Energy Transmission

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Electrical Transmission
Definitions

- Energy is the capacity to do work

- Power is energy per time interval
(Watt, horsepower, etc)

- Running a 100 Watt motor for one hour requires 100 Watt-hours of energy. The amount of work one horse can do in an hour is a horsepower-hour.

- 1 Watt-hour = 859.8 calories
- 1 horsepower = 746 watts

Electrical Transmission
Definitions

- The magnitude of electricity is characterized by two parameters: voltage (potential) and current.
- The garden hose analogy:
  - Voltage is like pressure
  - Current is like the flow rate
- The amount of power delivered is proportional to the voltage times the current

Electrical Transmission

Definitions

- V (voltage) = 110 volts,
  I (current) = 10 Amperes (amps)
  Power = 110 * 10 = 1100 Watts
  Why 110 volts?
- Power = 100,000 volts * 10 amps = 1 Million Watts (1 MegaWatt)
- High voltage or high current or both will be needed for large-scale power transmission

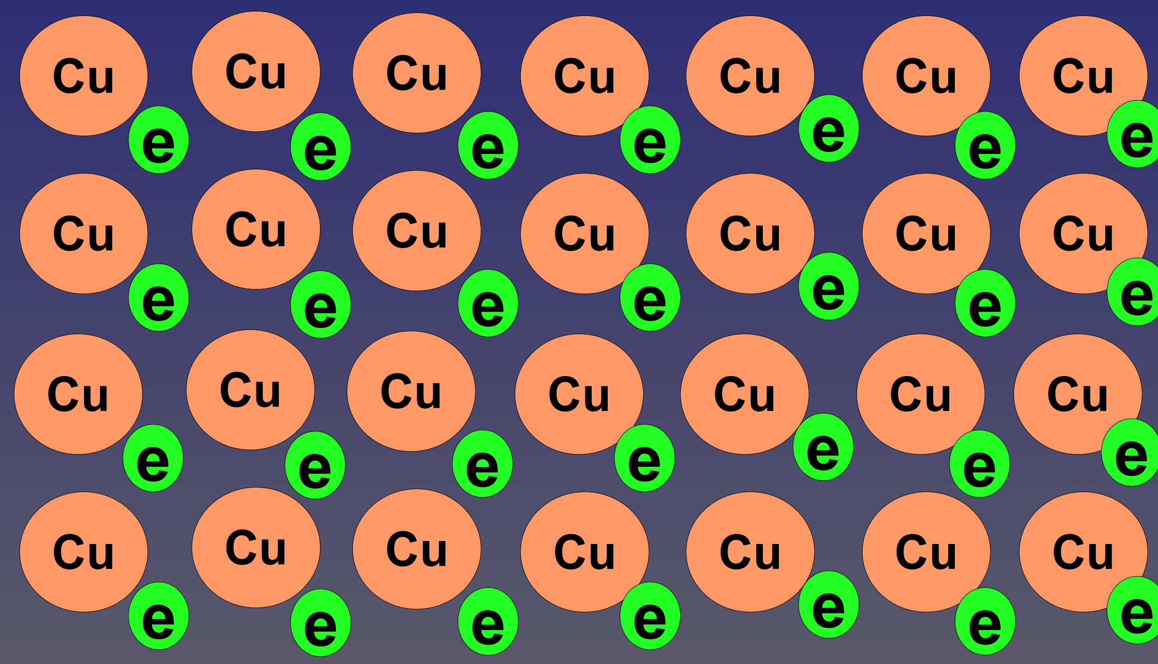
Electrical Transmission
Definitions

- Resistance: The resistance of an object to the flow of electric current
- Insulators have a very high resistance, and conductors have a low (not zero) resistance
- Superconductors have zero resistance (more later)

Electrical Transmission

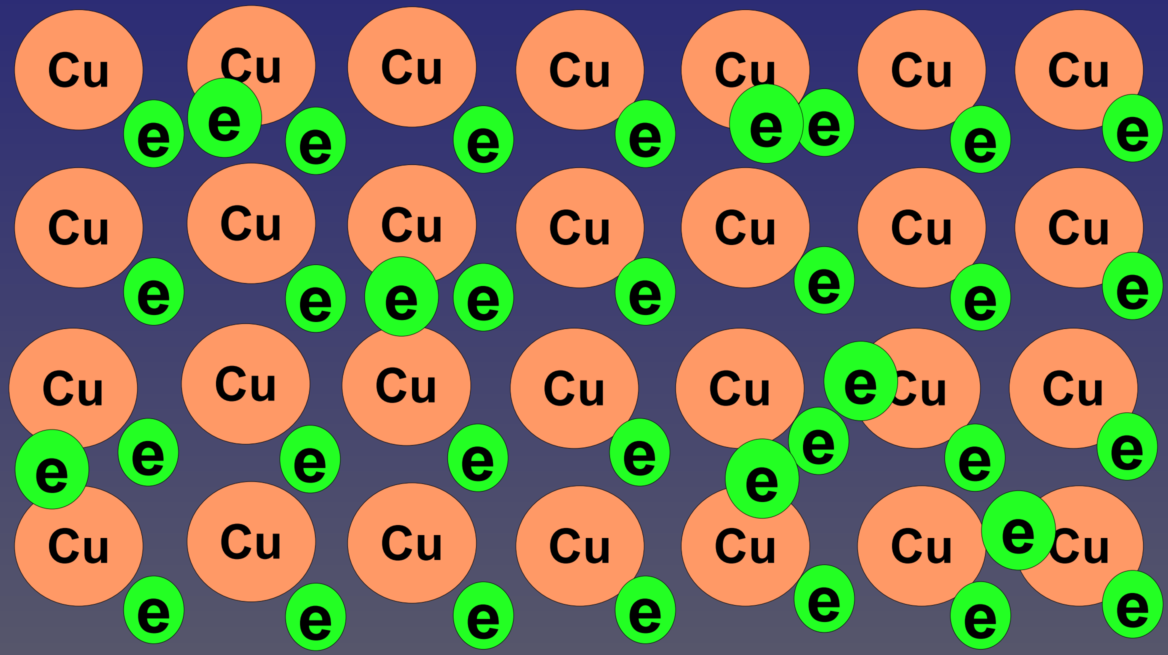
What is electric current?

- Copper: 29 protons(+) and 29 electrons(-)
- Equal numbers of + and minus charges cancel each other
- One electron from each atom is free to move through the space between atoms



Electrical Transmission
What is electricity?

- When extra electrons are present, the copper becomes negatively charged, it has a negative voltage

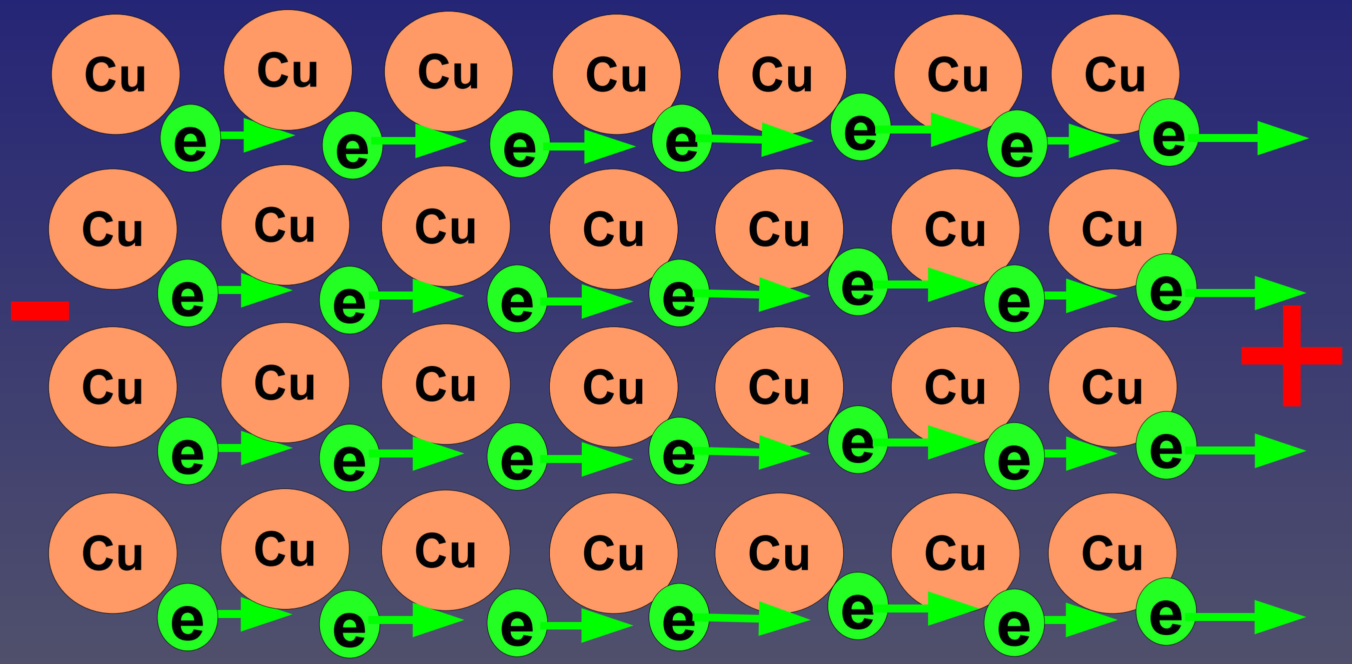


Electrical Transmission

What is electricity?

