Why use electrical energy?

- Electricity delivers energy:
  - Cleanly
  - Efficiently
  - Economically
  - Flexibly

What is its main drawback?

- Storing large amounts of electrical energy is difficult or expensive
- Electrical energy must be delivered as a continuous process
- Rate of energy delivery i.e., power, is a fundamental concept
- Reliable, continuous delivery requires coordinated operation of a set of devices i.e., a **power system**

What are the attributes of a good power system?

- Reliability
- Economy
- Sustainability
- These objectives conflict:
  - Improving reliability costs money
  - Cheapest form of electricity generation are not always sustainable

Physical structure of power systems

- Multiple sources connected to multiple loads
- Enhances reliability
  - Single failure does not result in a loss of power to the consumers
- Improves economy
  - Aggregating loads reduces the amount of generation capacity needed
  - Load can be supplied by most economical generation
- Supports sustainability
  - Aggregated wind and solar generation is less variable and more predictable

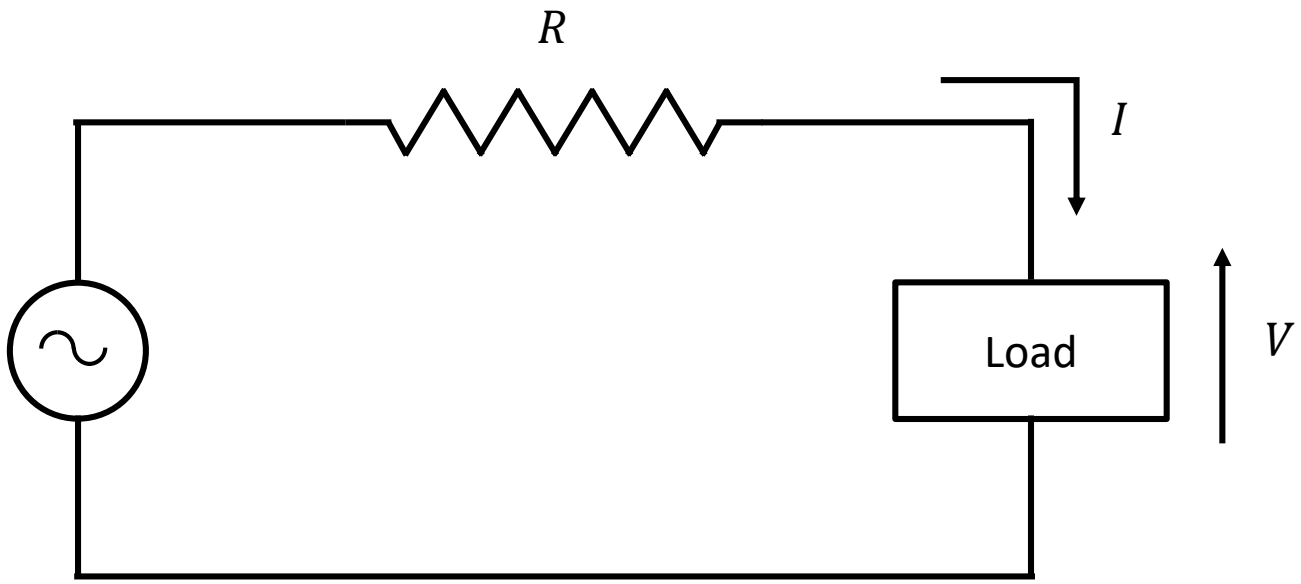
Why ac?

$$P_{load} = V.I$$

$$P_{losses} = I^2 R$$

$$P_{losses} = \frac{P_{load}^2}{V^2} R$$

Operating at higher voltages significantly reduces losses



Why ac?

Voltage	Relative Losses
110 V	1
220 V	0.25
13 kV	$71.6\ 10^{-6}$
132 kV	$694.4\ 10^{-9}$
345 kV	$101.7\ 10^{-9}$

ac transformers

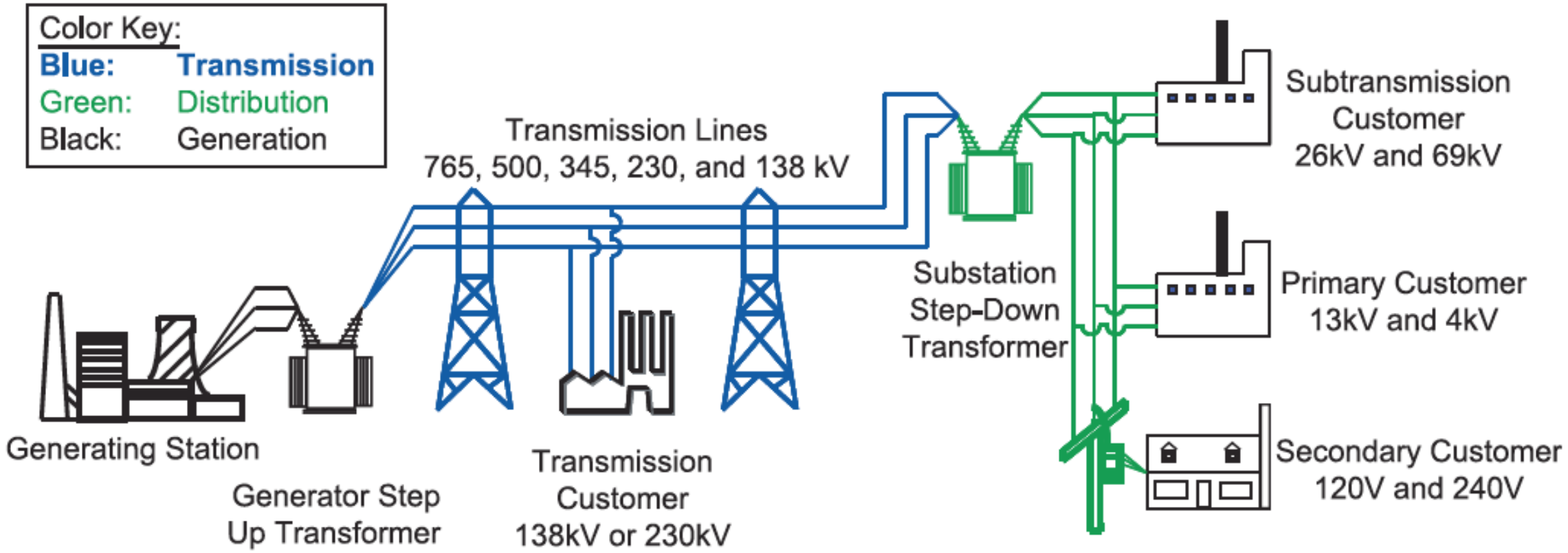
- Step-up the voltage
- Step-down the voltage
- Relatively cheap
- Highly reliable
- Must balance
  - Safety
  - Cost
  - Practicality

