**
  - William Stanley invents the transformer
    - Enables high-voltage transmission

History of Electrical Power Distribution



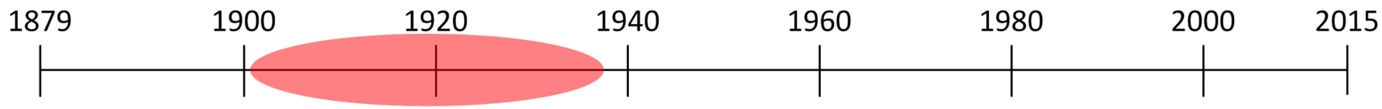
- **<u>1889</u>**
  - First single-phase AC transmission line in the U.S.
    - 21 km, Oregon City to Portland
    - 4 kV
- **<u>1892</u>**
  - Samuel Insull leaves GE for Chicago Edison
    - Father of the U.S. electrical grid
      - Consolidation
      - Mass production
      - Rural Electrification – load balancing
      - Two-part pricing – fixed and variable
      - Networked power – reliability

History of Electrical Power Distribution



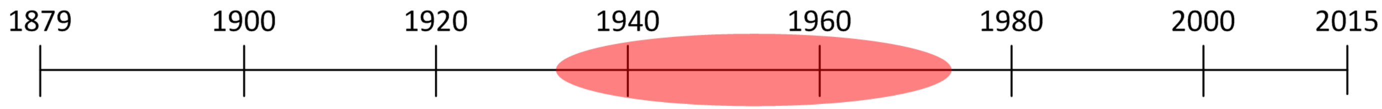
- **<u>1893</u>**
  - First three-phase AC transmission line in the U.S.
    - 12 km, California
    - 2.3 kV
- **<u>1896</u>**
  - Hydro-generated electricity from Niagara Falls powers Buffalo
    - 30 km

History of Electrical Power Distribution



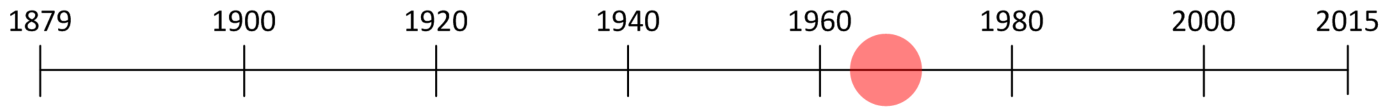
- **<u>Early 1900s</u>**
  - Local utilities form as *vertical monopolies*
    - Generation, transmission, distribution, retail
  - Local regulation fails
  - State public utility commissions established in most states to regulate pricing
  - Holding companies buy up and consolidate local utilities, driving up prices
- **<u>1935</u>**
  - Public Utilities Holding Company Act (PUHCA) passed
    - Breaks up holding companies

History of Electrical Power Distribution



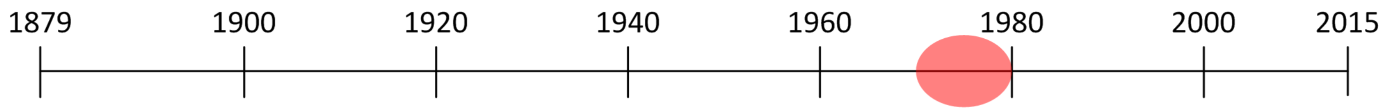
- **<u>1935</u>**
  - Federal Power Act establishes the Federal Energy Regulatory Commission (FERC)
    - Charged with regulating the wholesale power market
- **<u>1947 – 1973</u>**
  - Little change in overall industry structure
    - Average 8% annual growth
    - Steadily decreasing electricity rates

History of Electrical Power Distribution



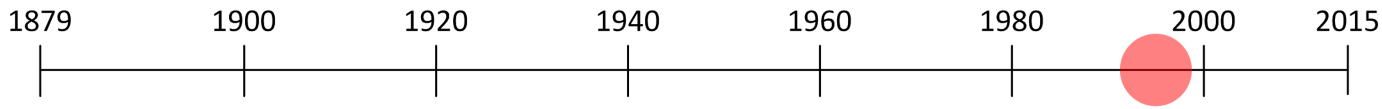
- **<u>1965</u>**
  - Northeast Blackout
    - 30 million customers loose power for over 13 hours
- **<u>1968</u>**
  - North American Electric Reliability Council (NERC) formed
    - Establishes policies and practices to ensure reliability and adequate capacity
    - Compliance is voluntary

History of Electrical Power Distribution



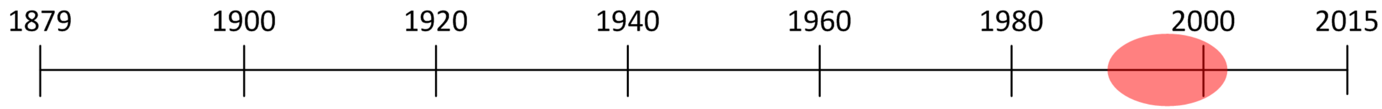
- **<u>1970s</u>**
  - Energy Crisis
  - Rising rates
- **<u>1978</u>**
  - Public Utilities Regulatory Policies Act (PURPA)
    - Utilities required to purchase power from independent generators
    - Increased competition
    - Beginning of a trend toward deregulation