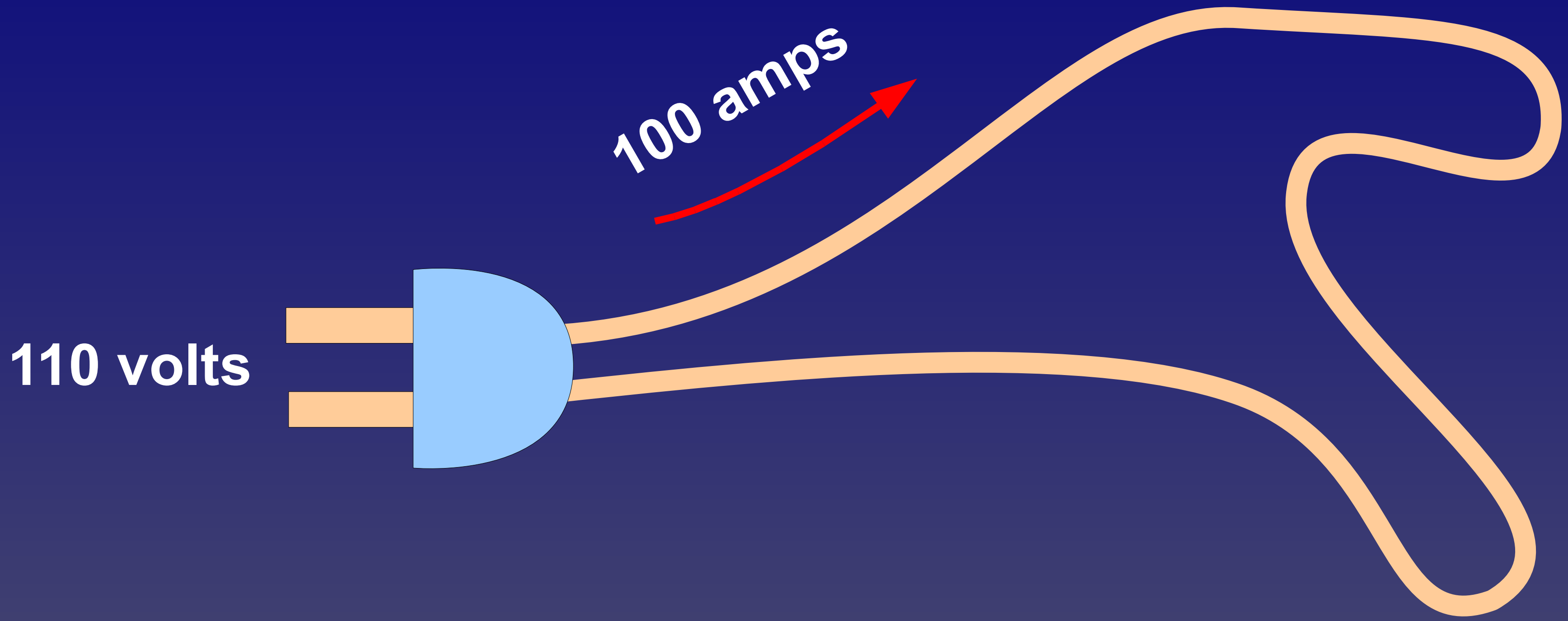
When the voltage varies through the copper, the free electrons are forced along from the negative part to the positive part. This is an electric current.

The movement is not completely free. The electrons bounce around and slow down. That creates resistance.



Electrical Transmission

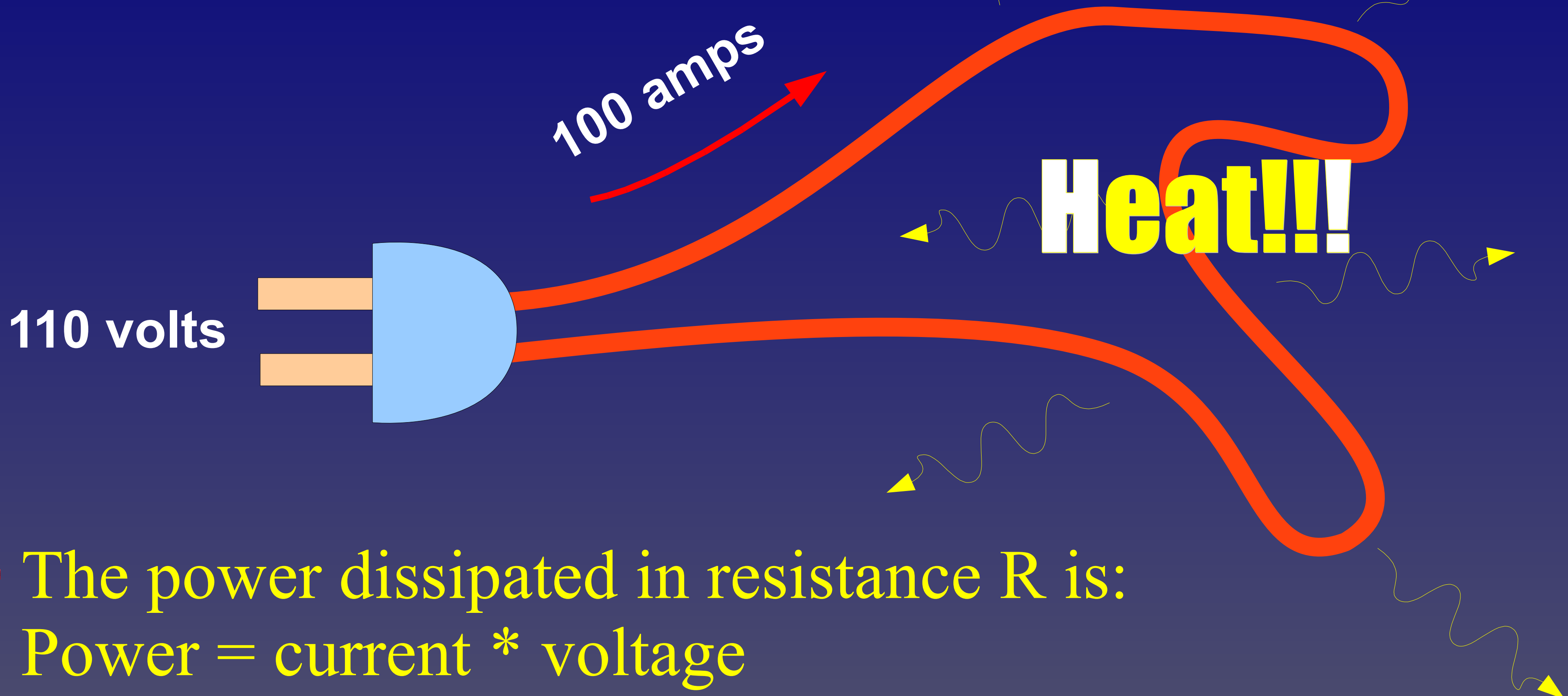
Power considerations



110 volts * 100 amps = 11,000 watts. Where does the energy go?

Electrical Transmission

Power considerations



- The power dissipated in resistance R is:
  Power = current * voltage
  $= current^2 * R = 11{,}000$ watts
- High current produces energy loss in wires

Don't try this at home!!!