→ Use different voltages at different locations





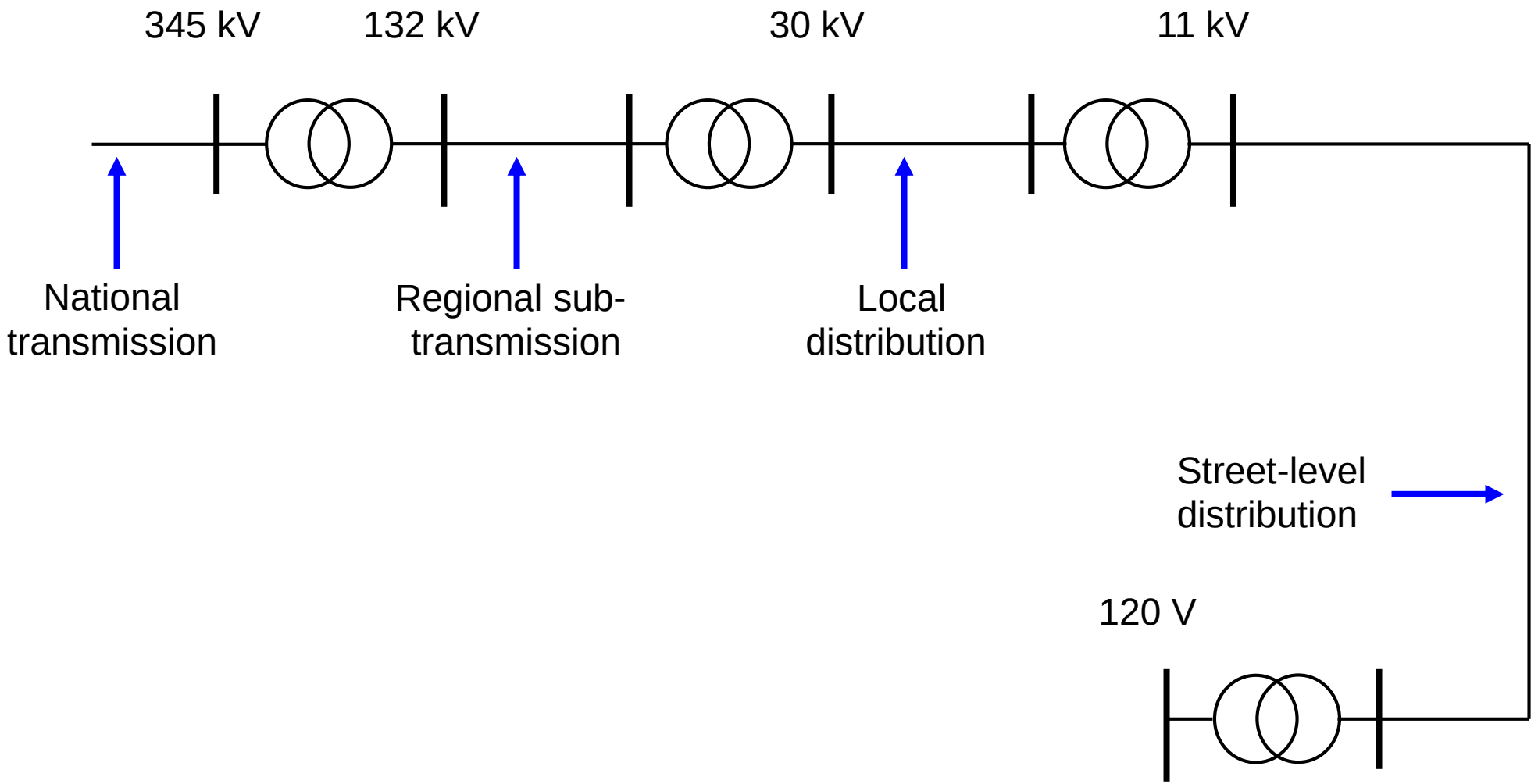
Typical operating voltages in large power systems



