Electric Power Grid Modernization

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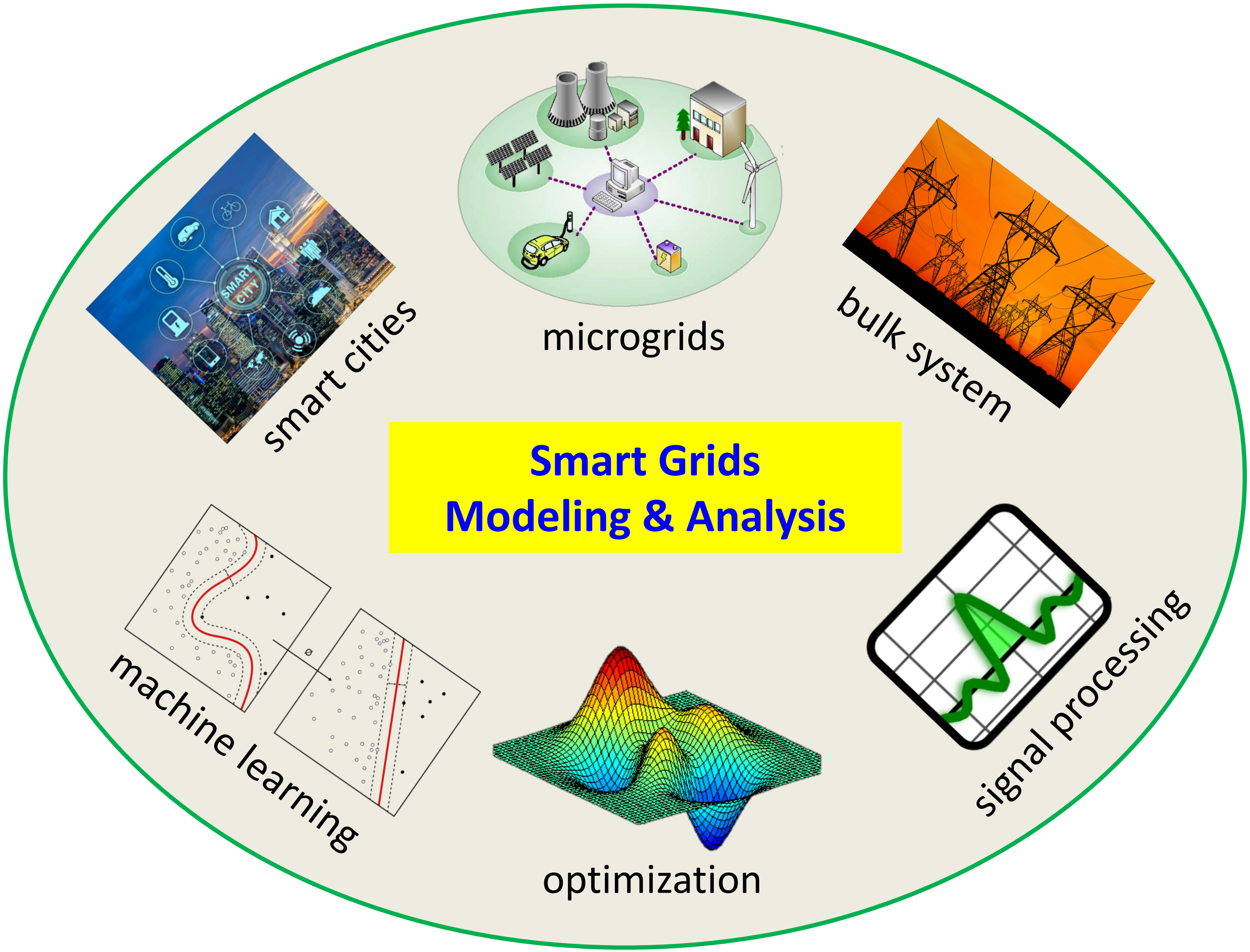
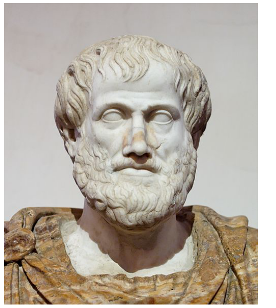
COSMOS Guest Lecture

Research Landscape



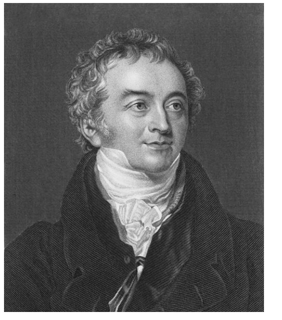
Energy

- The word energy derives from the Greek *en* (in) and *ergon* (work) *[wiki: Ancient Greek: ἐνέργεια, energeia, meaning 'activity, operation', possibly appears for the 1st time in Aristotle's work]*



Aristotle (384-322BC)
Greek philosopher

- In 1807, Thomas Young was possibly the first to use the term "energy" in its modern sense.



Young (1773-1829)
British physician

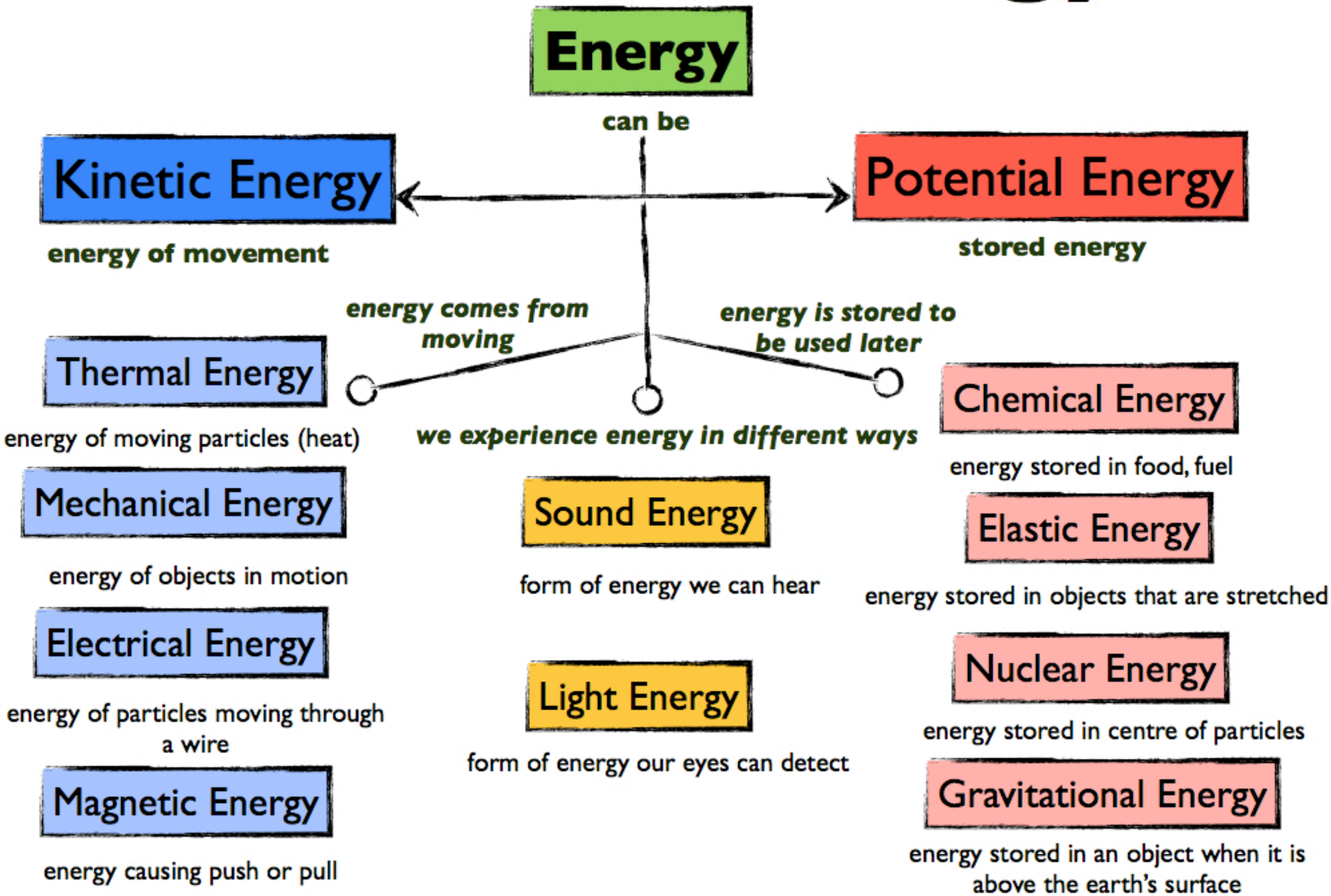
Broad definition: **the capacity to do work**

- How much potential a physical system has to change

Conservation Law of Energy:

Energy is a property that is not created/destroyed, although energy can change in form.

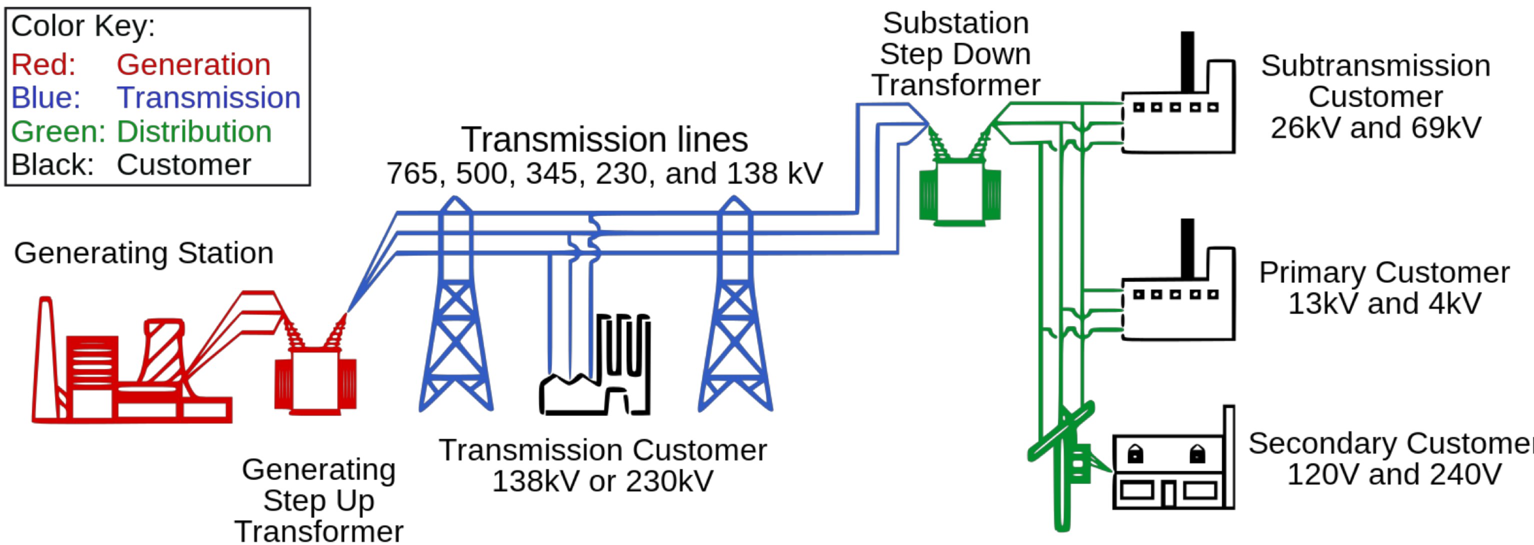
Forms of Energy



Pic source: mskuksclass.weebly.com/lesson-2-forms-of-energy.html

The Electrical Grid Then and Now

"Most significant engineering achievement of 20th century" [NAE Report'10]