Electrical Transmission
High voltage

- Power = V*I Loss = $R*I^2$
  Fractional loss = I*R / V

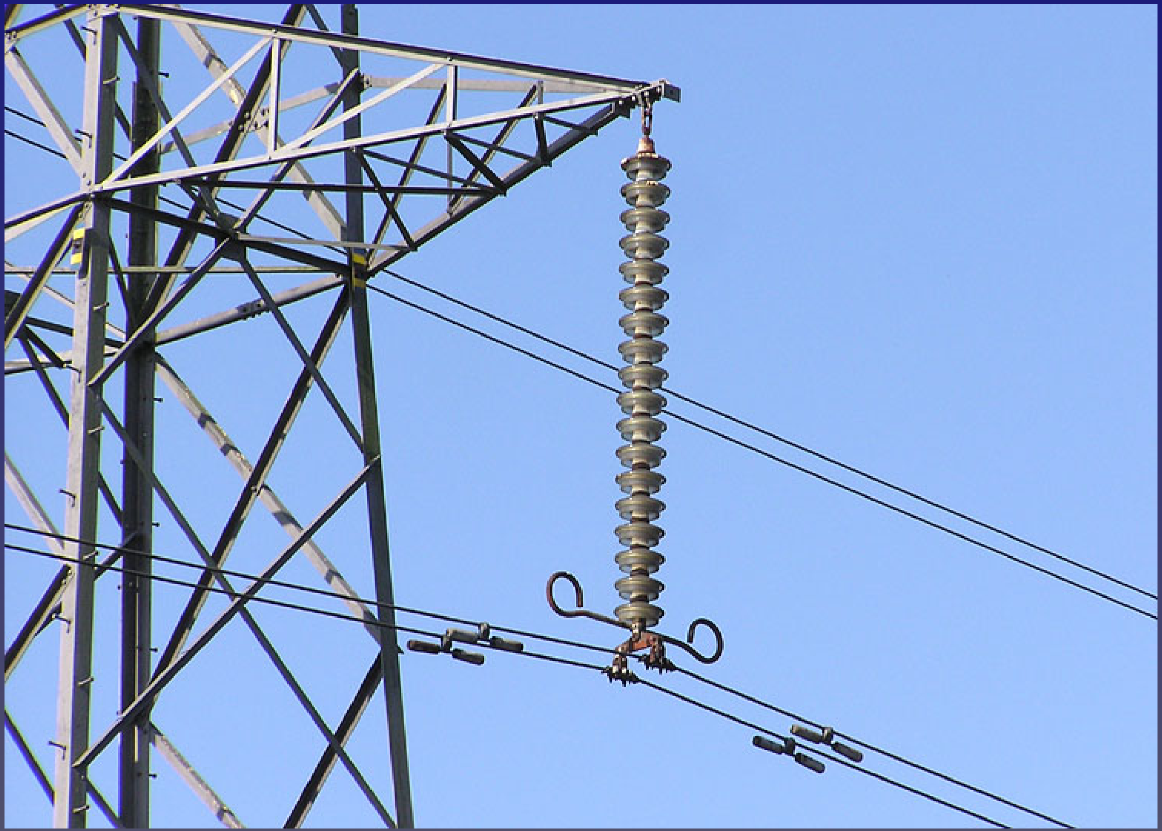
- We want very high voltage distribution lines to carry the maximum power with the lowest loss
  (less resistance heating)

- How high can we go?

Electrical Transmission

High voltage

Insulation and switching devices limit the voltage used in power transmission

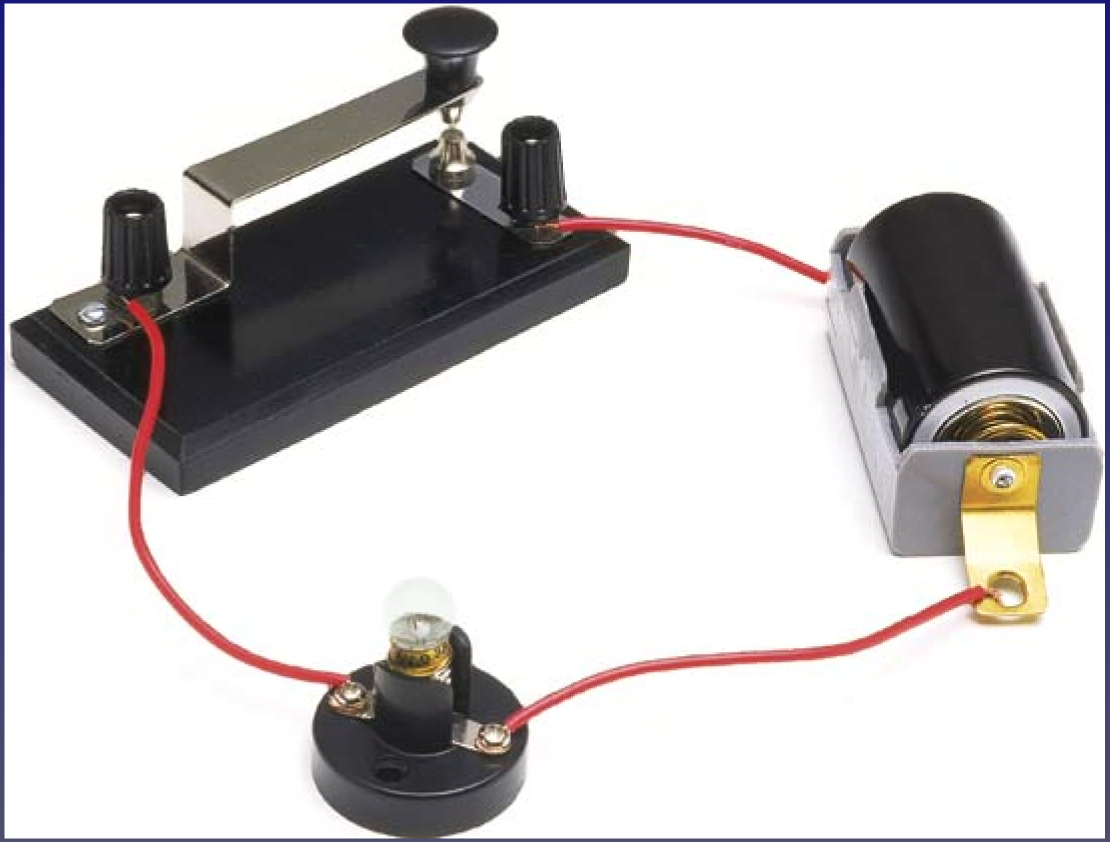


Switch failure

Electrical Transmission
AC versus DC

- Electric power is delivered only when the current can flow in a closed circuit from the source and back again

- When the switch is open, the current and power are zero



Electrical Transmission
AC versus DC

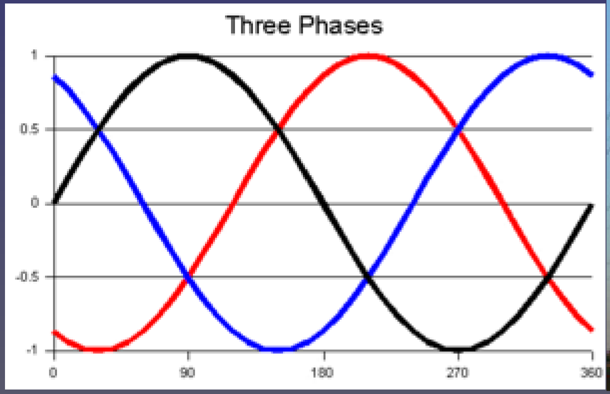
- Electric power is delivered in two forms:

  Direct current—steady voltage, one-directional current flow (batteries, carpet charging in winter, lightning)

  Alternating current—voltage changes smoothly from one polarity to the opposite and current reverses synchronously (never occurred before rotating electric motors and generators)