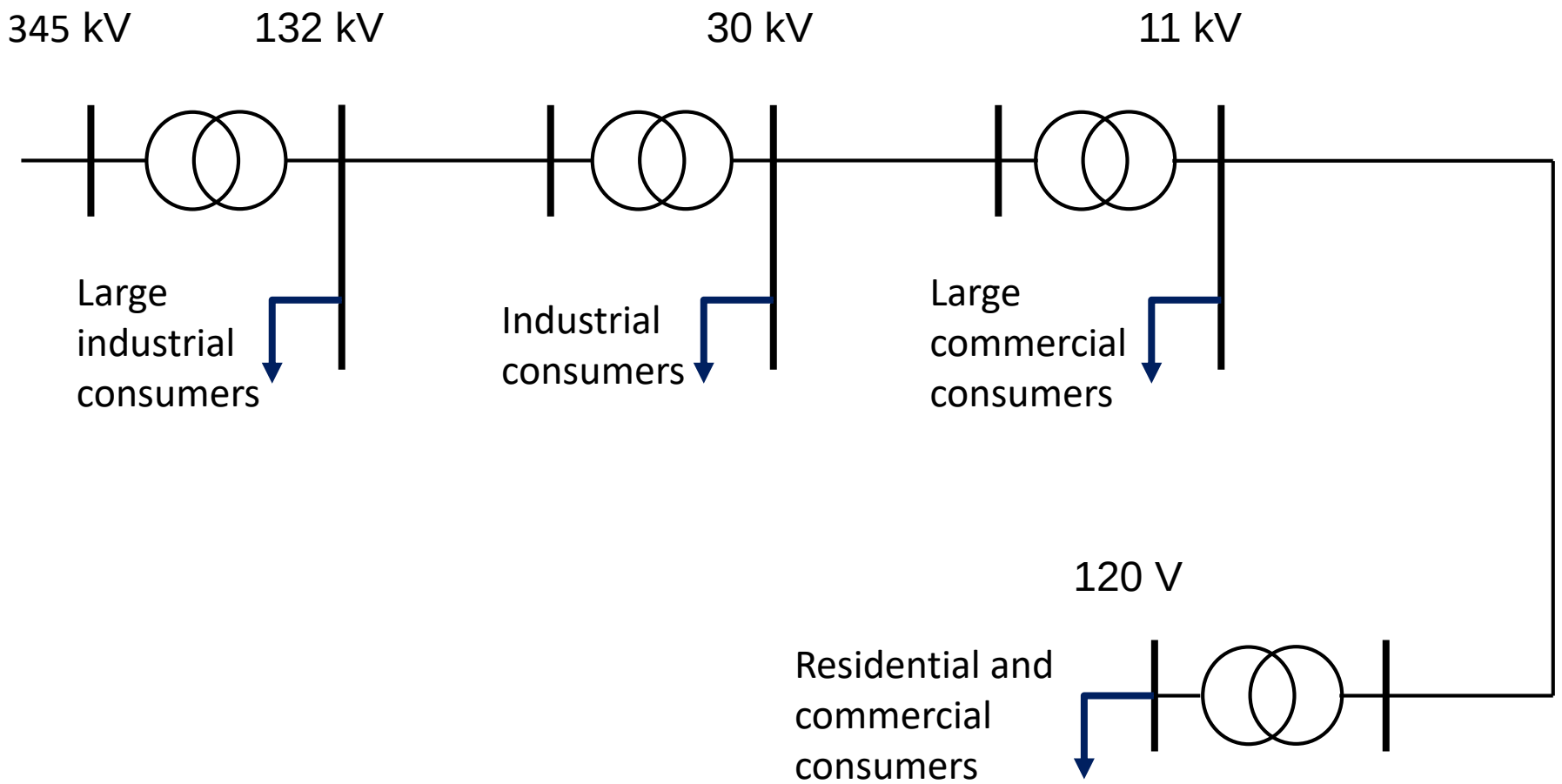
On average, only about 5% of the electrical energy generated in the United States is dissipated as losses in the transmission and distribution networks. Most of these losses occur in the low voltage distribution networks.

Image: United States Department of Energy, Blackout 2003, "Final Report on the August 14, 2003, Blackout in the United States and Canada: Causes and Recommendations"

Typical voltage levels



Typical consumer connections



Transmission and distribution networks

Transmission network:

- Transmit large amounts of power over long distances
- Meshed network
- Redundant paths:
  - Improve reliability
  - Improve economics
- Requires sophisticated protection schemes against faults

Distribution network:

- Distribute power to consumers over a limited area
- Typically, radial network
  - Except in some dense urban areas
- Lower reliability
  - Acceptable because faults affect fewer consumers
- Radial networks require less sophisticated protection schemes against faults

Centralized and distributed generation

Centralized generation

- Conventional generation
  - Coal plants
  - Gas plants
  - Hydro plants
  - Nuclear plants
- Renewable generation
  - Wind farms
  - Solar farms
- Connected to the transmission network

Distributed generation

- Rooftop solar panels
- Connected to the distribution network

What about high voltage dc transmission?