- Several challenges ahead
  - 99.97% reliable, but power outages still cost $150 billion/year
  - Customer engagement and environmental concerns

Picture source: FERC. "Final Report on the Aug. 14, 2003 Blackout in the US and Canada"

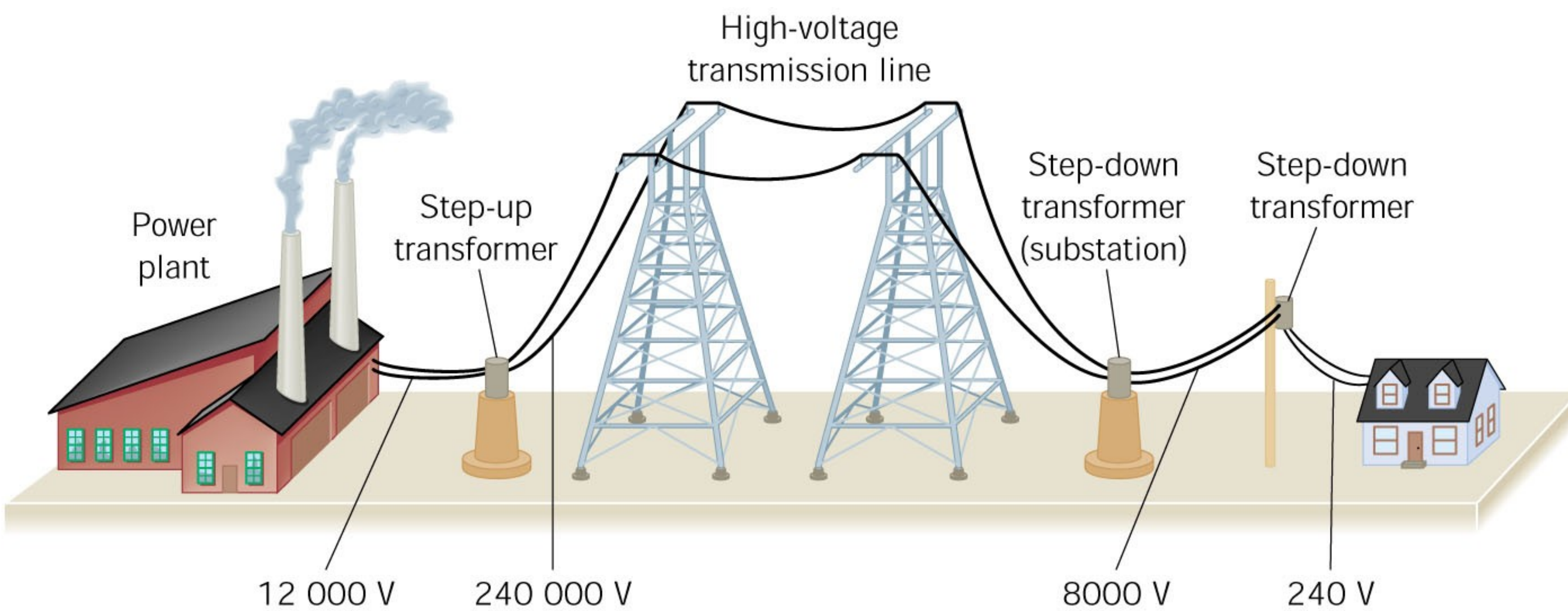
Transformers

Transformers make the voltage bigger or smaller, only work with AC

- this is a typical step-down transformers used to bring the line voltage down from 5000 V to 240 V before it gets to your home

- in your home two voltages are available: 240 V &120 V. The 240 is used for the high power appliances like the clothes dryer, oven, etc. The 120 V is for everything else

Power Line Losses

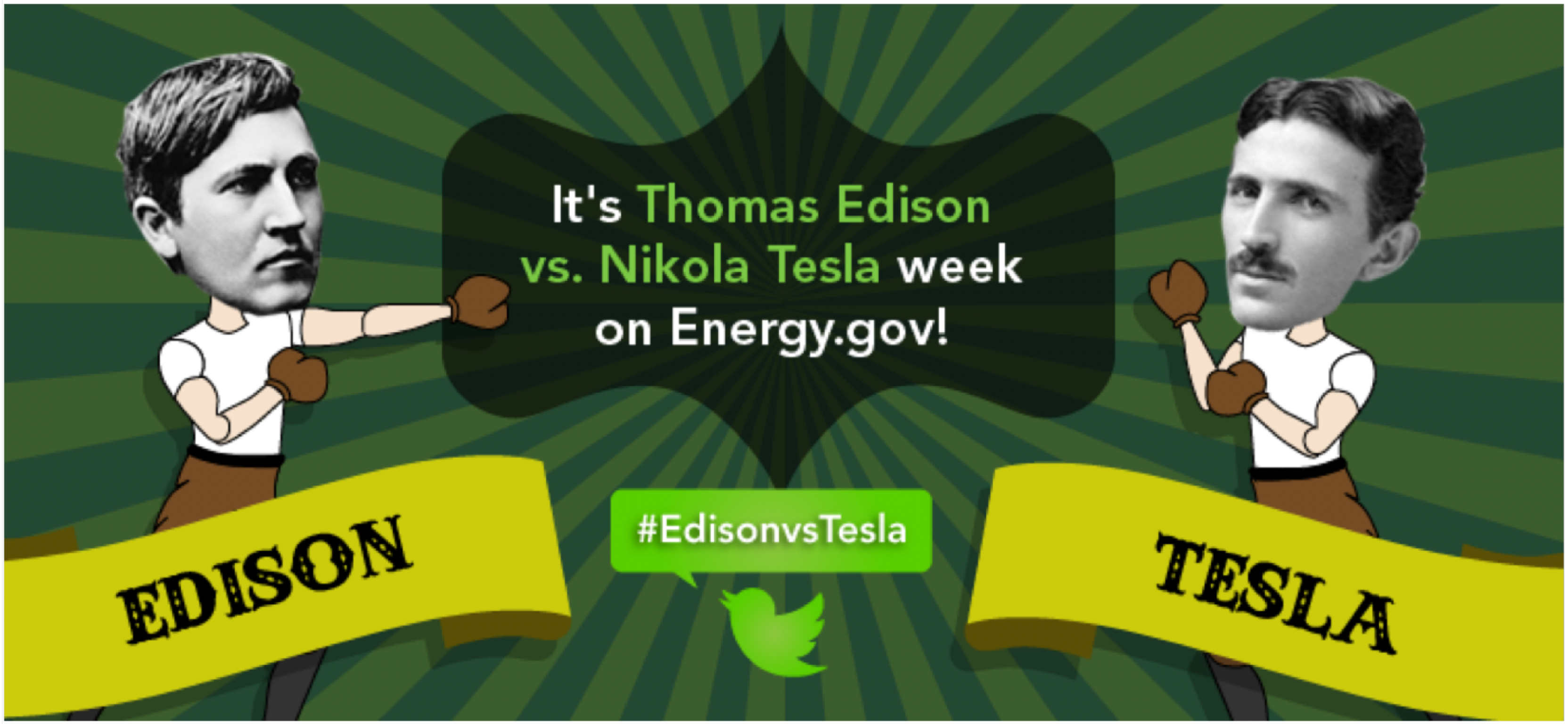


- It is more efficient to transmit electrical power (P = IV) at high voltage and low current.
- The losses along the transmission lines are reduced compared to transmission at low V.

Brief History of Electric Power

• Early 1880’s – Edison introduced Pearl Street DC system in Manhattan supplying 59 customers
• 1884 – Sprague produced practical DC motor
• 1885 – Invention of transformer
• Mid/late 1880’s – Westinghouse/Tesla introduce rival AC system (AC induction motor)
• 1893 – First 3 phase transmission line operating at 2.3 kV.
• 1896 – AC lines delivered hydrogen electricity from Niagara Falls to Buffalo, 20 miles away.
• Early 1900’s – Private utilities supply all customers in area (city)
• By 1920’s – Large interstate holding companies control most electricity systems.

Alternating Current (AC) vs Direct Current (DC)

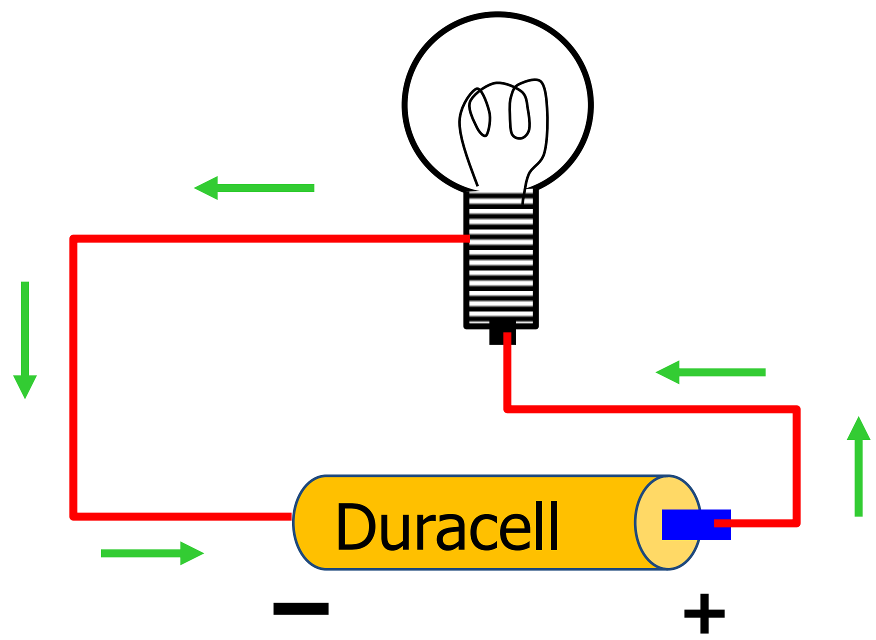


Edison "invented" the electric business, but Tesla "sealed" its future.