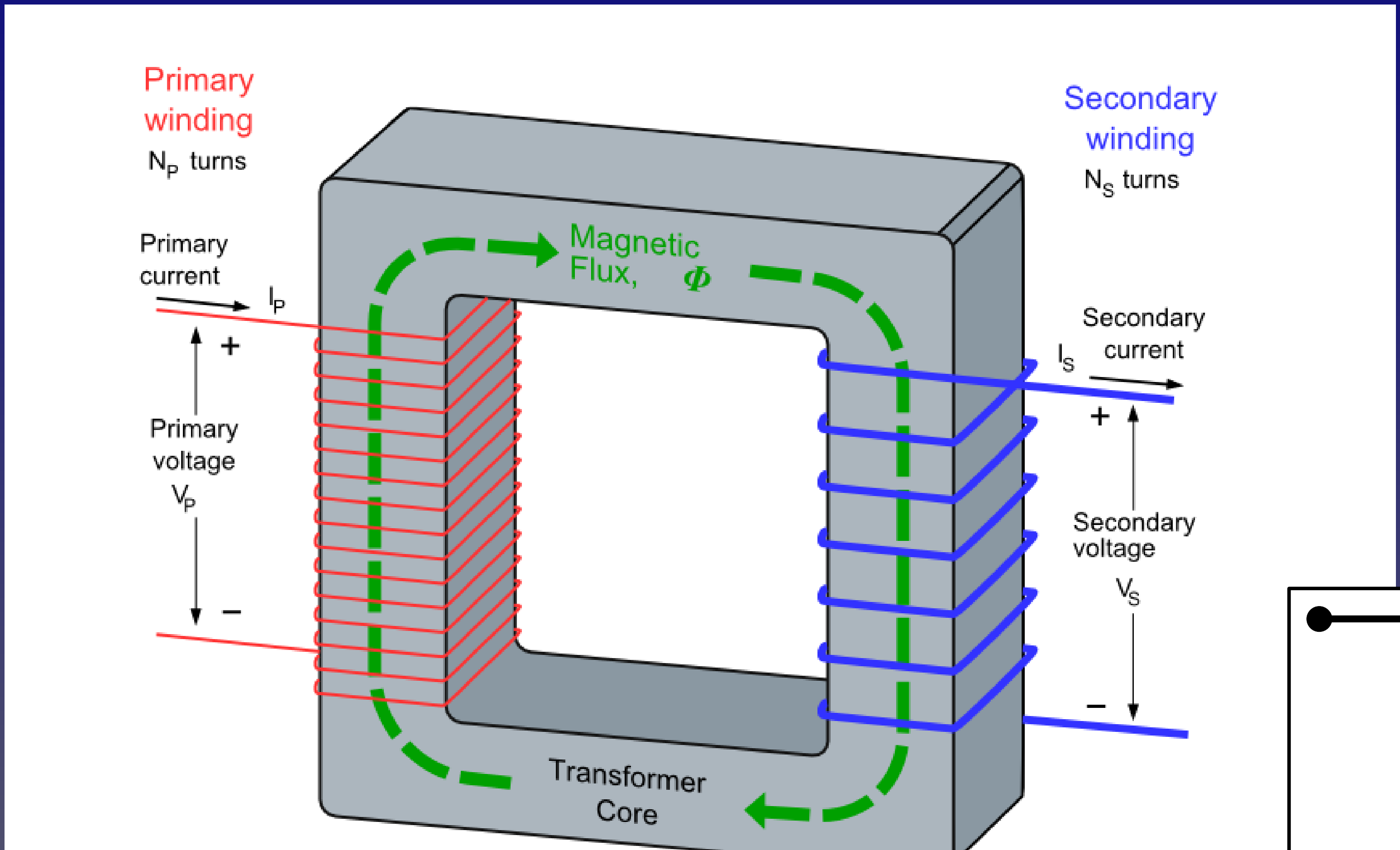
Electrical Transmission
High voltage

- 3-phase system

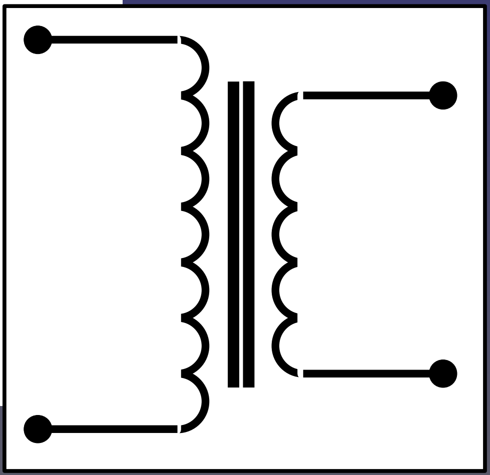


Electrical Transmission

AC Voltage change



A Transformer



Electrical Transmission

The War of the Currents

- In 1882, Edison had introduced 100 volt direct current service over distances of about one mile for lighting and motors and owned numerous patents. The generator produced 110 v to allow for some loss in transmission.
- George Westinghouse and Nicola Tesla had developed alternating current transmitted at high voltage and reduced by transformers, and they promoted its advantages.

Electrical Transmission

The War of the Currents

- Edison staged public electrocutions of animals with alternating current to highlight its danger.
- Most spectacularly, he electrocuted Topsy, a Coney Island elephant that had killed her trainer.

- He paid for the invention of the electric chair

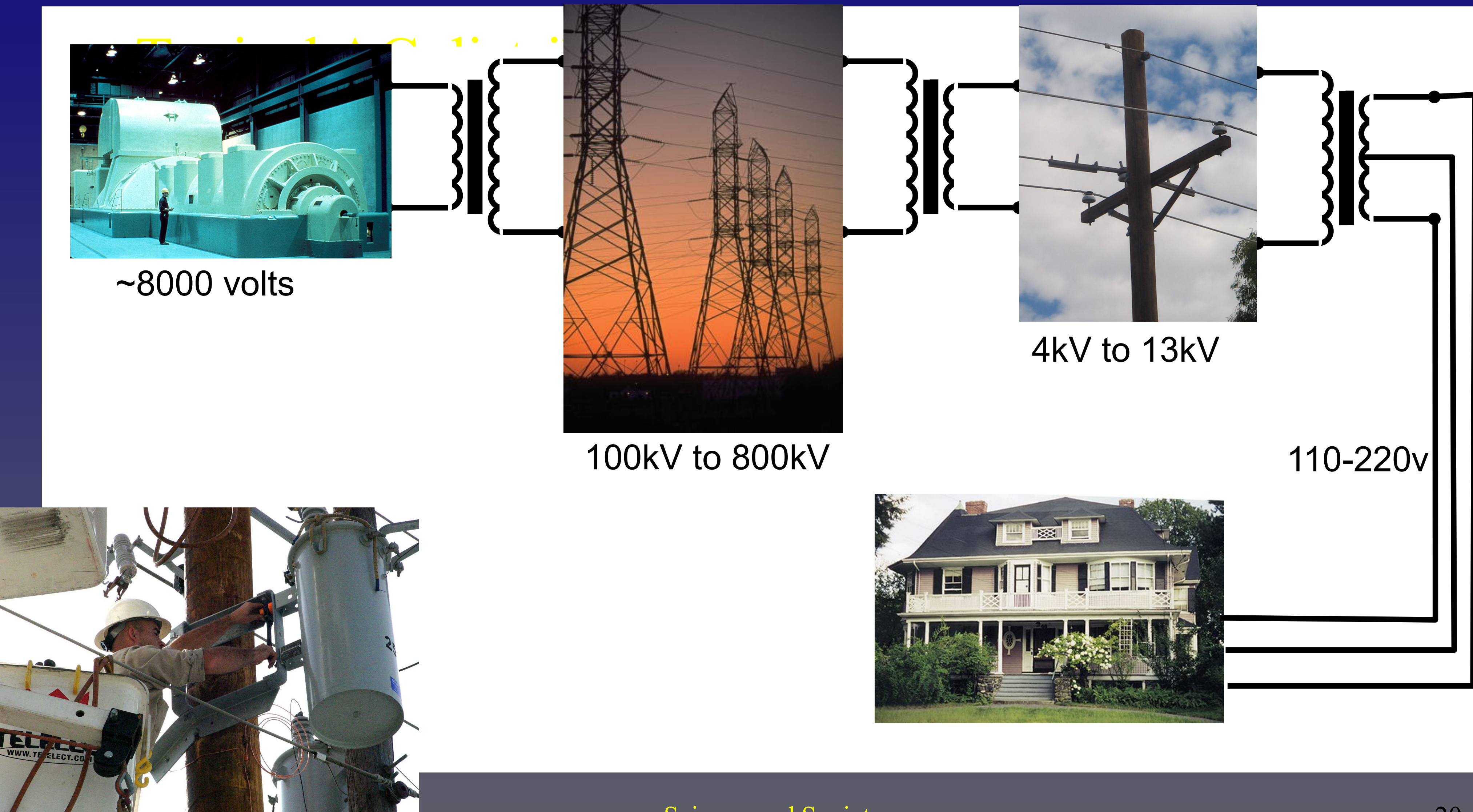
Electrical Transmission
The War of the Currents

- Alternating current won out due to the ability of the transformer to raise and lower the voltage efficiently and cheaply.

- Lawsuits over patents raged for years afterward.