- Requires power electronics
- Convert high voltage ac into high voltage dc at one end of the line
- Convert dc back into ac at the other end
- These converter stations are very expensive
- Justified when:
  - A lot of power must be transmitted over a long distance
    - Transmitting this power using ac could create stability problems
  - Two power systems operating at different frequencies must be connected
  - A long underground or submarine cable is required

Cyber infrastructure



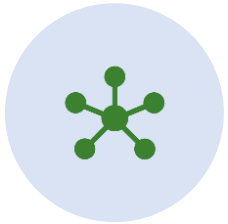
CONTROL SYSTEMS



RELAYS



METERS



COMMUNICATION NETWORKS



COMPUTERS



CONTROL CENTERS

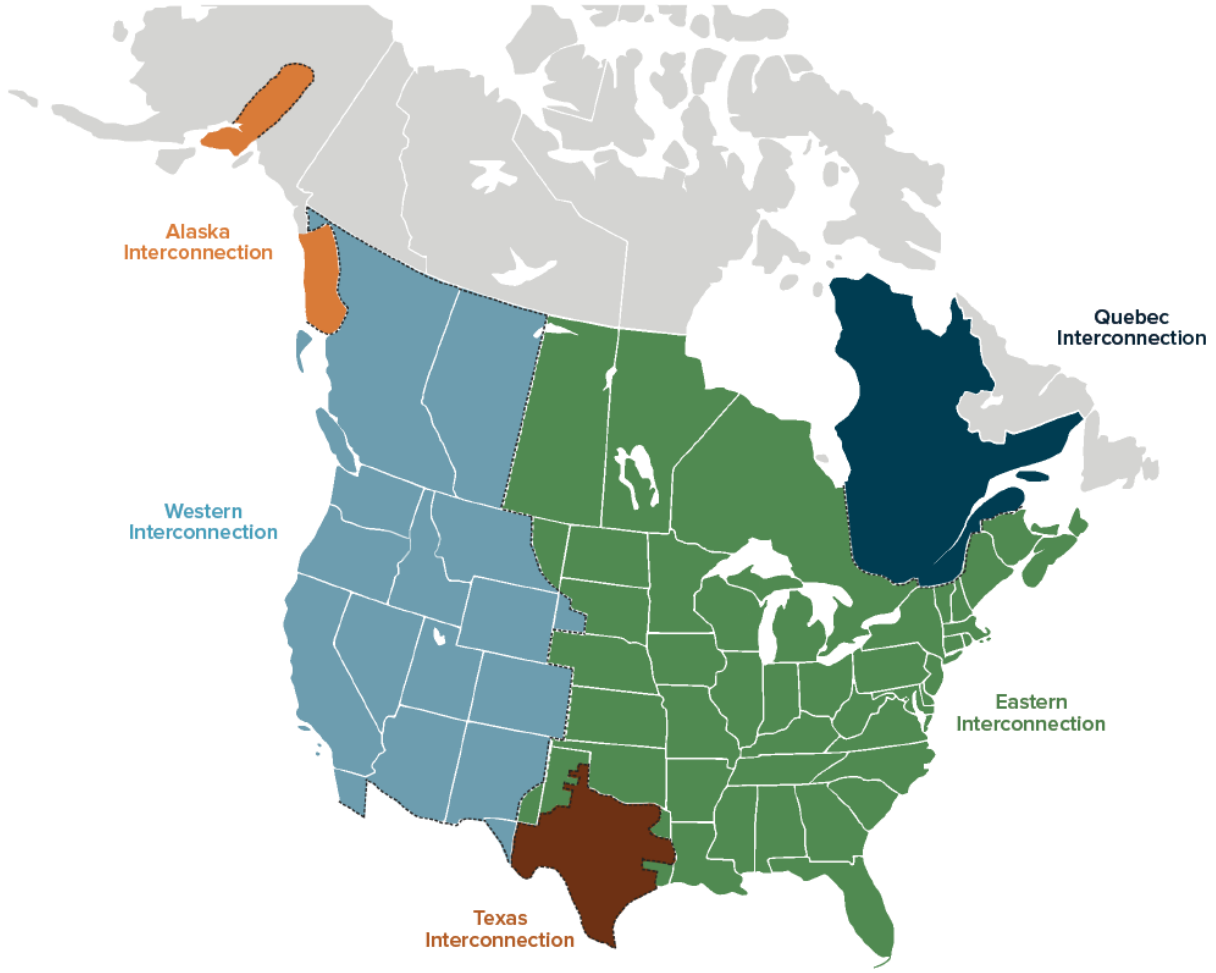
Organizational structure

- Traditional electric utility
  - Owns and operates all the generation, transmission, and distribution assets
  - Has a monopoly for the sale of electricity over its service territory
  - Vertically integrated monopoly
  - Investor-owned utilities are regulated by government body
- Unbundled competitive market
  - Generating companies compete to sell electrical energy in open market
  - Transmission and distribution remain regulated monopolies
  - System operator is responsible for reliability and efficient operation
  - In some locations consumers buy electricity from their local distribution utility
  - On other locations, they have a choice of supplier
- More details in Chapter 12