History of Electrical Power Distribution



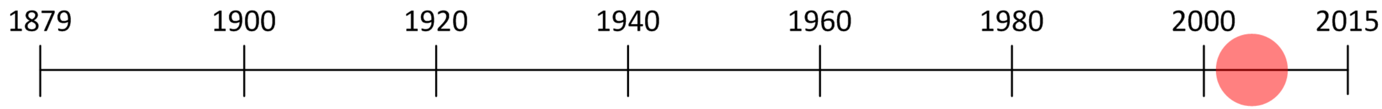
- **<u>1992</u>**
  - Energy Policy Act (EPACT)
    - Required nondiscriminatory access to transmission networks for independent generators
    - Regulatory power shifted somewhat from state to federal level
- **<u>1996</u>**
  - CA and RI pass legislation allowing consumers to choose their power utility
    - Other states follow suit
    - Currently, 16 states allow choice of utility providers

History of Electrical Power Distribution



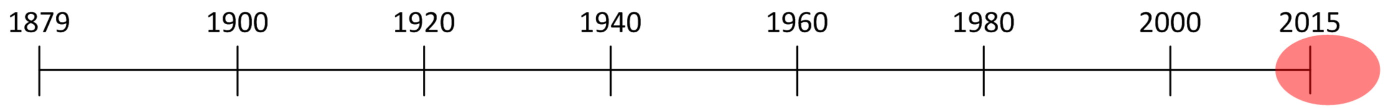
- **<u>1990s</u>**
  - Energy marketers/brokers enter the energy market
    - E.g., Enron
- **<u>2000 – 2001</u>**
  - CA energy crisis
    - Blackouts
    - Caused by market manipulations

History of Electrical Power Distribution

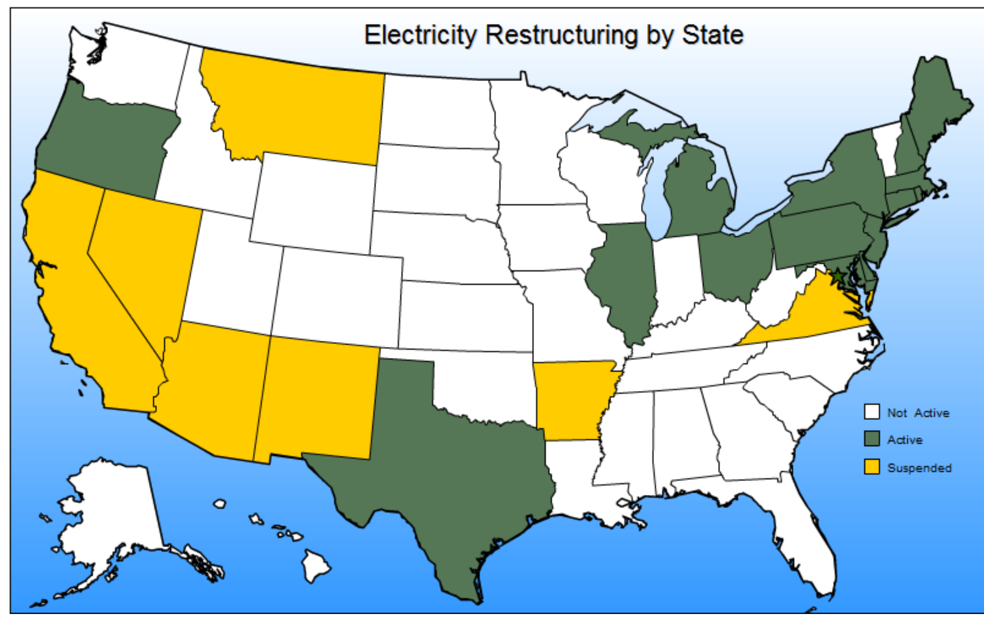


- **<u>2003</u>**
  - Northeast blackout
    - ~50 million people, up to 4 days
    - Failure to follow voluntary NERC guidelines
- **<u>2005</u>**
  - Energy Policy Act of 2005
    - Promotes energy efficiency
    - Repeals PUHCA
    - Amends PURPA
    - Electric Reliability Organization (ERO) to enforce reliability standards
- **<u>2006</u>**
  - FERC grants NERC (now North American Electric Reliability *Corporation*) authority as ERO for the U.S.

History of Electrical Power Distribution



- **<u>Currently</u>**
  - Restructuring and/or deregulation
  - 16 states and D.C. have restructured electricity markets
    - Consumers can choose electric utility
    - Oregon among them (sort of)