Figure: Source credit: Dr. Merwin Brown at UC Berkeley

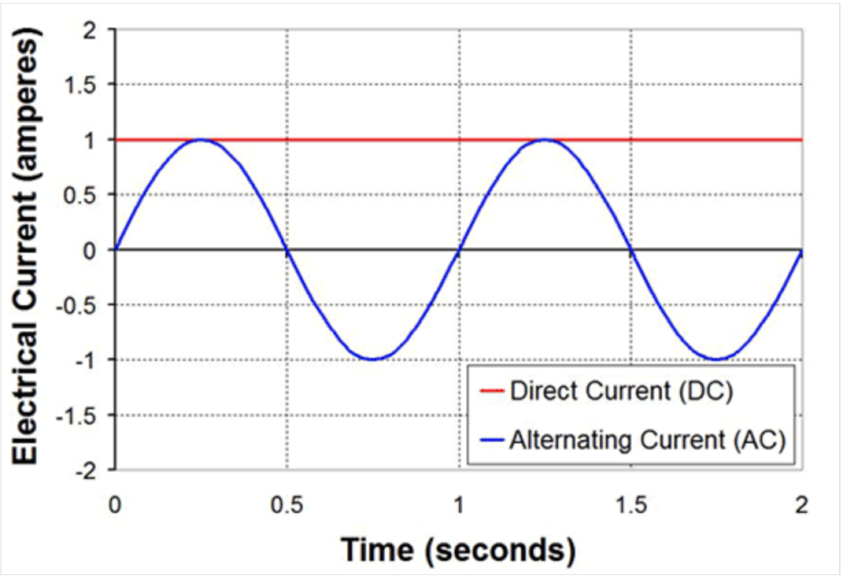
Direct Current (DC)

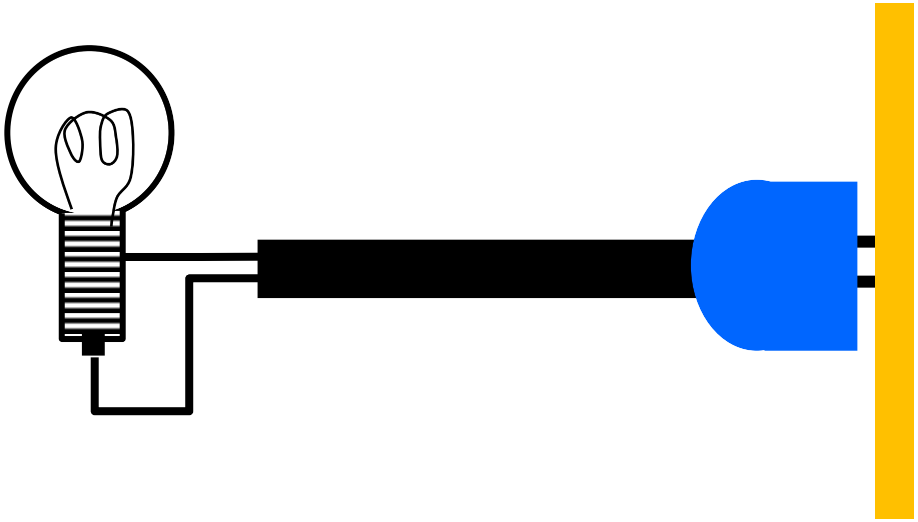
- A circuit containing a battery is a DC circuit
- In a DC circuit the current always flows in the same direction **same direction**



Alternating Current (AC)

- In an AC circuit the current **reverses direction periodically**
- AC is what you get from utility companies





AC (cont'd)

- Line voltage reverses polarity 60 times/second (60 Hertz)
- Current through the bulb reverses direction 60 times/second
- For heaters, hair dryers, irons, toasters, the fact that the current reverses makes no difference
- Cell phone chargers convert the AC to DC

Why AC is Better Than DC

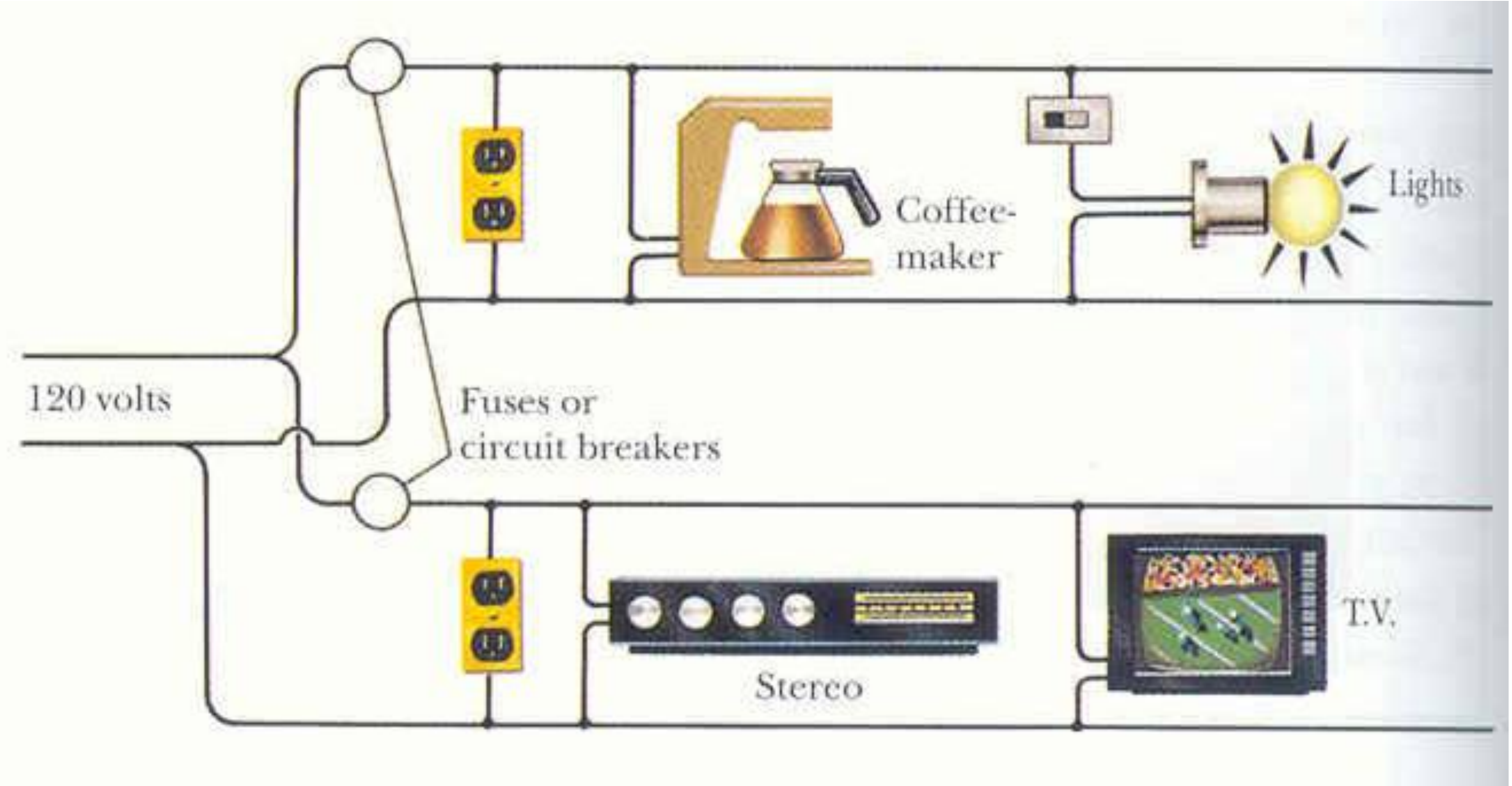
- DC power is provided at one voltage only
- AC power is easier to generate, and can be stepped up or down to provide any voltage required
- DC is very expensive to transmit over large distances compared to AC, so many plants are required
- DC power plants must be close to users
- AC plants can be far outside cities
- By 1895 DC was out and AC was in

Power System Examples

- Interconnection: Range from quite small, such as an island, to one covering half the continent:
  - *large parts of the world is operated at 50 Hz.*
  - *Americas and parts of Asia it is typically 60 Hz.*
  - *Japan uses both*
  - *No great technical reason to prefer one over the other*
  - *no apparent desire for complete worldwide standardization*

  - Airplanes and Spaceships: Reduction in weight is primary consideration; frequency is 400 Hz
- Ships and submarines
- Automobiles: DC with 12 volts standard and higher voltages used in EVs
- Battery operated portable systems

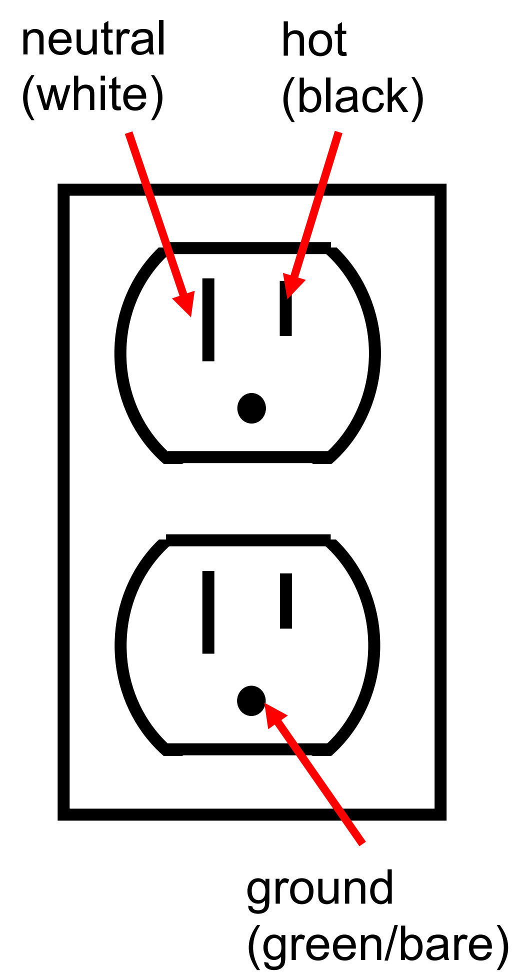
House wiring



All circuits are connected in parallel !