Historical evolution

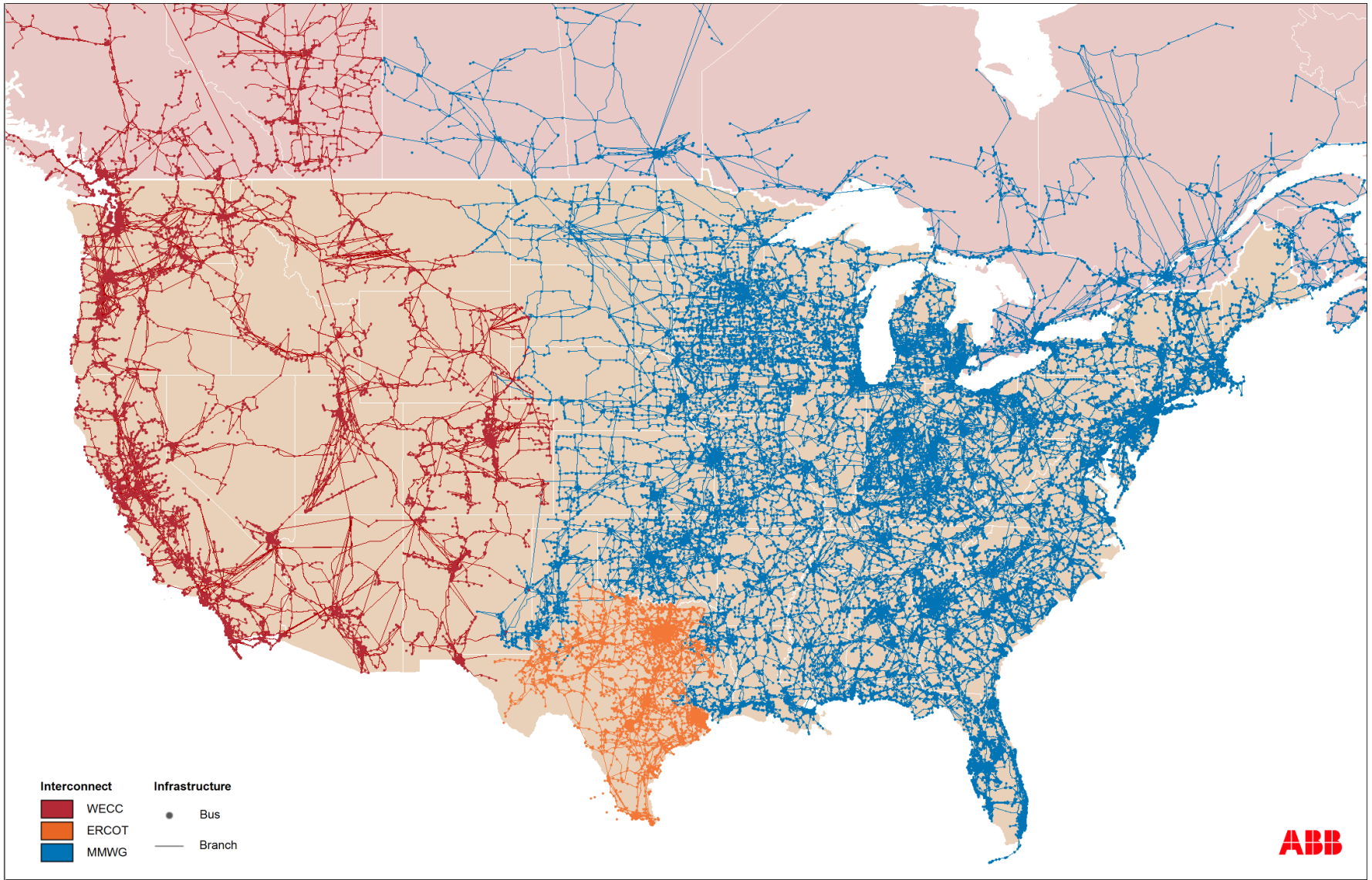
- Originally:
  - Local generation supplying local consumers
  - Mostly in urban areas
- Economic and reliability benefits
  - Development of transmission lines connecting remote generation to cities
  - Interconnections between power systems
- 1930s: large scale rural electrification
- 1950s-1960s: development of continent-scale interconnections