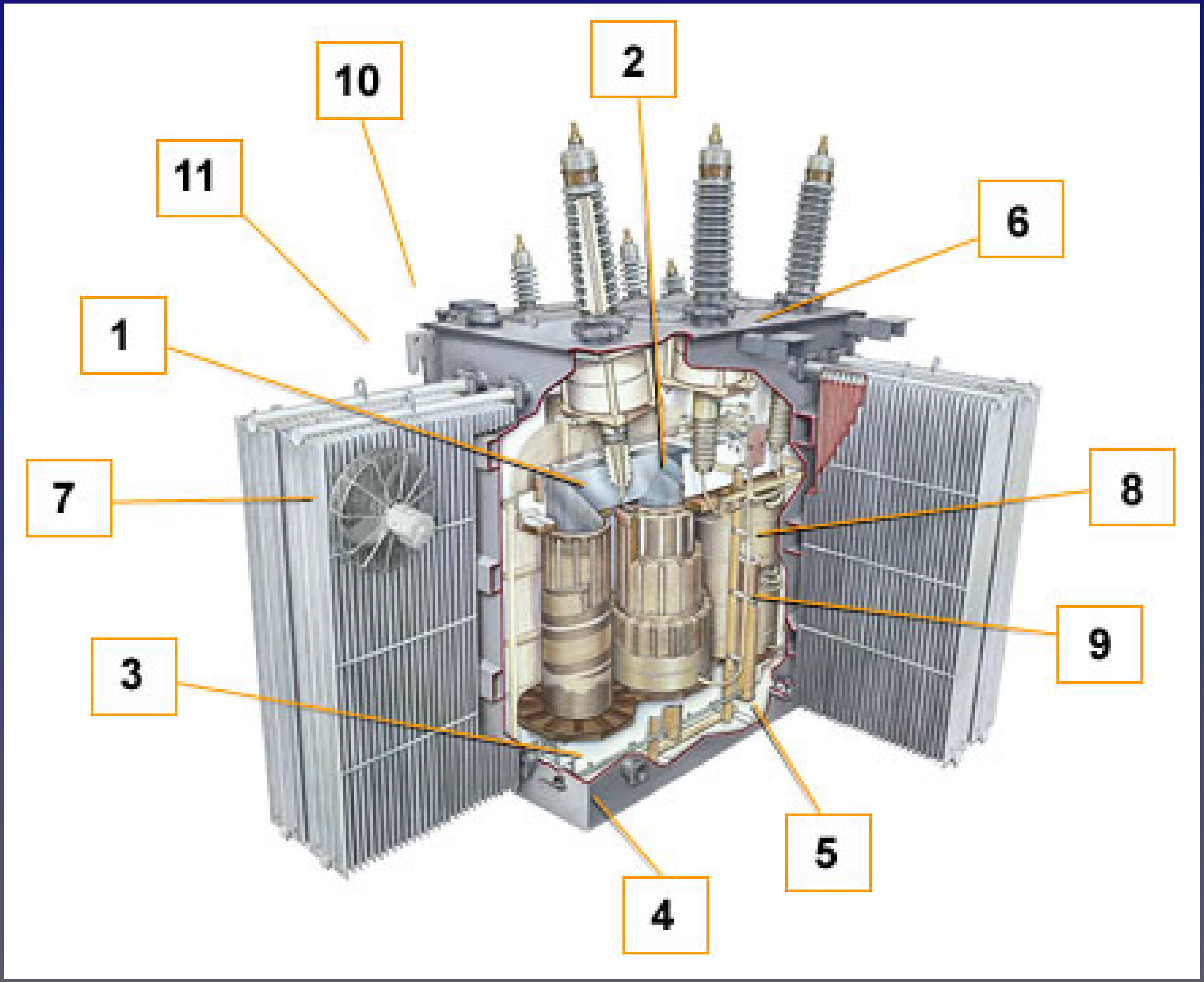
Electrical Transmission

High voltage



Electrical Transmission

Transformers



Electrical Transmission

Transformers

Electrical Transmission
Transformers

Electrical Transmission

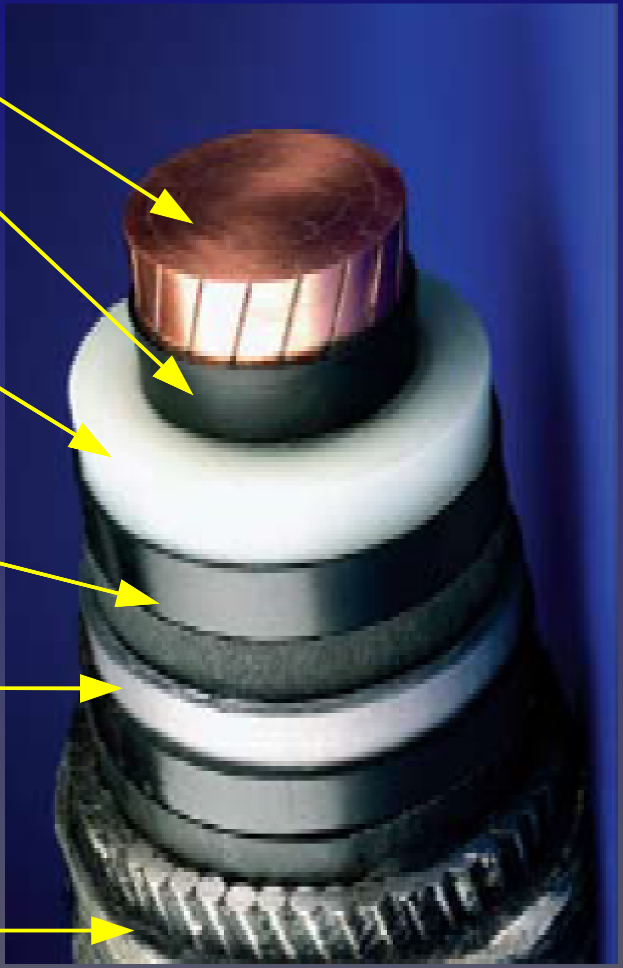
High voltage

- AC lines require transformers at regular intervals to boost the voltage
- Very high voltage lines cannot be easily buried
- All generators tied into the line must be synchronized to a fraction of a rotation
- DC transmission avoids all these problems

Electrical Transmission

High voltage

- Conductor
- Conducting plastic
-
- Insulation
-
- Conducting plastic
-
- Multiple protective layers



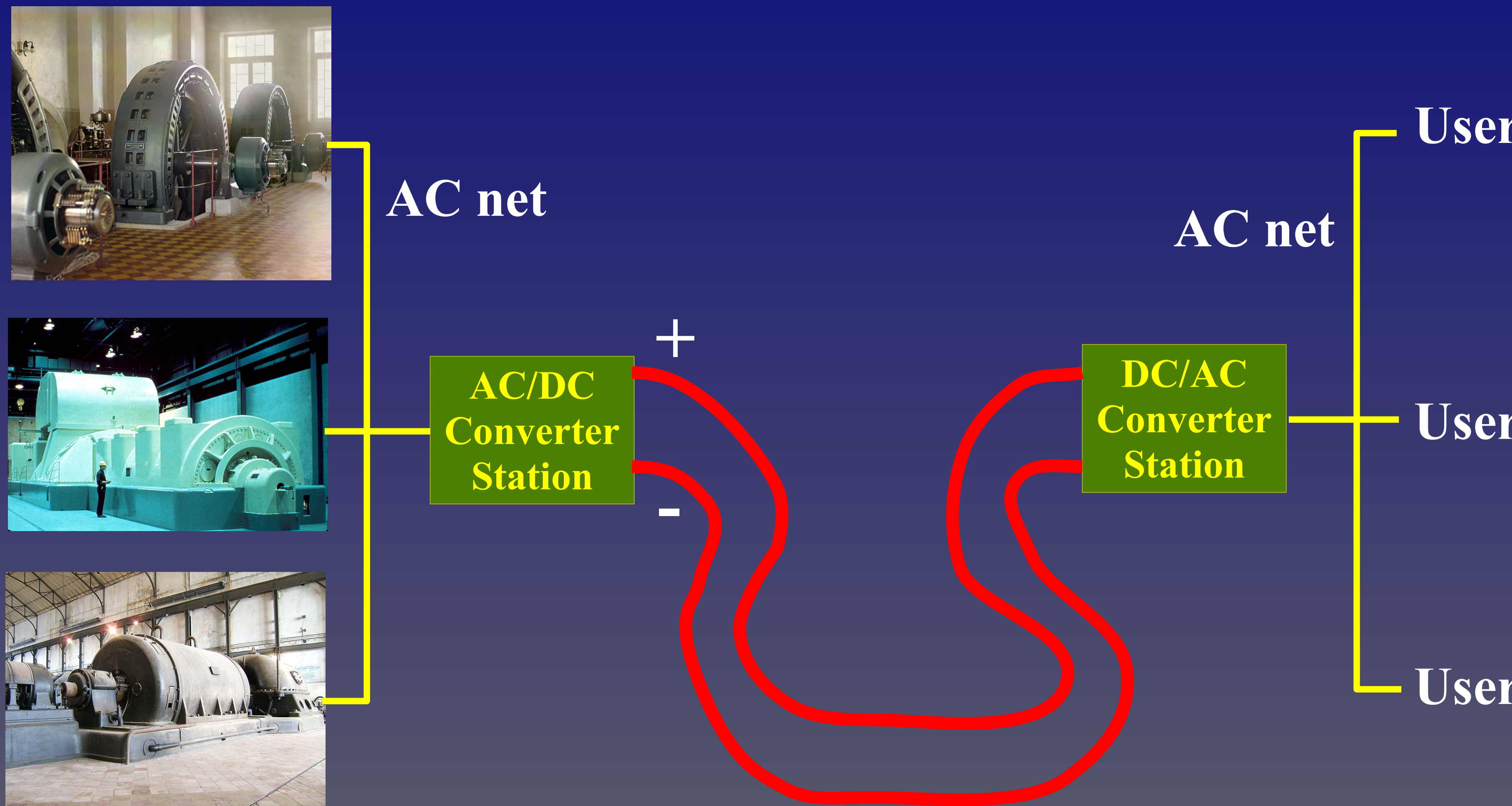
Electrical Transmission

High voltage

- Alternating current causes currents in the insulation that produce heating, loss of energy, and aging of the insulation
- Insulated cables can be used for higher voltages with HVDC

Electrical Transmission

High voltage



Electrical Transmission
HVDC

An AC/DC converter for the Sao Paulo line

Electrical Transmission
HVDC

- HVDC transmission needs improvements
  - UHVDC (Ultrahigh voltage DC, $\geq \pm 800$ kV)
  - Standards and regulations
  - Better, longer-lasting insulation
  - Improved, more-efficient AC/DC converters
- UHVDC is a key component of moving to renewable energy
- No American company produces HVDC systems