Electric Outlets

- The current is supposed to flow from the hot side to the neutral, if too much current flows the fuse blows or the circuit breaker trips.
- The ground is there for protection → to provide a safe path for current in the event of a short circuit
- For some circuits (kitchen/bathroom) there is additional protection → Ground-Fault Circuit Interrupter (GFCI), which interrupts the circuit very quickly if current flows thru anything other than the hot or neutral



Paying for Electricity

- You pay for the total amount of electrical energy that is used
- Energy is measured in kilowatt-hours (kwh)

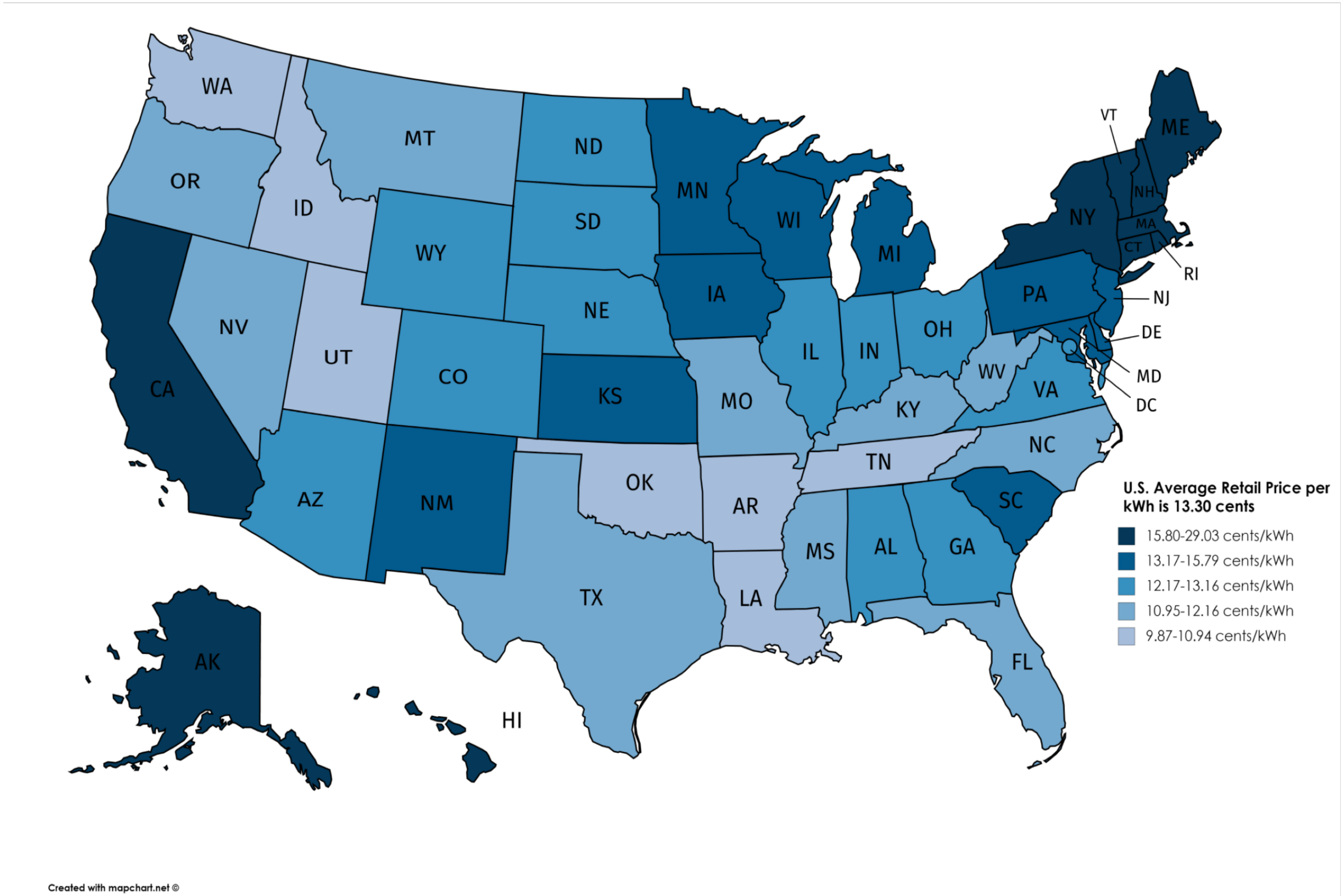
Example: At a rate of 10 cents per kWh, how much does it cost to keep a 100 W light bulb on for one day?

Solution: 100 W = 0.1 kW, 1day = 24 hours, so

cost = 0.1 kW x 24 hours x $0.10/kWh = $0.24 = 24 ¢

→ for one month (30days) that amounts to $7.20

Residential electric supply rates in 2018



10 Most Expensive States to Live In

Rank	State	January 2018 Rate (cents per kWh)
1	Hawaii	31.14
2	Rhode Island	22.24
3	Alaska	21.67
4	Massachusetts	20.60
5	Connecticut	20.00
6	New Hampshire	19.23
7	**California**	**18.81**
8	New York	17.74
9	Vermont	17.36
10	Maine	16.02

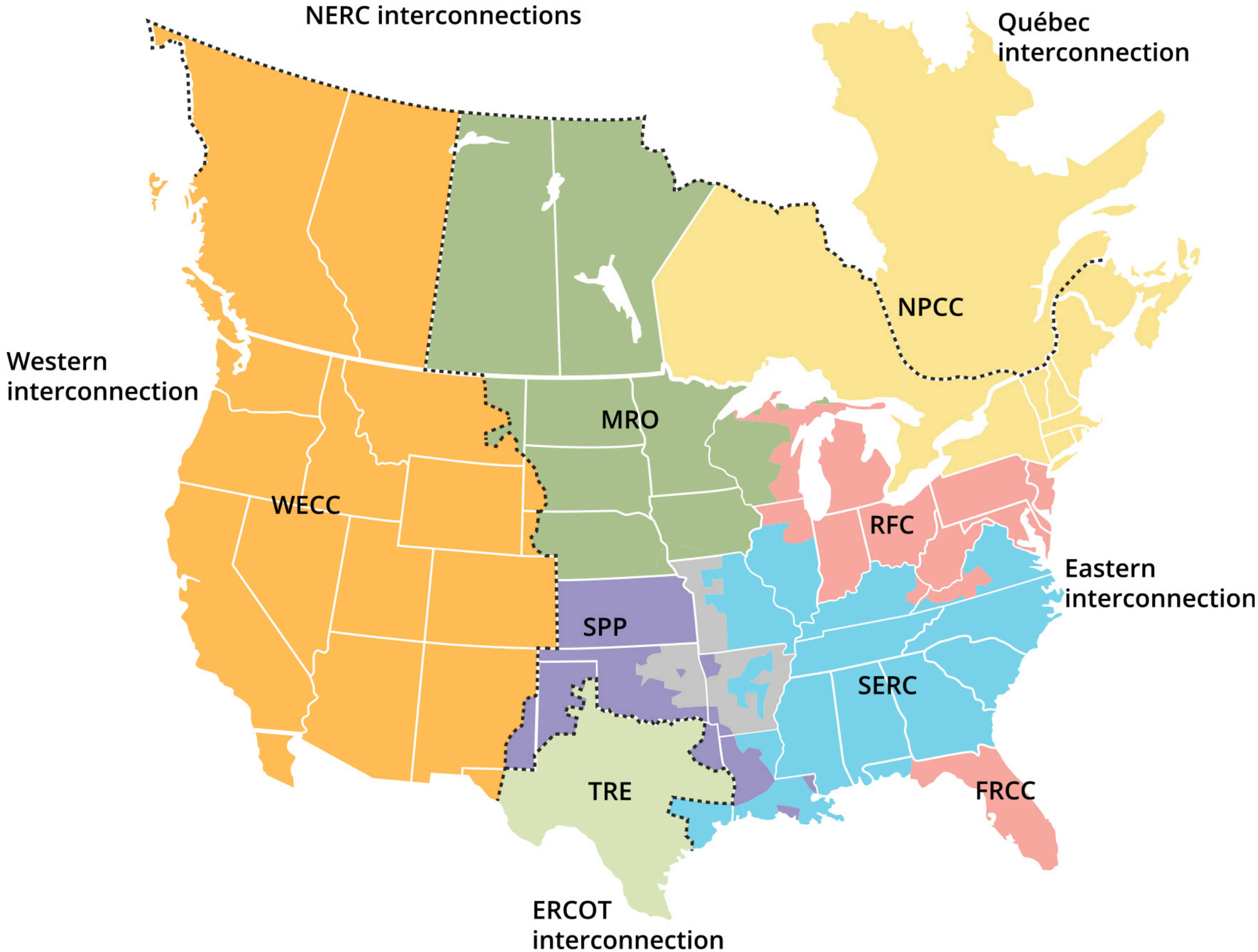
10 Most Cheapest States to Live In

Rank	State	January 2018 Rate (cents per kWh)
1	Louisiana	8.72
2	Oklahoma	8.79
3	North Dakota	9.00
4	Missouri	9.19
5	Nebraska	9.29
6	Arkansas	9.36
7	Washington	9.51
8	Kentucky	9.78
9	Tennessee	10.02
10	North Carolina	10.27