North-American interconnections



Source: Congressional Budget Office

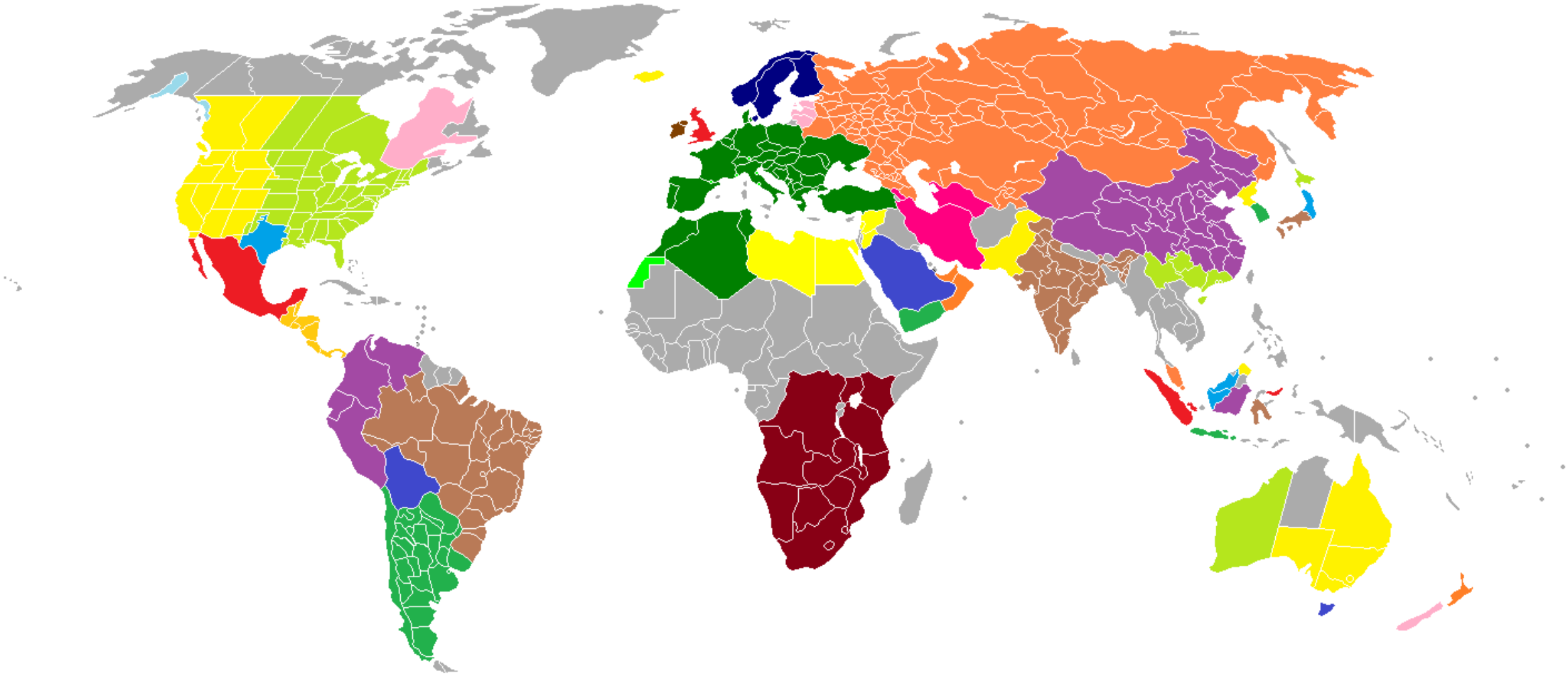
North-American interconnections



Interconnected network of Continental Europe