Electrical Transmission
US Grid

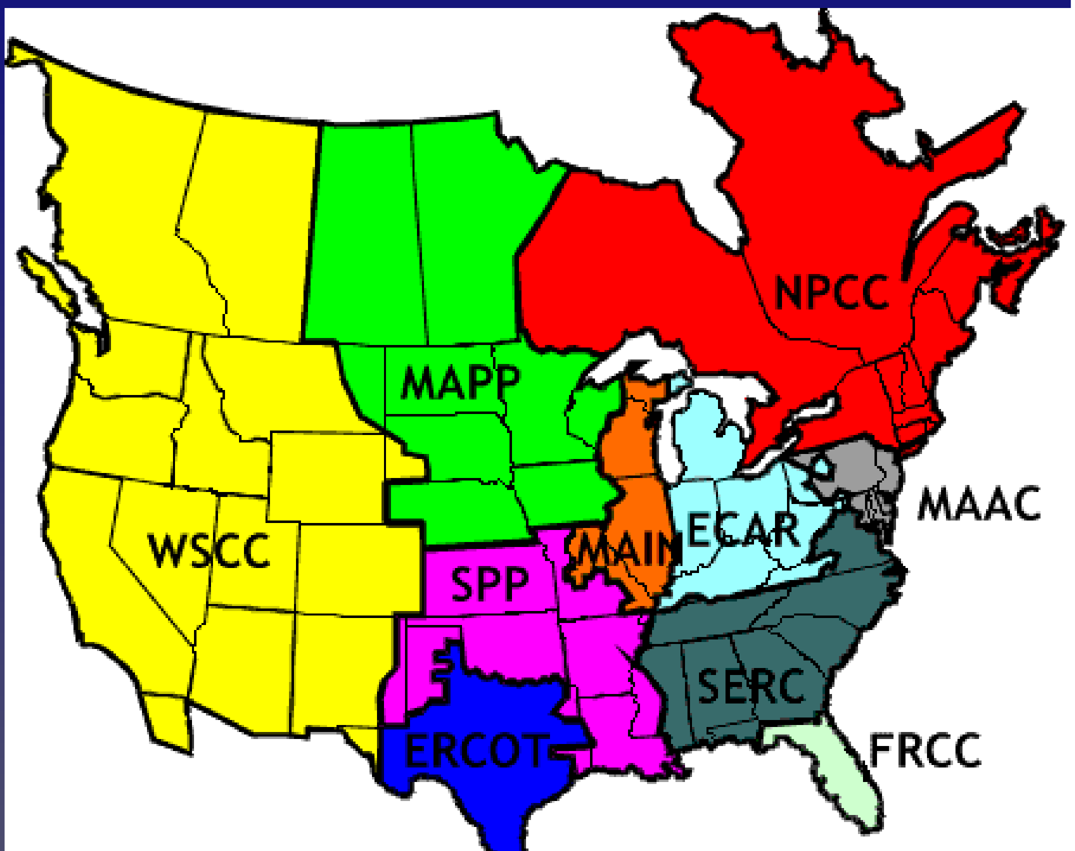
The Intermountain DC transmission line in Utah, ±500kV

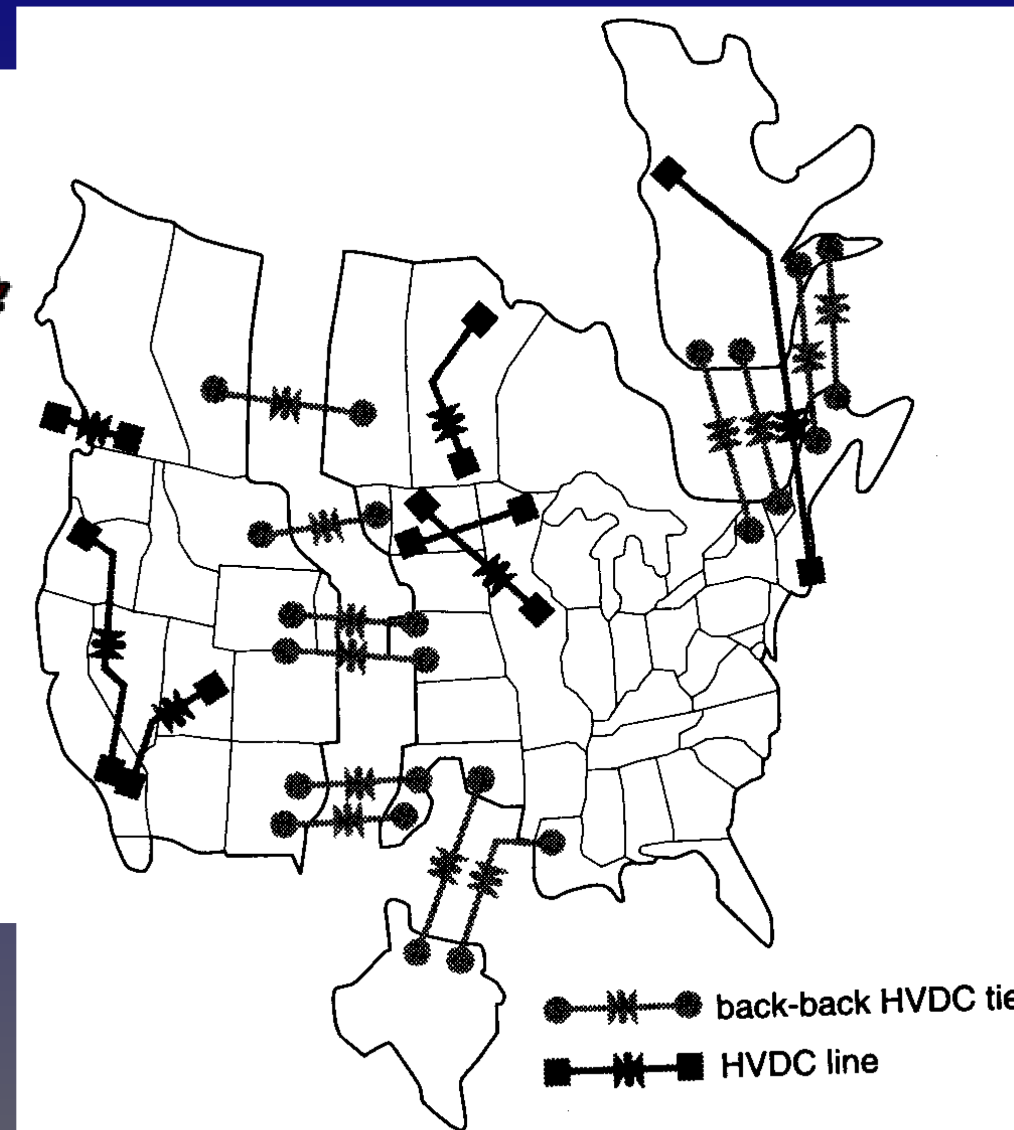
Electrical Transmission
US Grid

Grid Map

- The highest voltage AC line is in Kazakhstan—1,150,000 volts
- The highest voltage DC line is in Sao Paulo, Brazil — +/-600,000 volts

Electrical Transmission
US Grid





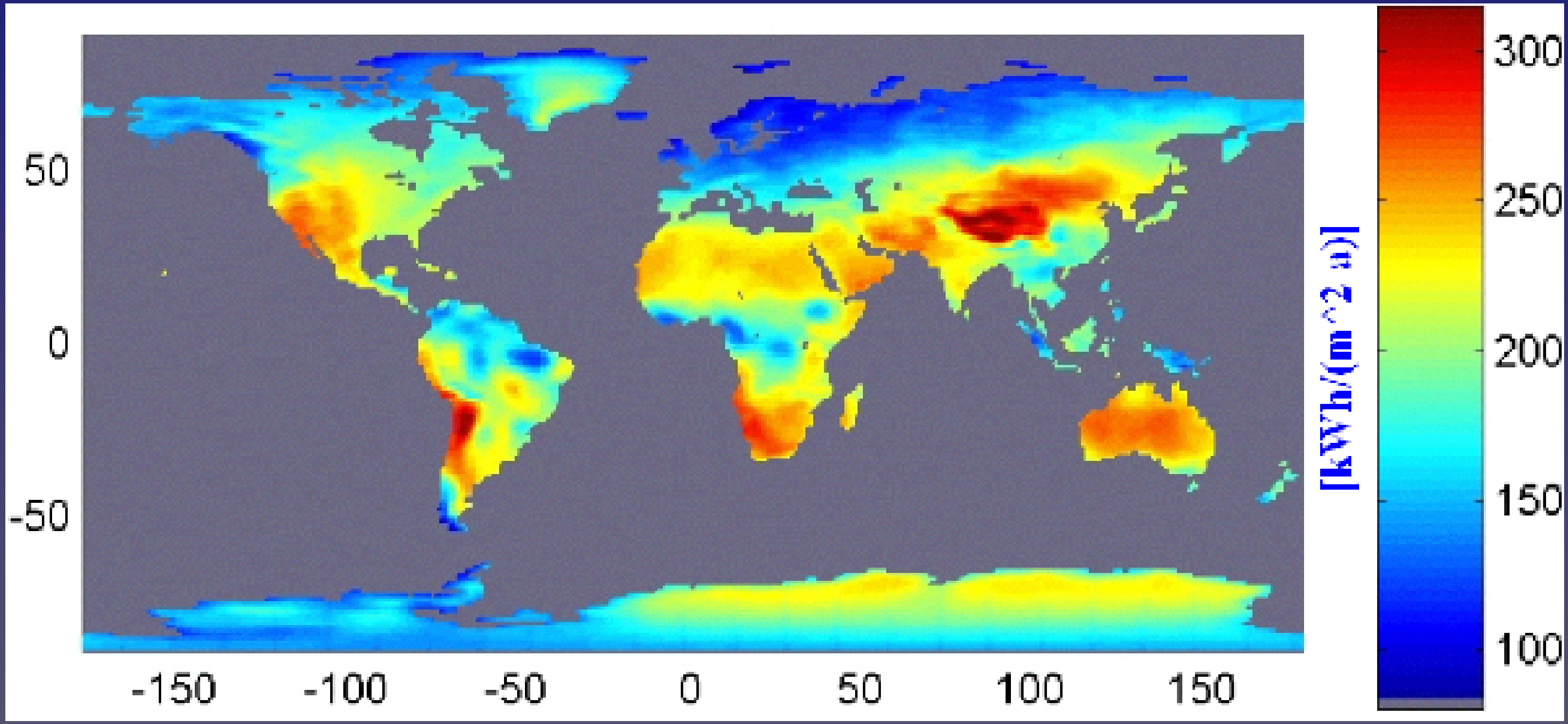
Electrical Transmission

DC transmission

- Proposed Neptune Project: 1,000 km 1,200 MW submarine cable from Nova Scotia to Boston, New York city and NJ.
  - Take natural gas energy to NY with less visual impact, while avoiding a NIMBY problem in NY and allowing an old oil-fired plant in NY to be retired.
  - Help improve network stability and reliability.
  - The southern end has a summer peak demand, the northern end a winter one, so a bi-directional link allows savings from electricity trade.