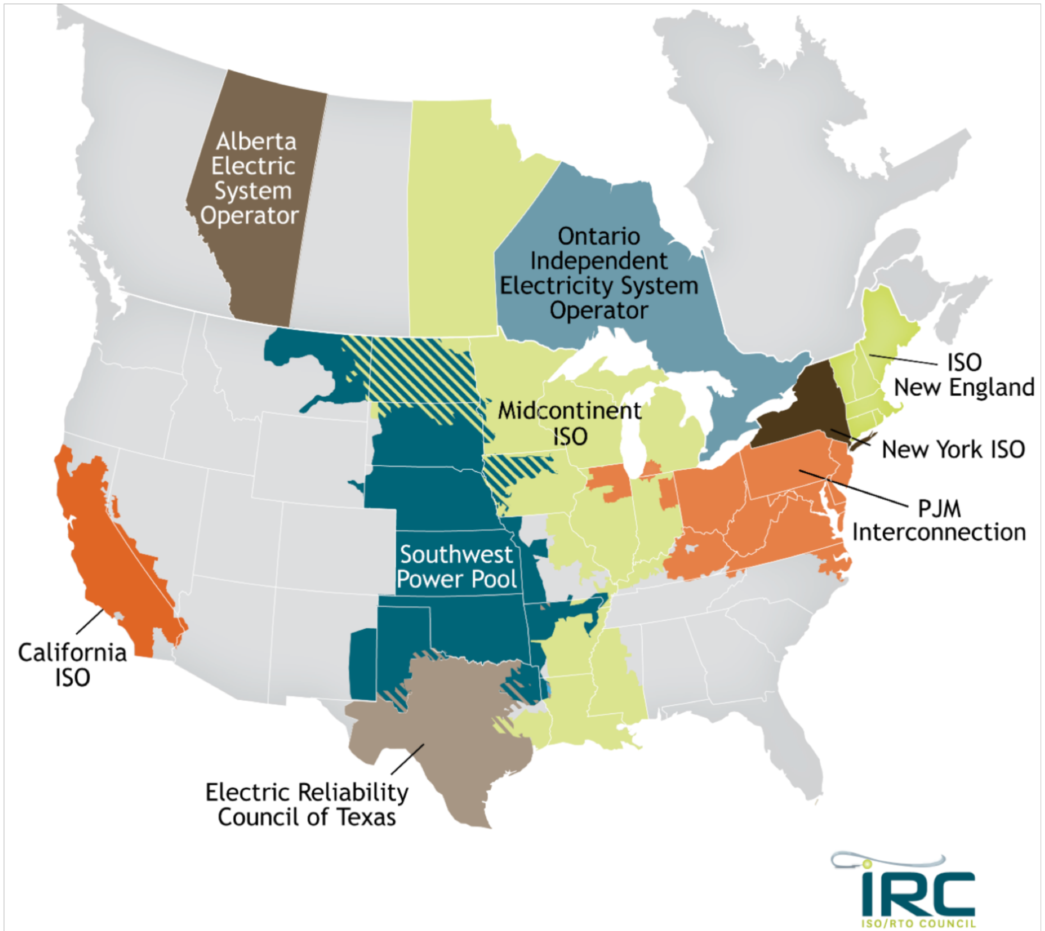
Goals of Power System Operation

- Supply load (users) with electricity at
  - specified voltage (120 AC volts common for residential)
  - specified frequency (50/60 Hertz)
  - at minimum cost consistent with operating constraints, safety, reliability, sustainablity, etc.

North America Interconnections



Independent System Operators (ISO)



The role of ISOs/RTOs

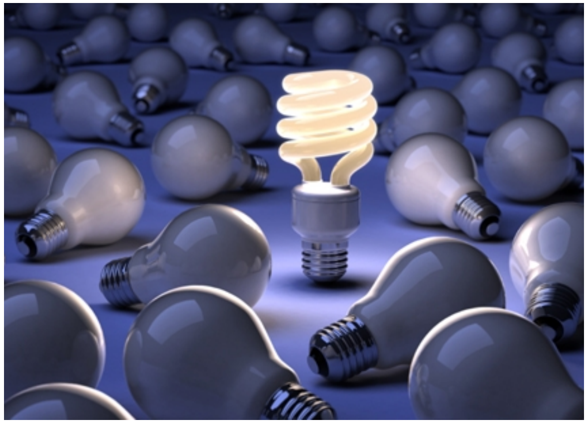
- Match power generation instantaneously with demand

- Coordinate utilities, suppliers, consumers

- Goal: ensure access to affordable, reliable and sustainable power via efficient administration of independent and transparent wholesale energy markets

Features of Smart Grids

controllable



efficient

resilient

green/sustainable

self-healing

situational awareness

US Dept. of Energy, “The smart grid: An introduction.”