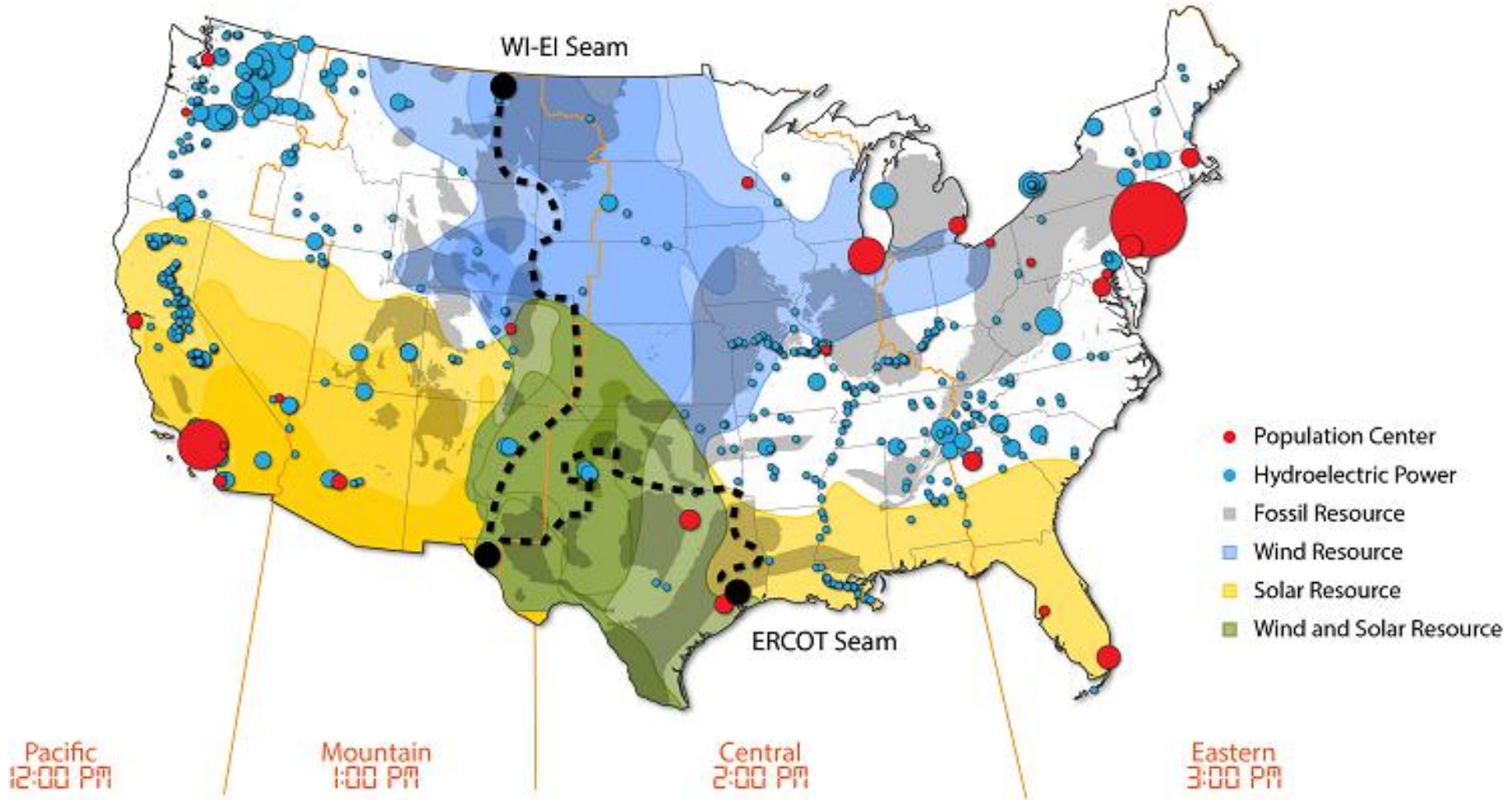


Worldwide interconnections



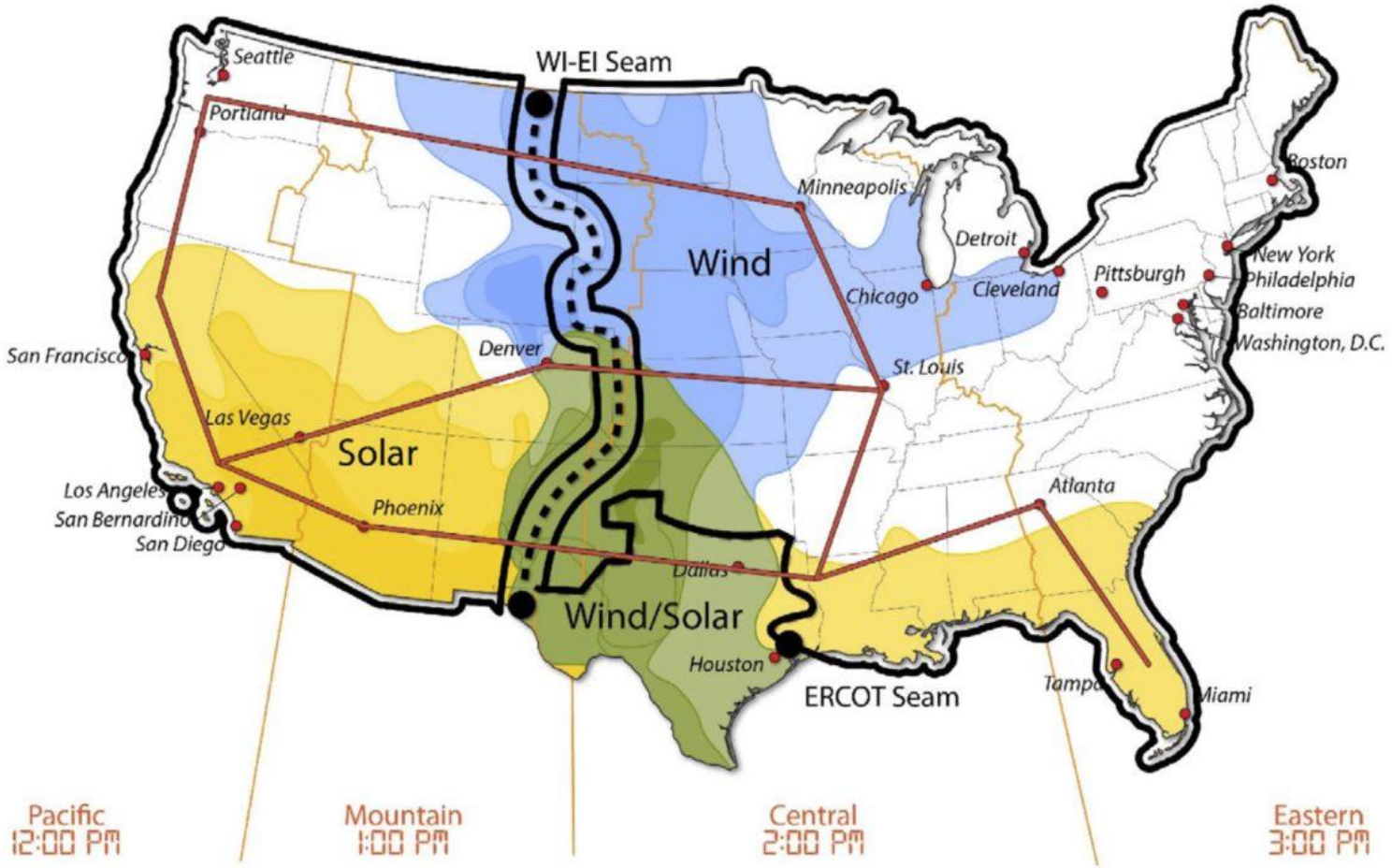
By Alinor at English Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=30154547