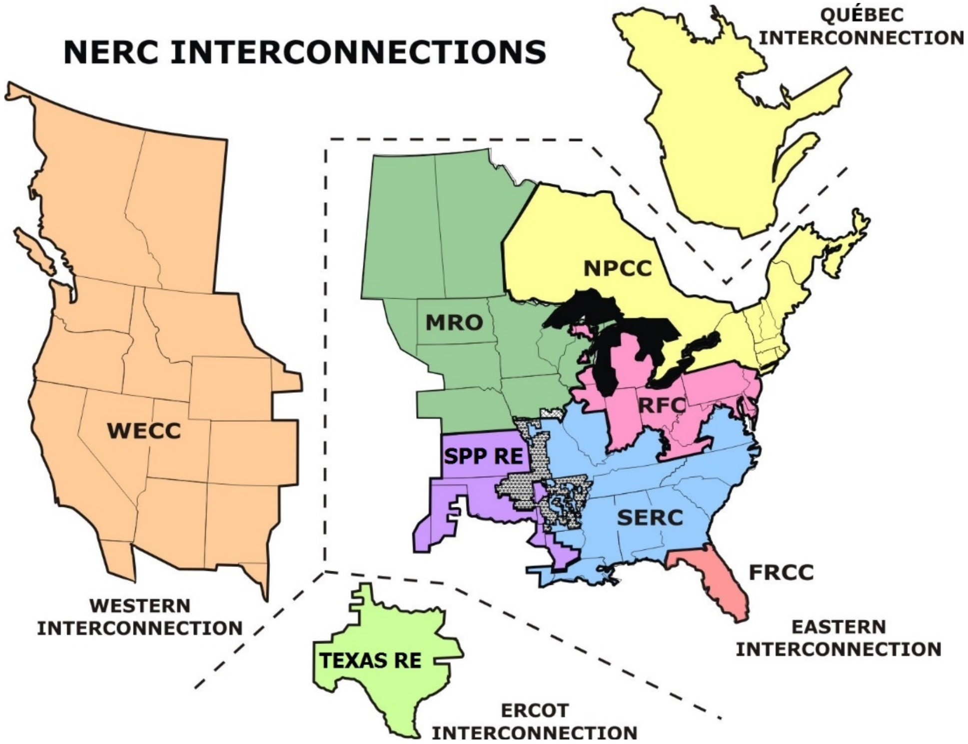


http://www.eia.gov/electricity/policies/restructuring/restructure_elect.html

The US Electrical Grid

US Electrical Grid

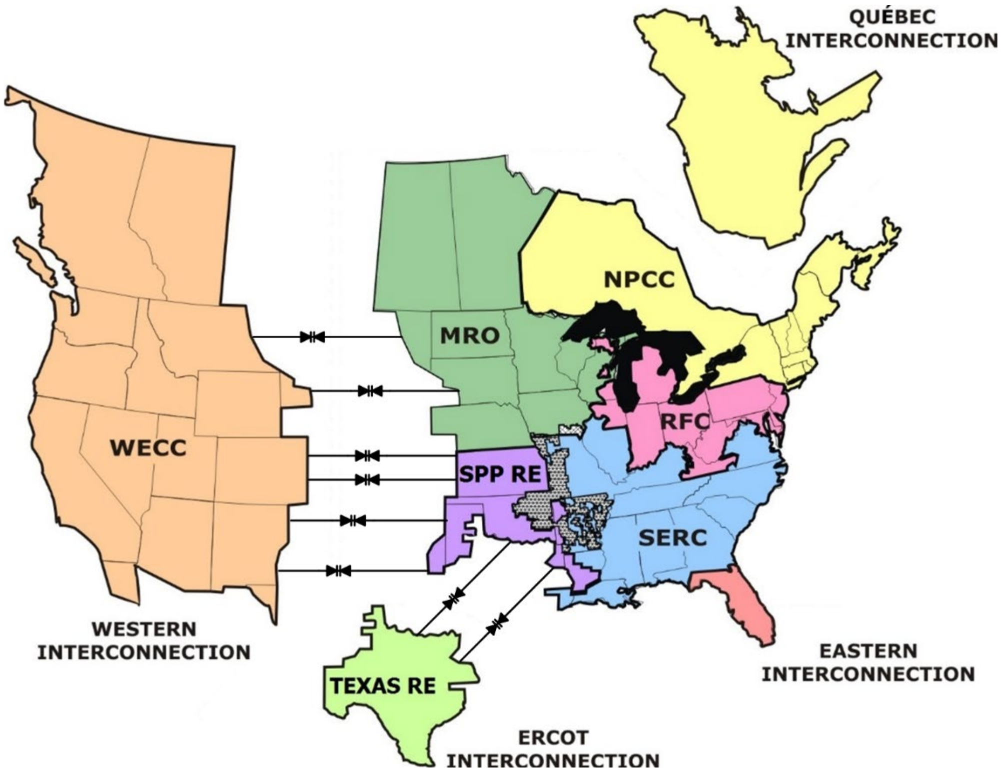
- Five main ***interconnections*** in North America
  - Eastern Interconnection
  - Western Interconnection
  - Texas Interconnection
  - Quebec Interconnection
  - Alaska Interconnection
    - Completely isolated