Electrical Transmission
US Grid

Distribution of solar energy potential

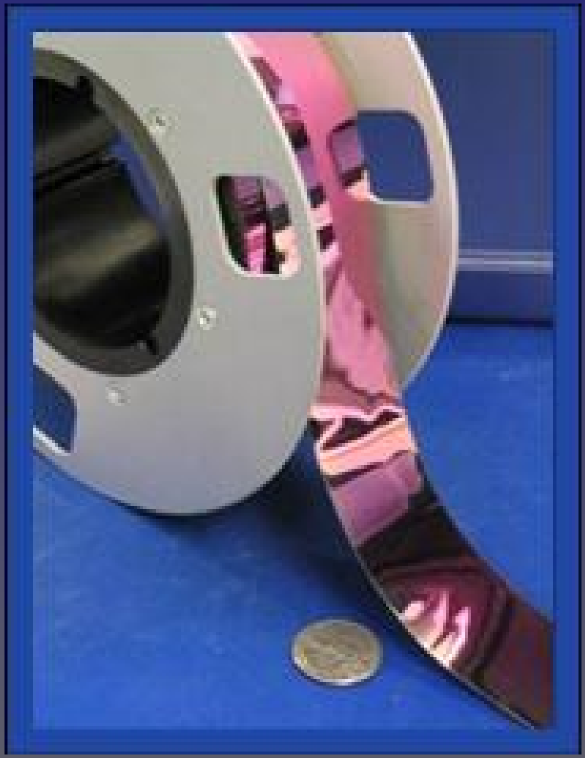


Electrical Transmission

Superconductors

Several crystalline materials that don't conduct electricity at room temperature become perfect conductors when they are cooled to about -200°C

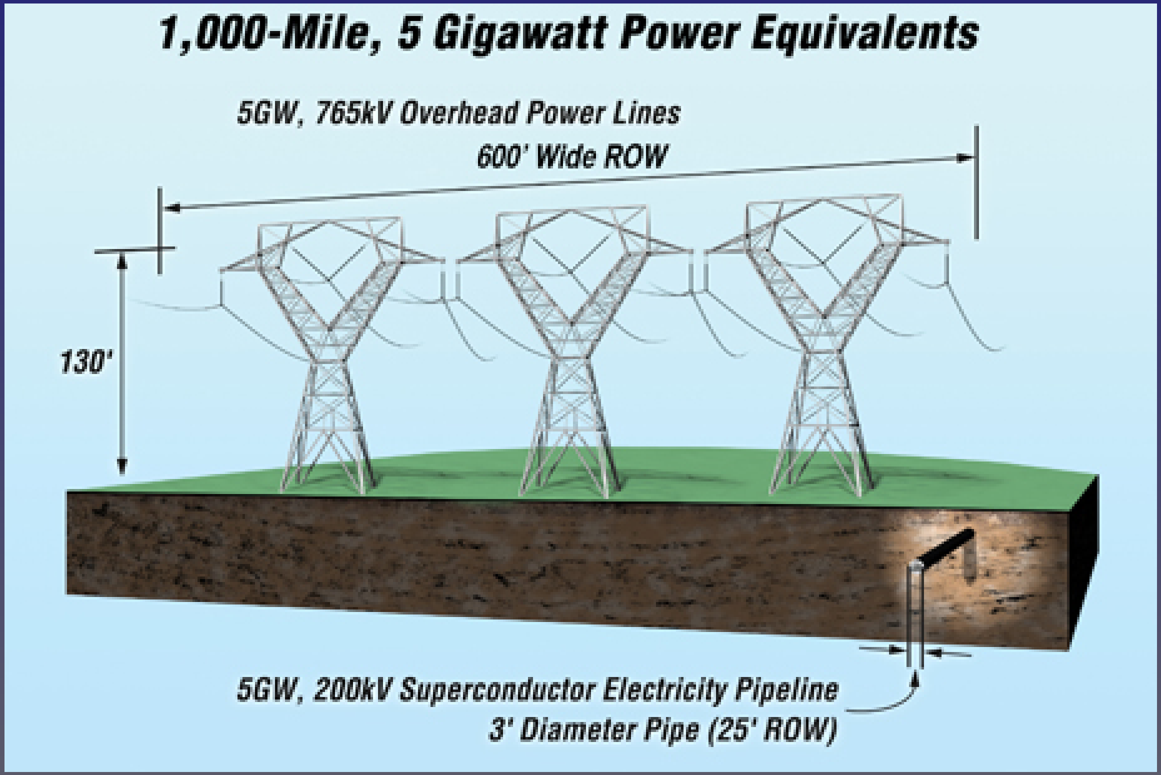
One material is $YBa_2Cu_3O_7$, Yttrium Barium Copper Oxide



Electrical Transmission
Superconductors

Because they produce no heat from lost electricity, they can be packaged in smaller cables

Because they have to be kept cold, they have to be insulated and refrigerated



Superconducting cable installation

Energy Transmission
Natural gas pipelines

- Usually in steel pipes buried underground
- Pumping stations every 40-100 miles
- Pumps are driven by either the gas or electricity