Best renewable resources and largest load centers



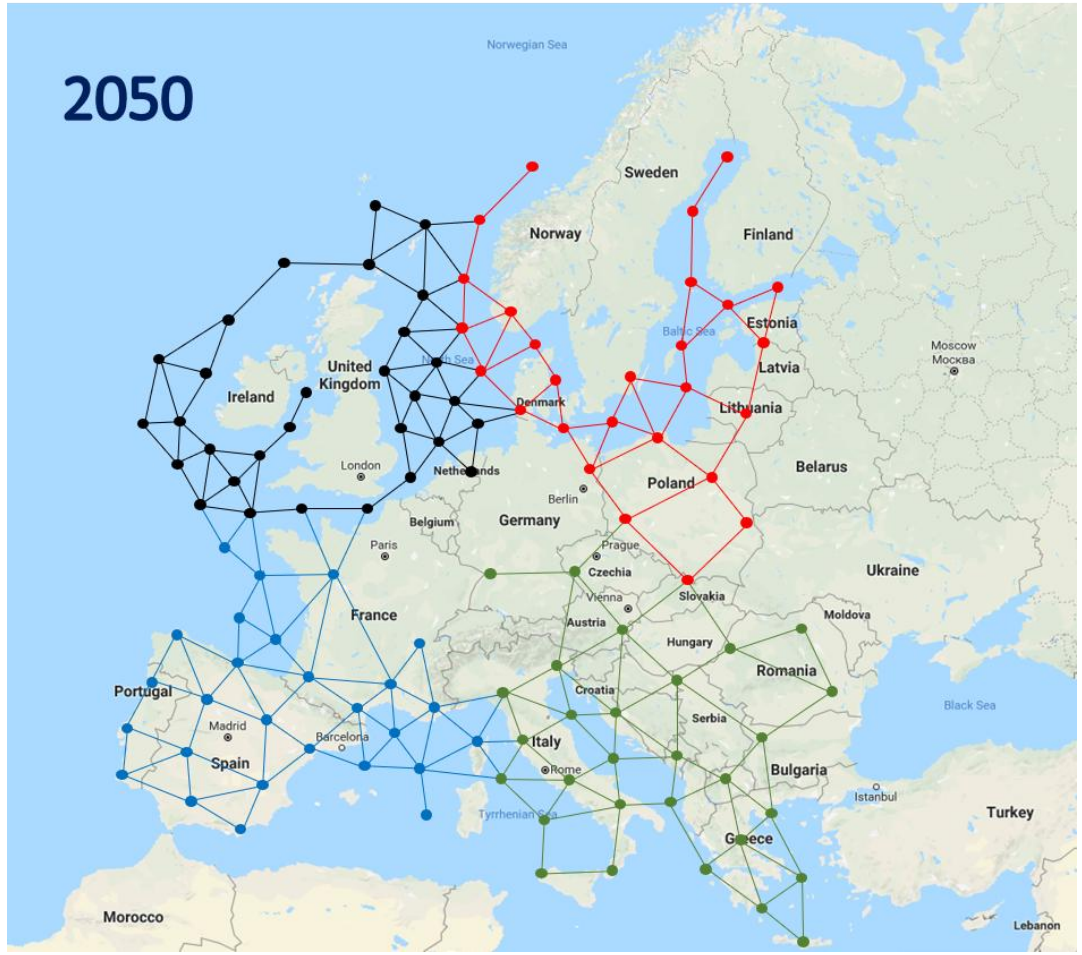
Source: NREL

Proposed United States supergrid



Source: NREL

Proposed European supergrid



Emphasis on offshore wind

Residential and commercial solar generation





Connected to the distribution network

Microgrids

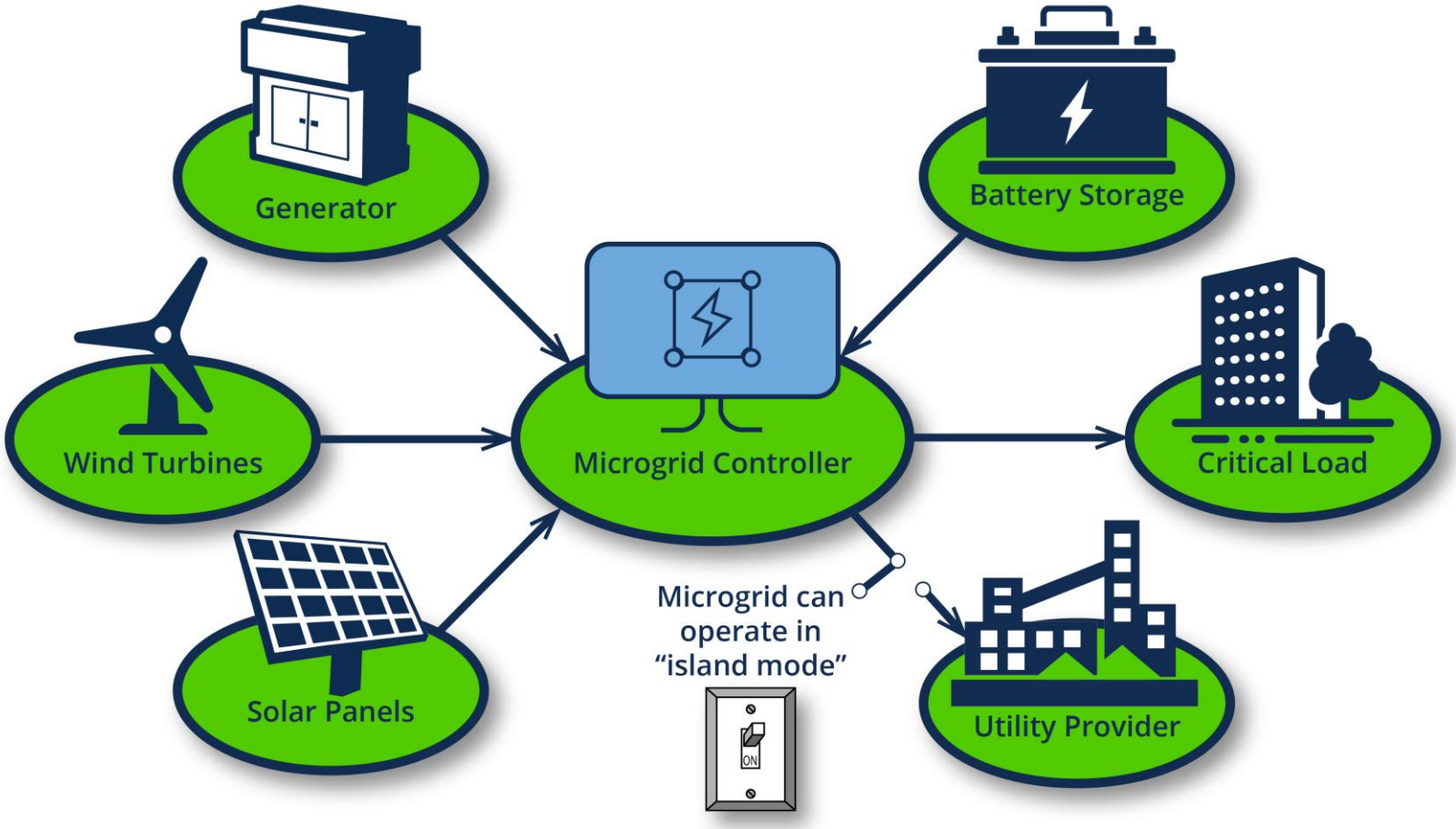


Image: MESA Solutions