- Same frequency
  - 60 Hz
- Not synchronous

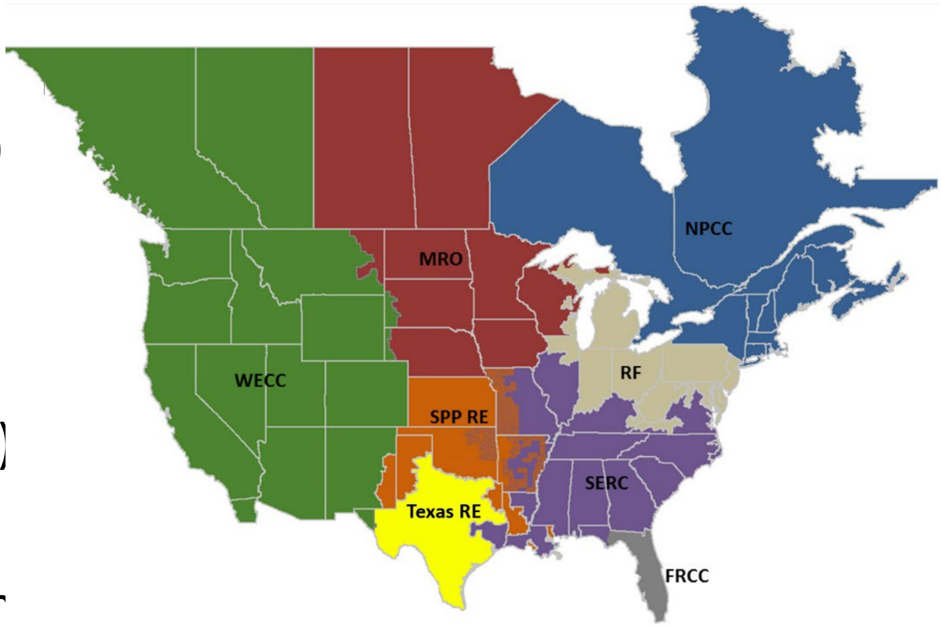
North American Interconnections

- Interconnections are linked by back-to-back DC converters
  - AC-DC-AC
  - Allows for power transfer between interconnections
  - Six between Eastern and Western Interconnections
  - Two between Texas and Eastern Interconnections



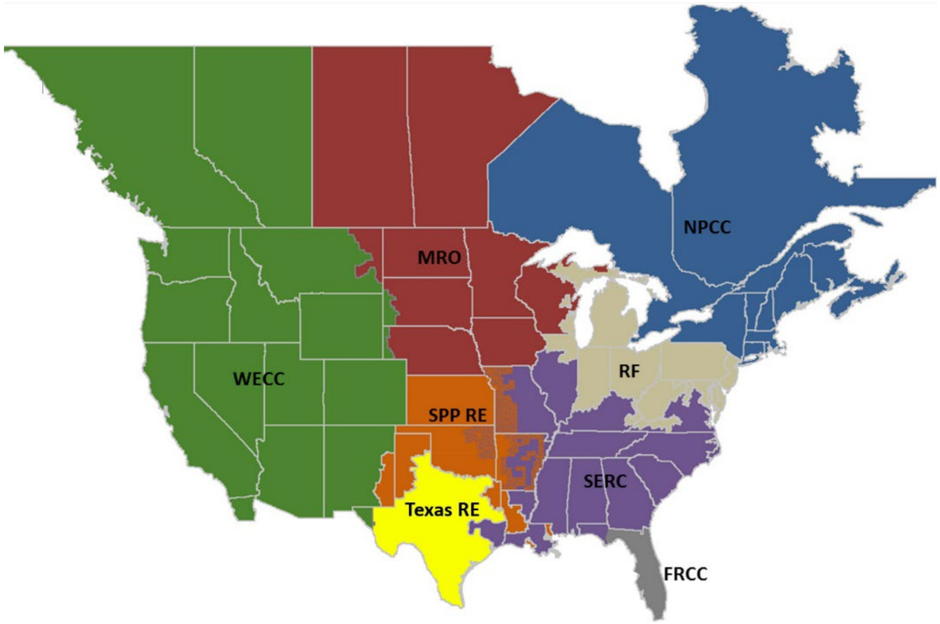
Regional Reliability Councils

- Each interconnection comprised of one or more ***regional reliability councils***
  - **<u>Eastern Interconnection</u>**
    - Florida Reliability Coordinating Council (FRCC)
    - Midwest Reliability Organization (MRO)
    - Northeast Power Coordinating Council (NPCC)
    - Reliability First (RF)
    - SERC Reliability Corporation (SERC) (SERC was Southeast Electric Reliability Council)



Regional Reliability Councils

- **Western Interconnection**
  - Western Electric Coordinating Council (WECC)
- **Texas Interconnection**
  - Texas Reliability Entity (TRE)
- **Alaska Interconnection**
  - Alaska Systems Coordinating Council (ASCC)
- **Quebec Interconnection**
  - Northeast Power Coordinating Council (NPCC)



North American Reliability Corporation

- Regional reliability councils overseen by ***North American Electric Reliability Corporation*** (***NERC***)
  - Designated by the Federal Energy Regulatory Commission (FERC) as the ***Electric Reliability Organization*** (***ERO***) for the US in 2006
  - Mission is to assure reliability of the North American bulk power system
  - Develops and enforces reliability standards
  - Non-profit corporation
  - Subject to FERC oversight

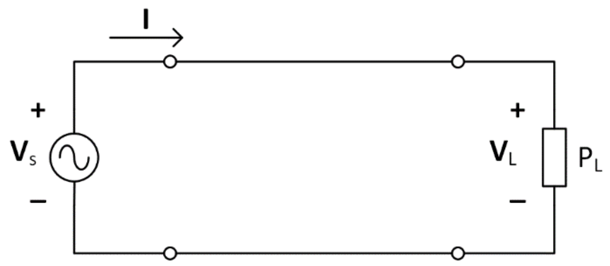
High-Voltage AC Transmission

High-Voltage AC Transmission

- Electrical power is transmitted at high voltages
  - 100s of kV
  - Far exceeding voltages at which it is consumed
  - Why?
- Nearly all electrical power is distributed as AC
  - Much is (or could be) consumed as DC
  - Why?