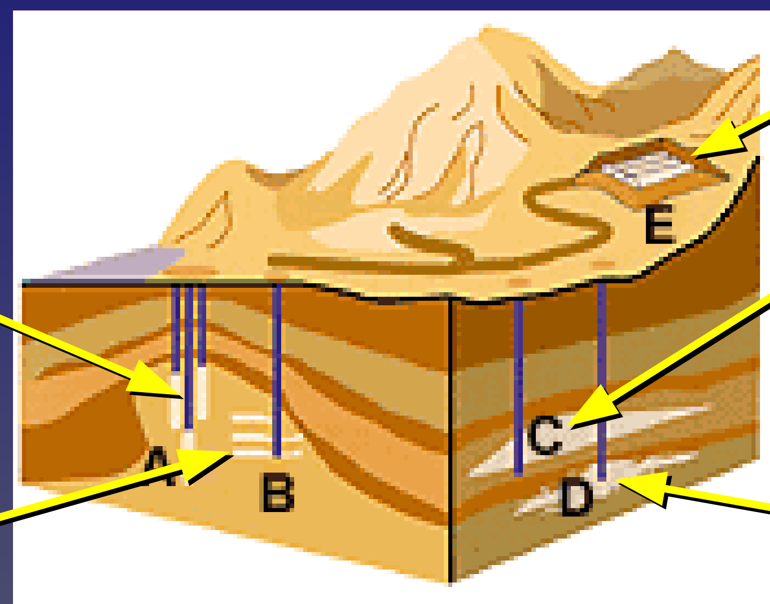
Map of US natural gas pipelines

Energy Transmission

Gas storage

Salt mined out by dissolving

Salt mined out mechanically



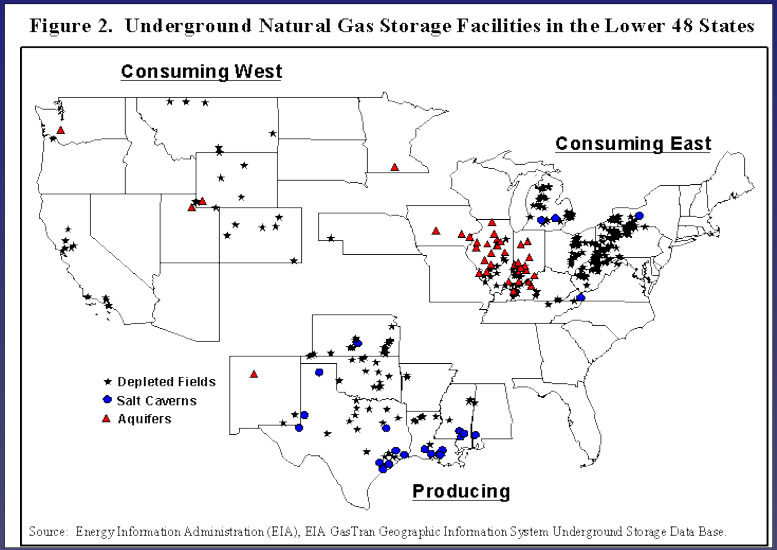
Hard rock mine

Acquifers

Depleted oil reservoirs

Energy Transmission

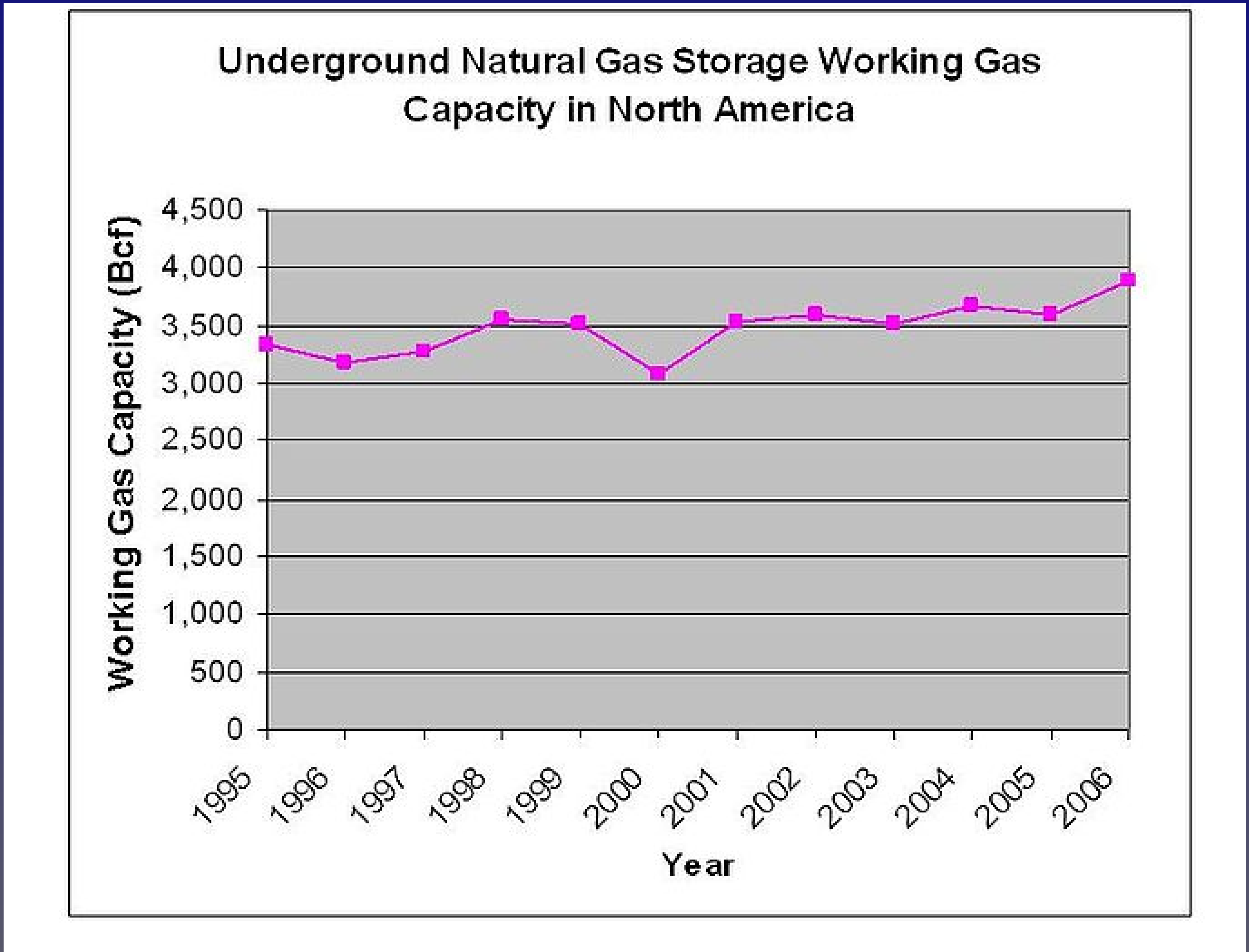
Natural gas storage



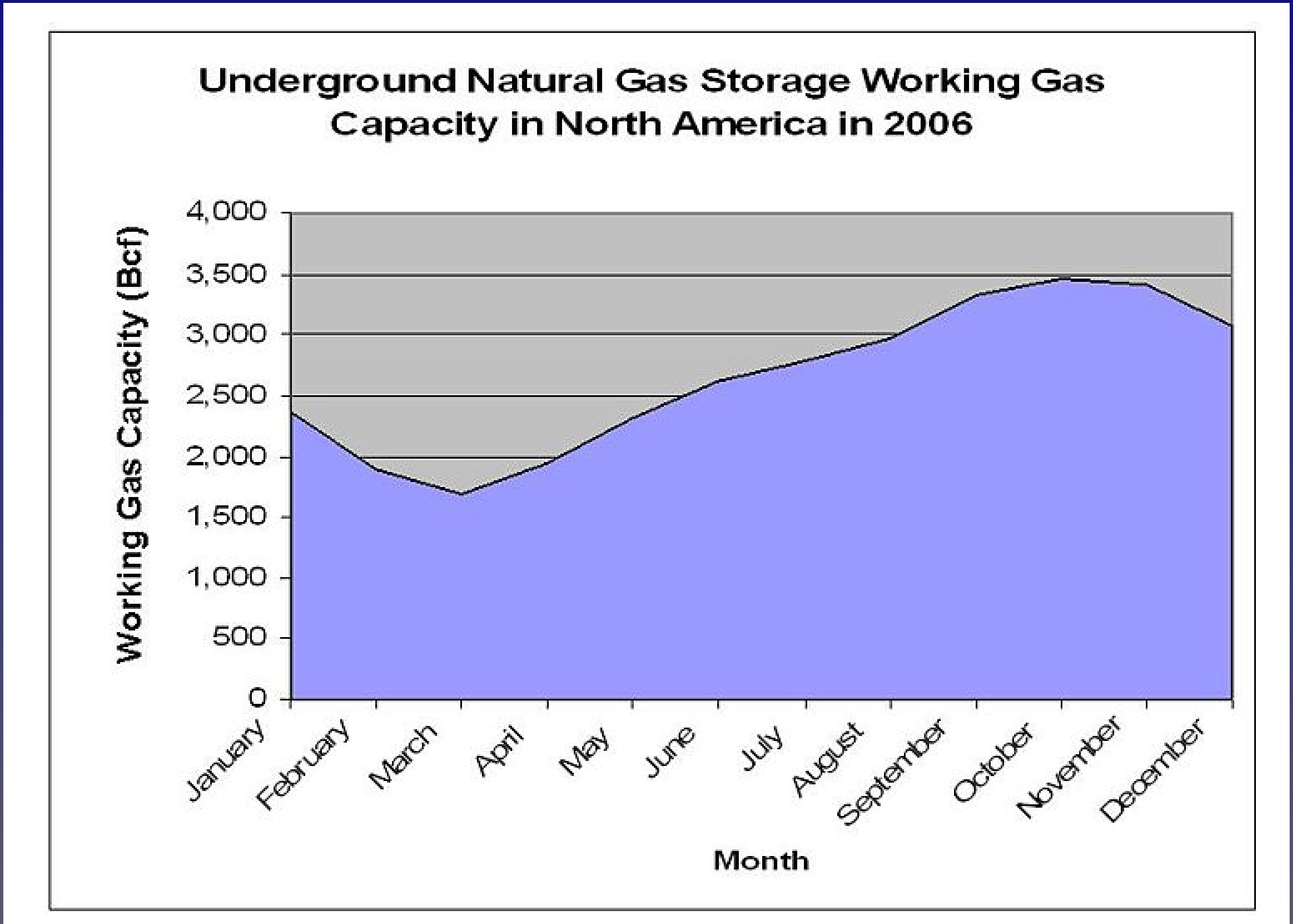
Energy Transmission
Hydrogen Pipelines

- The first hydrogen pipeline was the 1938 Rhine-Ruhr pipeline. It is still in operation.
- Uses the same technology as natural gas lines.

Energy Transmission
Gas storage



Energy Transmission
Gas storage



Energy Transmission
Hydrogen Storage

- Hydrogen has been stored underground since at least the 1980s
- The energy required for compression to 200 bar is 2% of the H_2 energy content (Wikipedia article on *Underground Hydrogen Storage*)
- The Conoco Phillips Clemens Terminal in Texas stores 1066 million standard cubic ft.

Energy Transmission
Summary

- Wind, solar, geothermal, and reprocessed nuclear energy sources can provide ample energy to drive the entire US for an indefinite time
- Wind and solar are time-variable, geographically uneven, and thus require large-scale transmission and storage
- Nuclear and geothermal can be located near consumers and run round-the-clock

Energy Transmission
Summary

- A dramatically larger and robust transmission (electric and H_2) and storage (H_2) system is needed to move the country to majority reliance on renewable energy
- Improved technology, particularly increased usage of HVDC power lines and hydrogen storage can provide the infrastructure for use of renewable energy.