Enabling Technology Advances

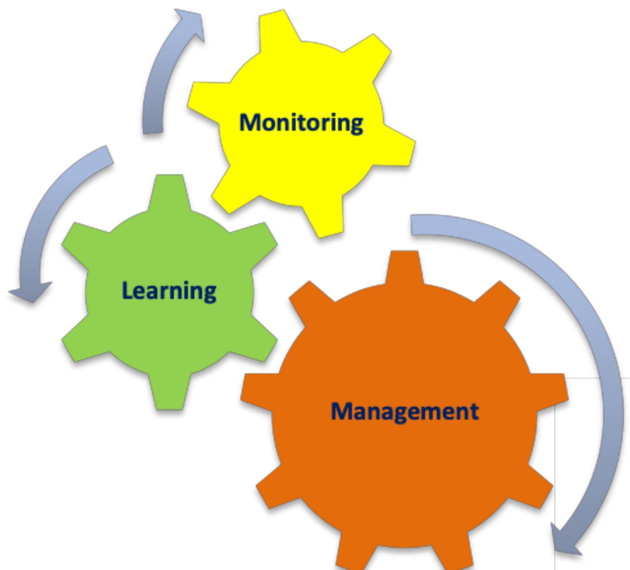
renewables

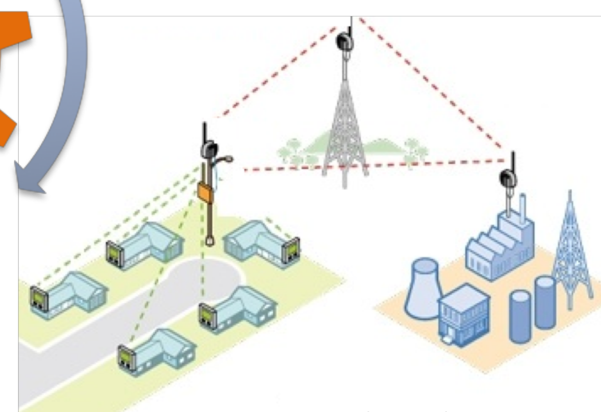
power electronics

energy storage

electric vehicles

metering



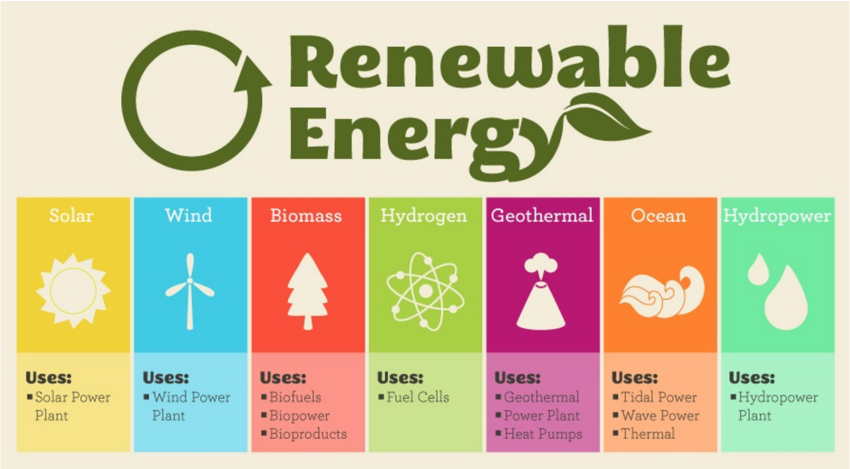


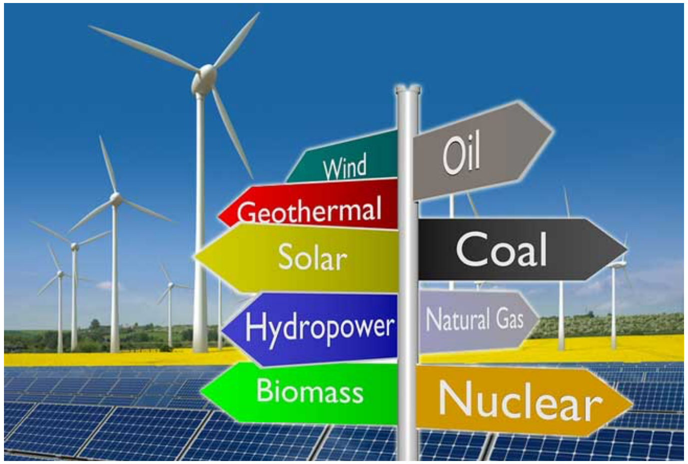
communications

demand response

Renewables vis-à-vis Non-renewables

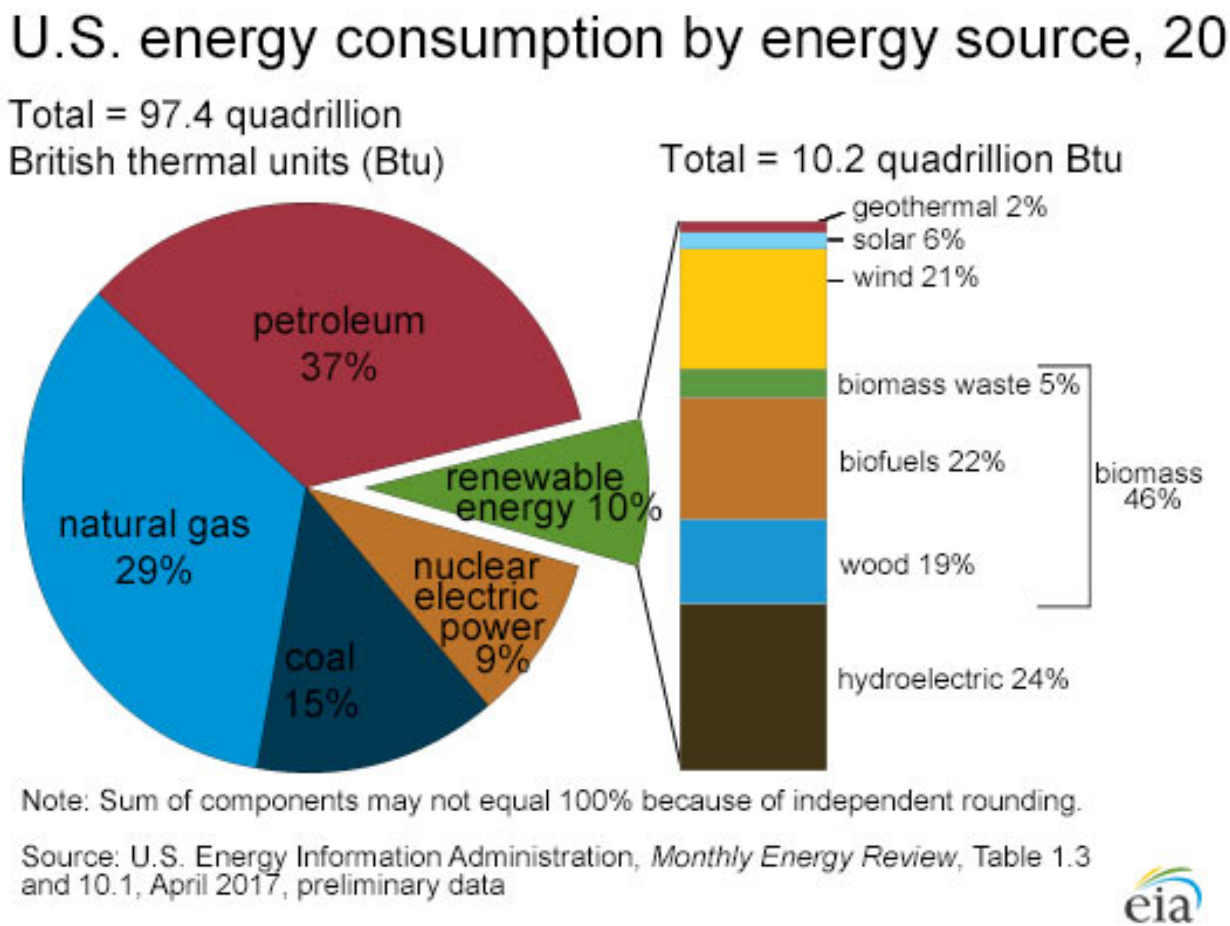
- **Renewable energy:** energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. [Wiki]
- Human timescale: "A good rule is that anything in space or geological is not on our time scale. Anything to do with our society and living organisms, excluding evolution, is." [Quora]
- **Non-renewable resource (finite resource):** resource that does not renew itself at a sufficient rate for sustainable economic extraction in meaningful human time-frames. e.g. earth minerals and metal ores, fossil fuels (coal, petroleum, natural gas) and groundwater. [Wiki]

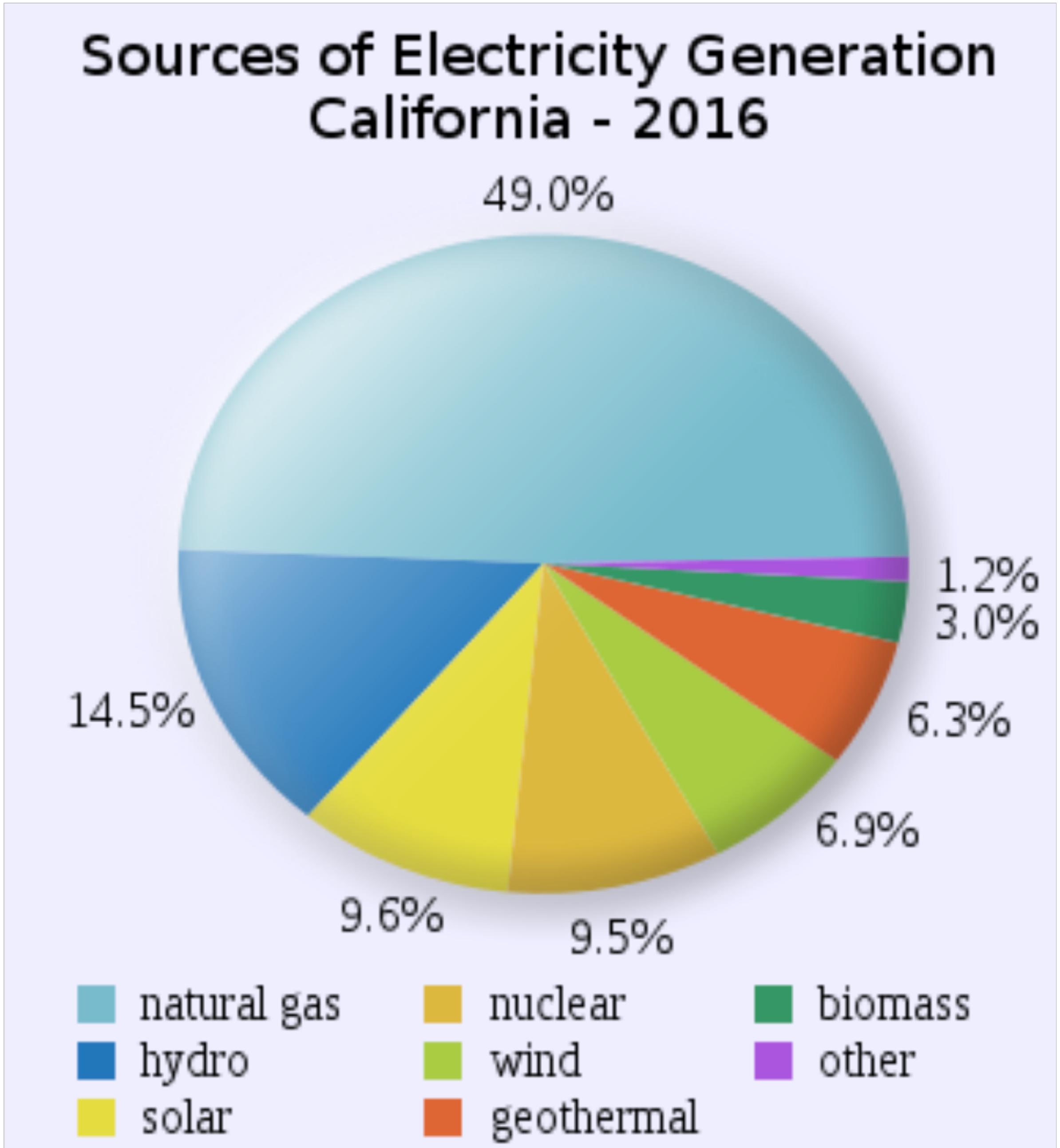




Energy Sources

Renewable/nonrenewable energy sources are used as primary energy sources to produce useful energy such as heat or used to produce secondary energy sources such as electricity.




Sources of Electricity Generation
California - 2016
49.0%
1.2%
3.0%
6.3%
6.9%
9.5%
9.6%
14.5%
natural gas
hydro
solar
nuclear
wind
geothermal
biomass
other

Solar Power

Solar power: conversion of energy from sunlight into electricity, either directly using photovoltaics (PV), indirectly using concentrated solar power (CSP), or a combination.

- PV cells convert light into an electric current using the PV effect.

- CSP systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam.

Concentrating Solar Power

The Crescent Dunes Solar Energy Project:

- Scale: 110 MW net solar thermal power + 1.1 GWh of energy storage
- Location: near Tonopah, 190 miles northwest of Las Vegas.
- Features: first utility-scale CSP plant with a central receiver tower + advanced molten salt storage tech from SolarReserve.
- Cost less than $1 billion
- Planned energy output was 500 GWh

Panda Solar

248-acre panda solar farm in Datong, Shanxi, China.

- Built by China Merchants New Energy Group, one of the country's largest clean energy operators.
- The 1st phase, which includes one 50 MW plant, was completed on 6/30/17. A second panda is planned…
- It will produce 3.2 billion kWh of solar energy in 25 years. That will reduce carbon emissions by 2.74 million tons.

Wind Power

Wind power: use of air flow through wind turbines to mechanically power generators for electricity. [wiki]

- Offshore turbines are located out at sea or in freshwater.
- Onshore wind refers to turbines located on land