High-Voltage AC Transmission

- Consider the following extremely simplified circuit modeling a power plant, transmission line, and load



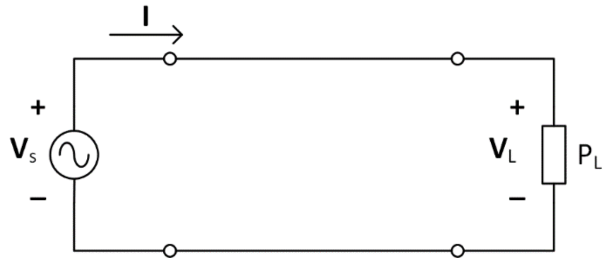
- The power generated (assuming unity power factor)

$$P_S = V_S I$$

- And, since there is no drop along the transmission line, the voltage at the load is the same as at the source

$$\boldsymbol{V}_L = \boldsymbol{V}_S$$

High-Voltage AC Transmission



- Power delivered to the load is the same as that generated by the source

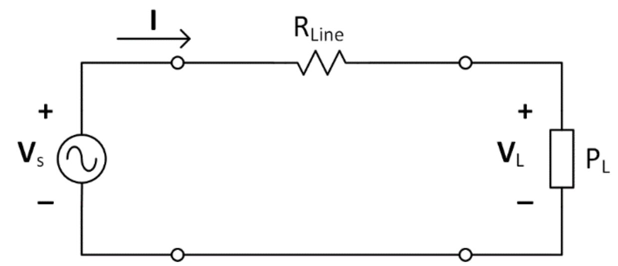
$$P_L = V_L I = P_S$$

- Assume a constant voltage is maintained at the load
  - Power demand at the load (variable) determines the current that must be supplied

$$I = \frac{P_L}{V_L}$$

High-Voltage AC Transmission

- So far, we have assumed an ideal, perfectly conducting (lossless) transmission line
  - Now, account for the non-zero resistance of a real transmission line



- The current required by the load stays the same

$$I = \frac{P_L}{V_L}$$

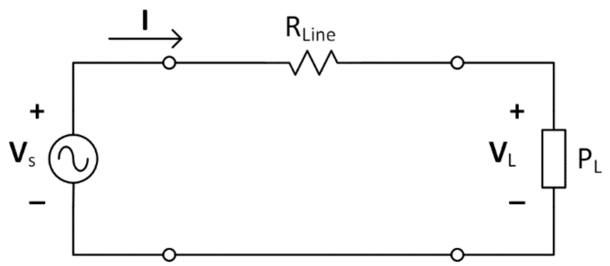
- But now, that current must flow through the line resistance
  - Power is lost in the transmission line

$$P_{Line} = I^2 R_{Line} = \frac{P_L^2}{V_L^2} R_{Line}$$

High-Voltage AC Transmission

- Line loss:

$$P_{Line} = \frac{P_L^2}{V_L^2} R_{Line}$$

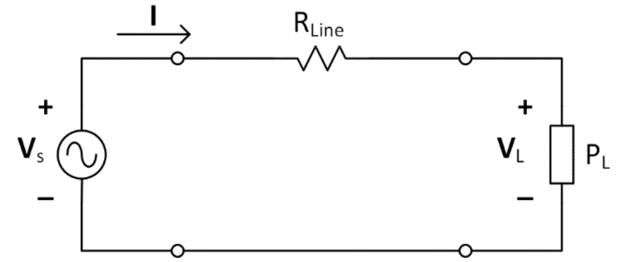


- How can we reduce line losses for a given load power?
  - Reduce line resistance
    - Larger conductors
    - More conductors
    - Higher conductivity
  - Increase line voltage, V_L
    - Step up for transmission, step down for consumption

High-Voltage AC Transmission

- Consider the following example:

$$R_{Line} = 0.5\ \Omega$$
$$P_L = 1\ MW$$
$$V_L = 1\ kV$$



- The current required by the load is

$$I = \frac{P_L}{V_L} = \frac{1\ MW}{1\ kV} = 1\ kA$$

- The power lost in the line is

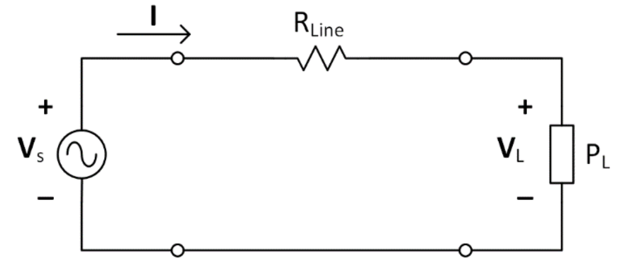
$$P_{Line} = I^2 R_{Line} = (1\ kA)^2 \cdot 0.5\ \Omega$$
$$P_{Line} = 500\ kW$$

- One third of the supplied power is dissipated in the line!
  - Not practical

High-Voltage AC Transmission

- Now, let's increase the line voltage:

$$R_{Line} = 0.5\ \Omega$$
$$P_L = 1\ MW$$
$$V_L = 345\ kV$$



- The current required by the load is

$$I = \frac{P_L}{V_L} = \frac{1\ MW}{345\ kV} = 2.9\ A$$

- The power lost in the line is

$$P_{Line} = I^2 R_{Line} = (2.9\ A)^2 \cdot 0.5\ \Omega$$
$$P_{Line} = 4.2\ W$$

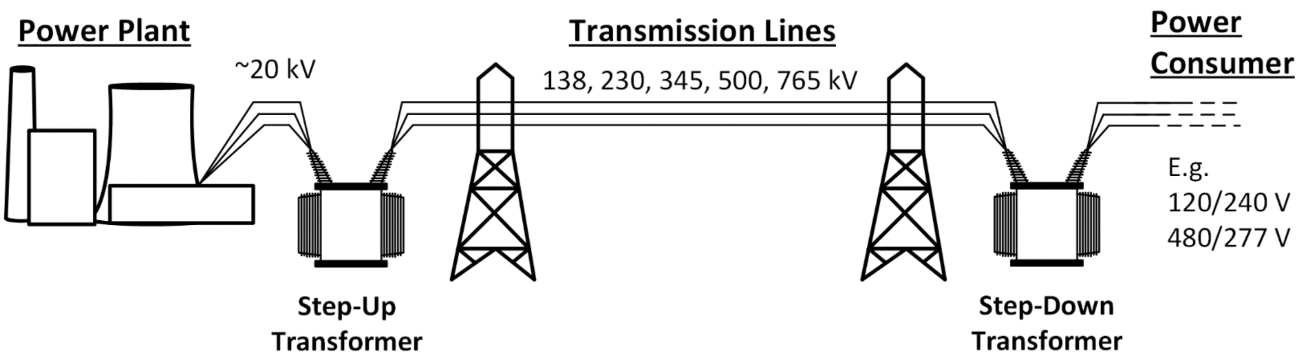
- Line losses reduced by the square of the line voltage increase

High-Voltage AC Transmission

- In the preceding example, the same power was delivered to the load in each case
  - ***High-voltage, low-current transmission results in lower line losses***
- This example illustrates why electrical power is transmitted at high voltage
  - But why is it transmitted as AC?
- Generators at power plants generate voltages in the range of 20 kV
  - How is that voltage increased to transmission voltages (e.g. 230 kV, 345 kV, 500 kV, 765 kV…)?
  - ***Transformers***
  - Transformers only work with AC voltages

High-Voltage AC Transmission

- Step-up transformers used to increase generation voltages (~20 kV) to transmission voltages (100s of kV)



- Step-down transformers used to decrease transmission voltages to levels used by consumers (e.g. 3-ϕ 480 V or 1-ϕ 120 V)

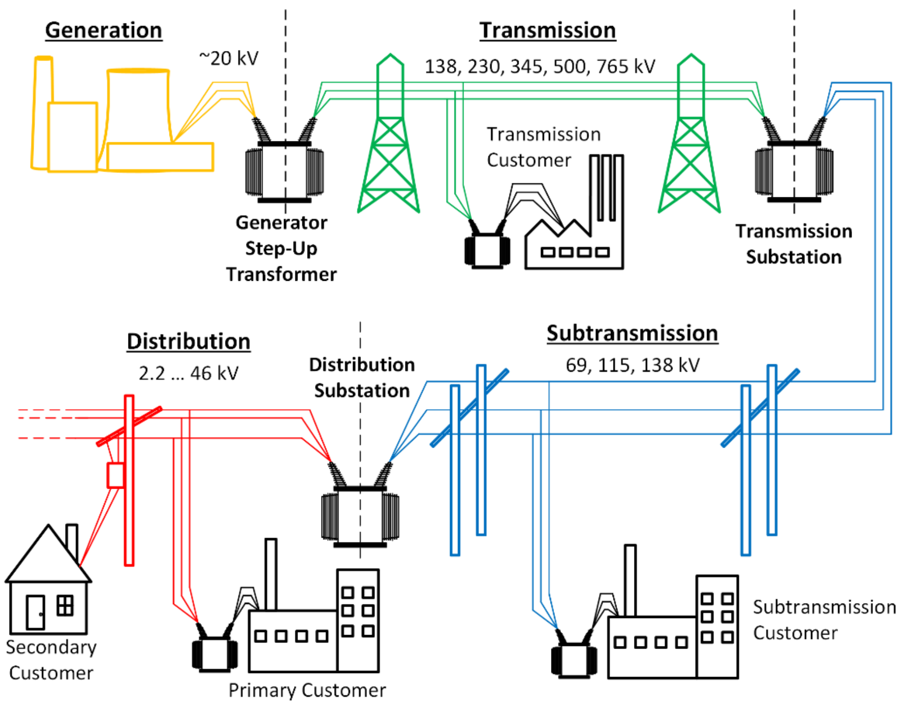
- Advances in power electronics have made it more practical to convert DC to step up/step down DC voltages
  - HVDC transmission
  - More on this topic later in the course