Wind Turbine

Blade transportation

Turbine explode

Other Renewables

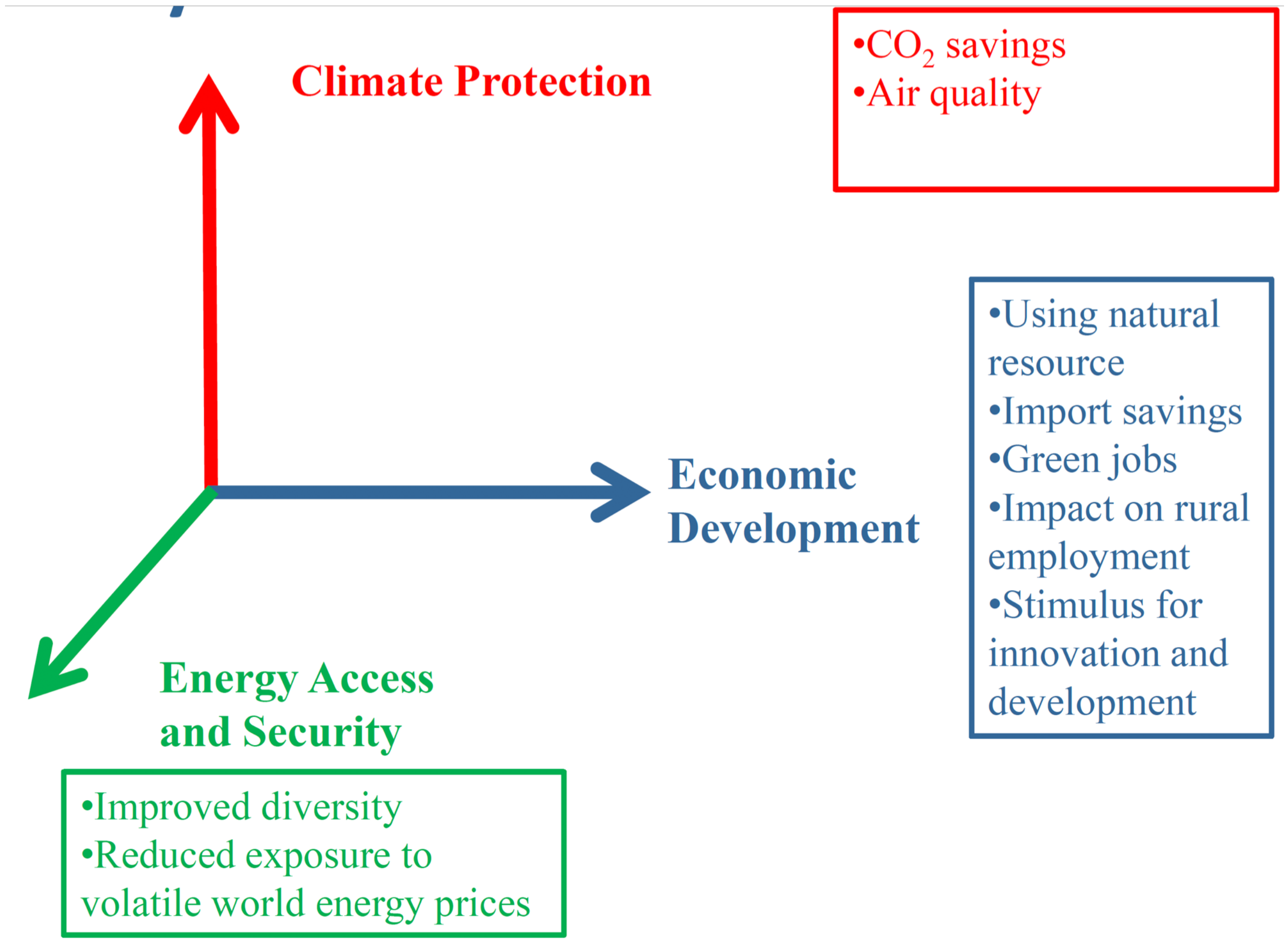
Hydropower

Geothermal energy

Bioenergy

Tidal energy

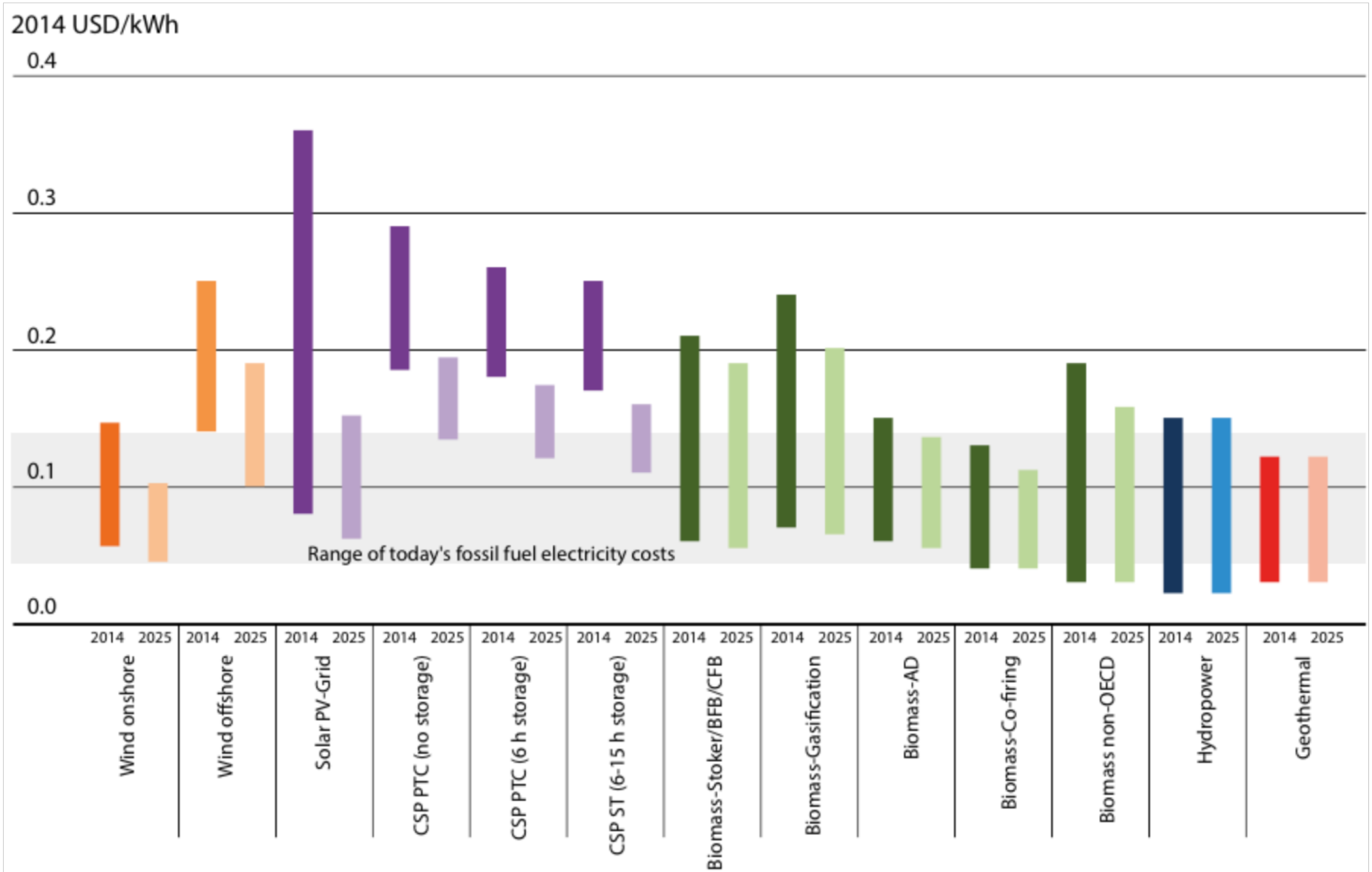
Why Renewables?



Pic credit: Amb. Richard H. Jones, Deputy Executive Director Intl Energy Agency

Costs of Renewable Energy

Source: IRENA Renewable Cost Database and Auctions Database.