The Electrical Grid

Electrical Power Distribution System

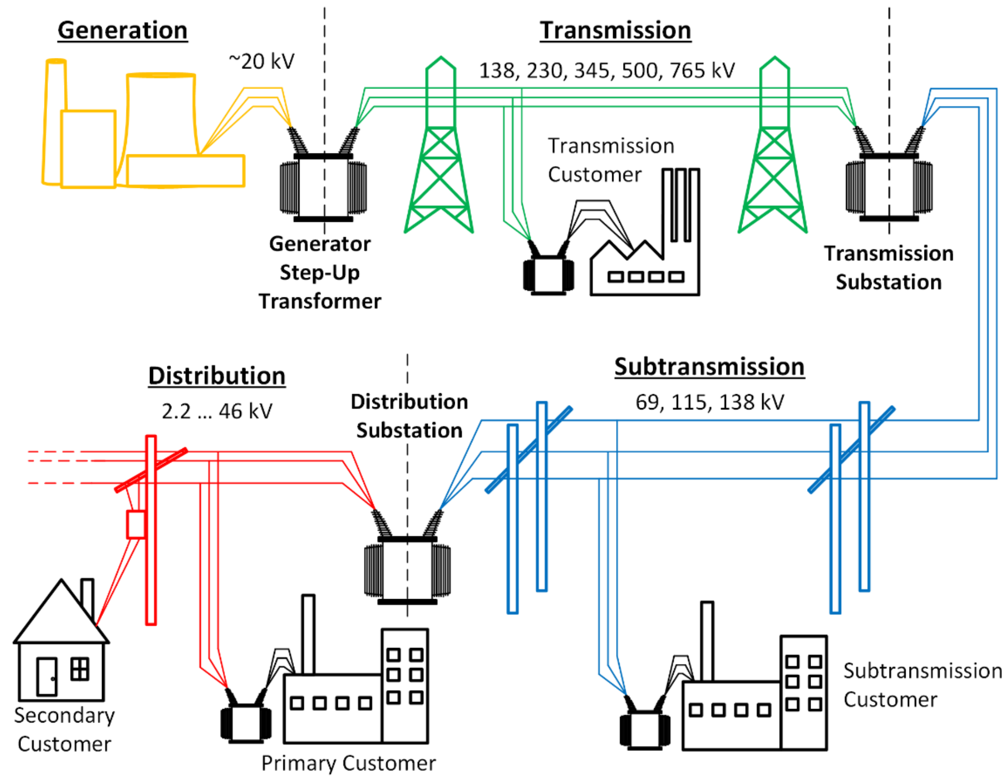
- Three primary components of the electrical distribution system
  - ***Generation***
    - ESE 450
  - ***Transmission***
    - Transmission
    - Subtransmission
  - ***Distribution***
    - Primary distribution
    - Secondary distribution

ESE 470



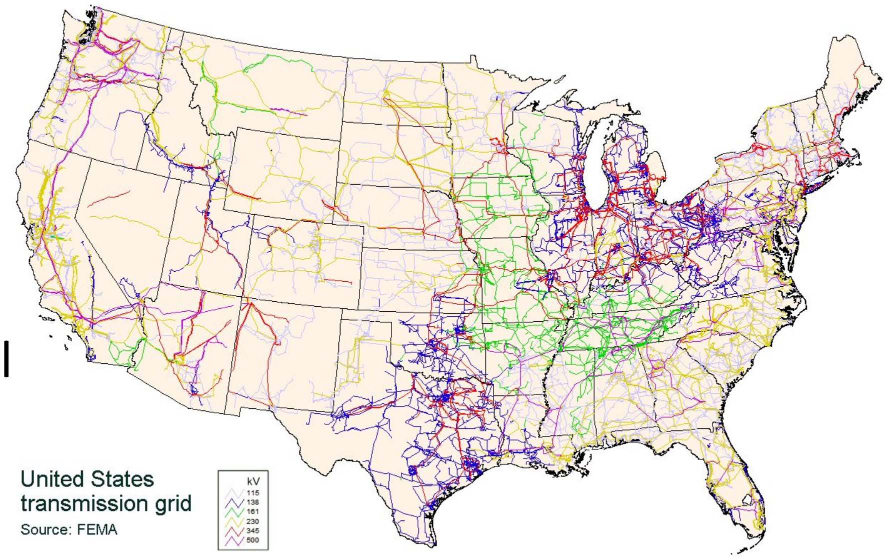
Generation

- ***Generation***
  - Turbine turns a generator
  - ~20 kV AC output
  - 100s of MW
  - Transformers step up output to extra-high voltage (EHV) for transmission
    - 100s of kV



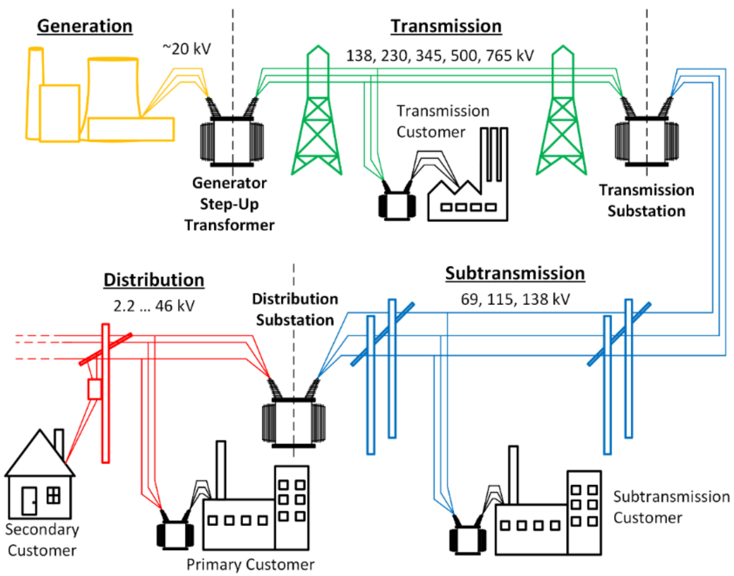
Transmission Network

- Provides ***bulk power*** from generators to the grid
- Interconnection point between separate utilities or separate generators
  - Power bought and sold at this level
- ***High voltage*** for low loss, long-distance transmission
  - 230…765 kV
  - Generator step up transformers at power plant
- ***High power***
  - 400…4000 MVA per three-phase circuit
- Transmission network terminates at ***bulk-power*** or ***transmission substations***



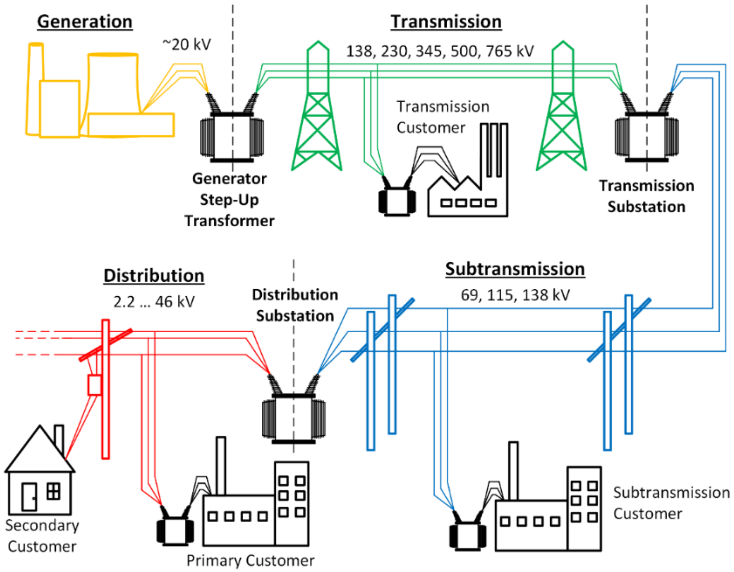
Subtransmission Network

- Voltage stepped down at ***bulk-power*** or ***transmission substations***
  - Typically 69 kV, but also 115 and 138 kV
- Large industrial customers may connect directly to the subtransmission network
  - Voltage stepped down at customer's substation
- Subtransmission network terminates at ***distribution substations***



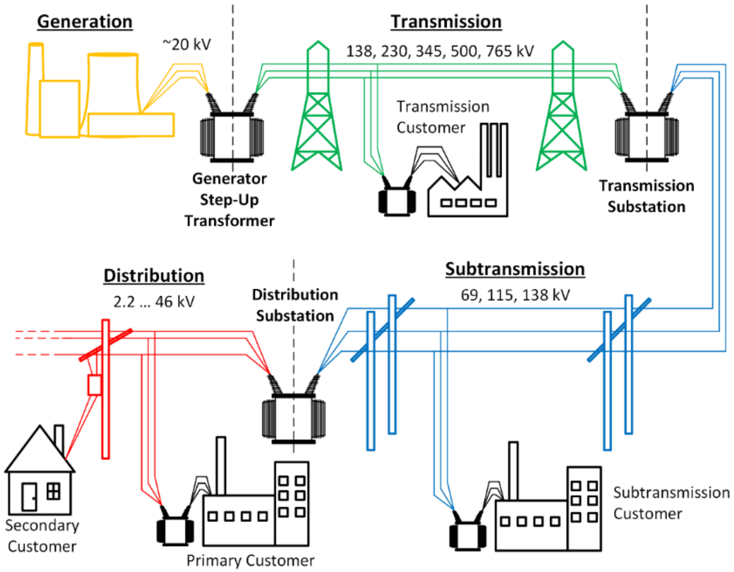
Primary Distribution Network

- Voltage stepped down at ***distribution substations***
  - 2.2 kV … 46 kV
  - 4 MVA … 30 MVA
- ***Feeders*** leave substations and run along streets
- ***Laterals*** tap off of feeders and run along streets
- Primary distribution network terminates at ***distribution transformers***



Secondary Distribution Network

- ***Distribution transformers*** step voltage down to customer utilization level
  - Single-phase 120 V … three-phase 480 V
- Secondary distribution is the connection to the customer
- May connect to a ***secondary main***
  - Serves several customers
- Or, one distribution transformer may serve a single customer



Course Overview

- Our focus:
  - How electricity gets from where it is generated to where it is consumed
    - The ***transmission*** and ***distribution*** networks
    - ***Modeling*** of equipment
    - ***Analysis*** of behavior

Section 1
- Overview of the Electrical Grid

Section 2
- Three-Phase Power Fundamentals

Section 3
- Power Transformers

Section 4
- Transmission Lines

Section 5
- Power Flow Analysis

Section 6
- High-Voltage DC Transmission

Section 7
- Fault Analysis

Section 8
- System Protection

Section 9
- Electrical Distribution System