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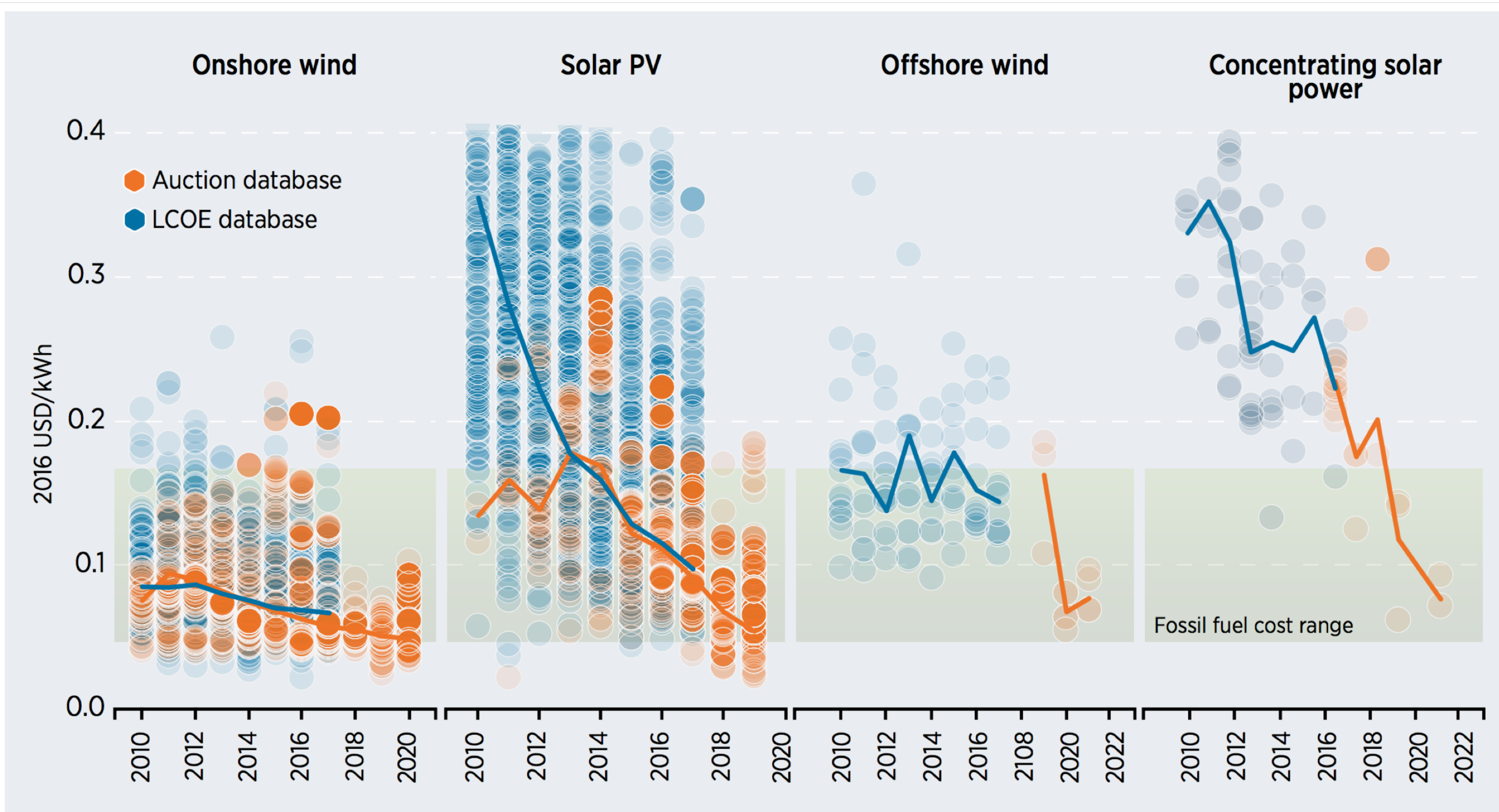
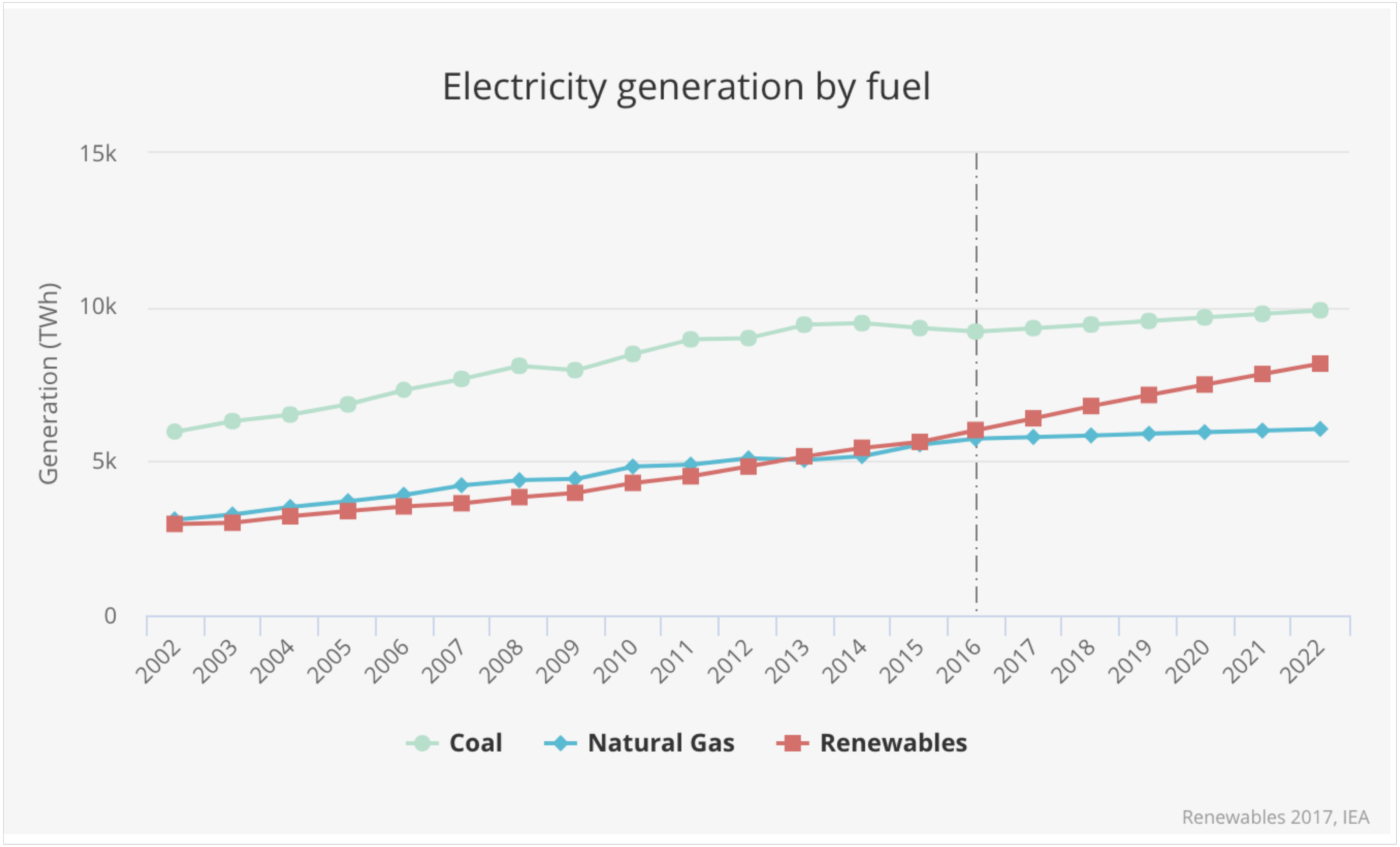
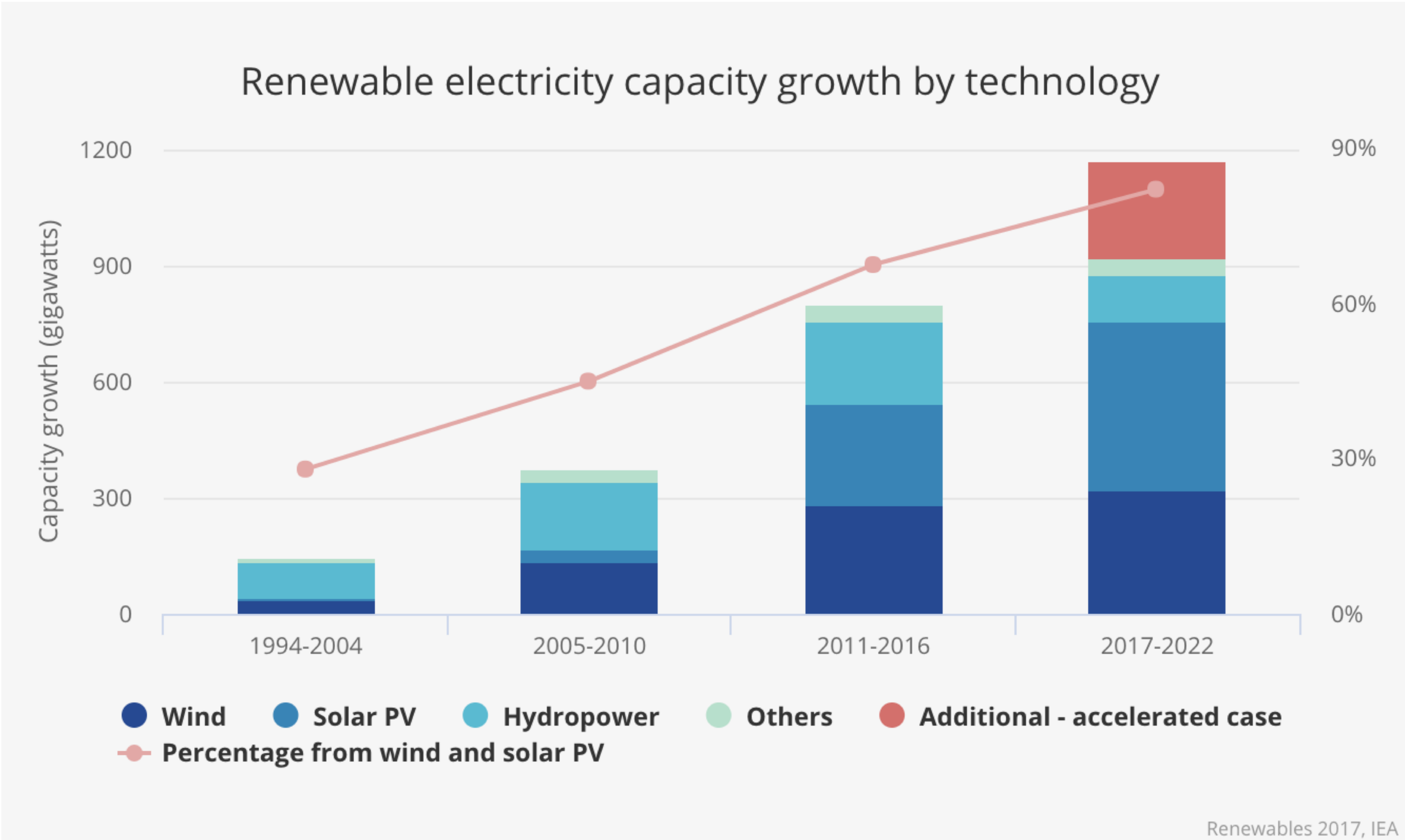


Each circle represents an individual project or an auction result where there was a single clearing price at auction.

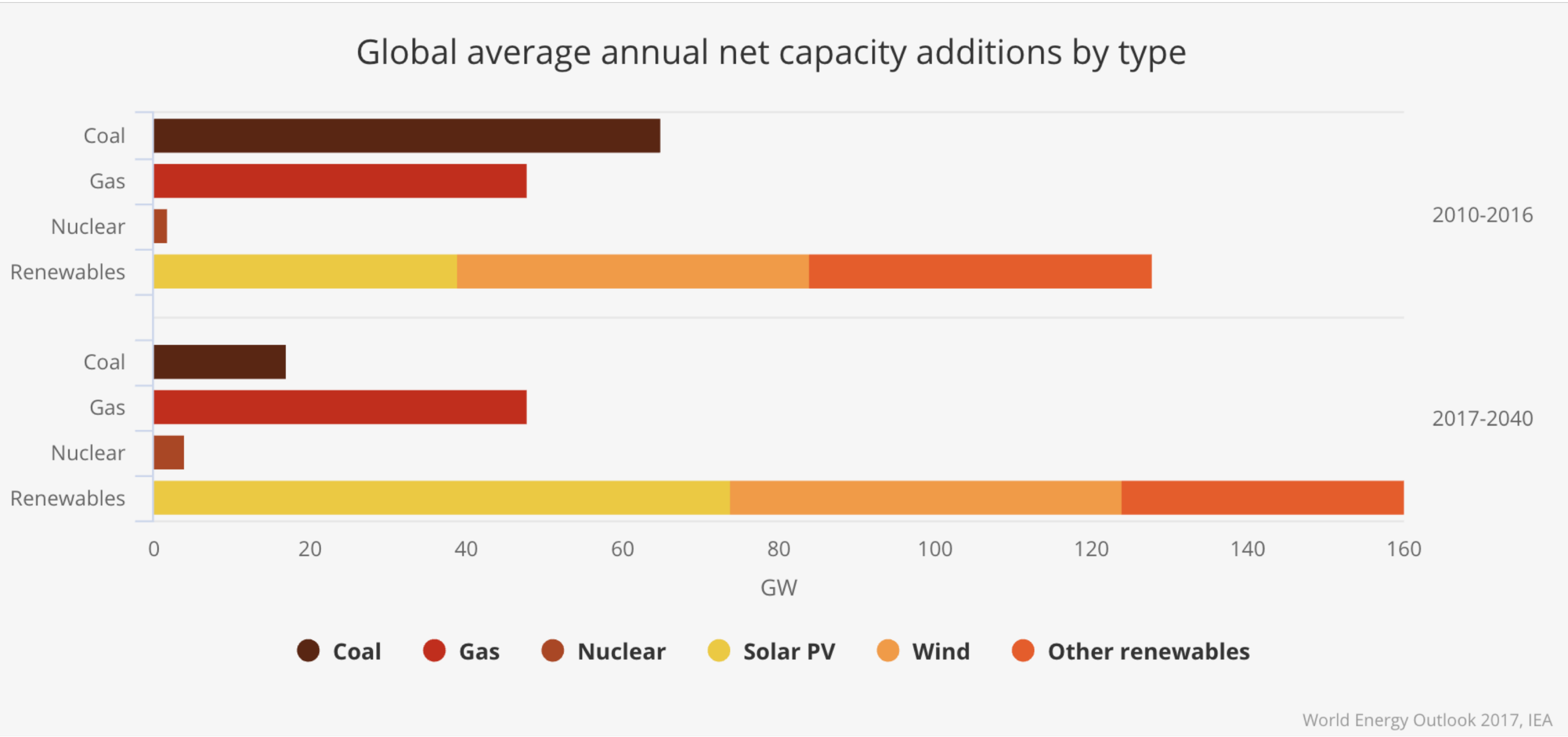
Electricity Generation



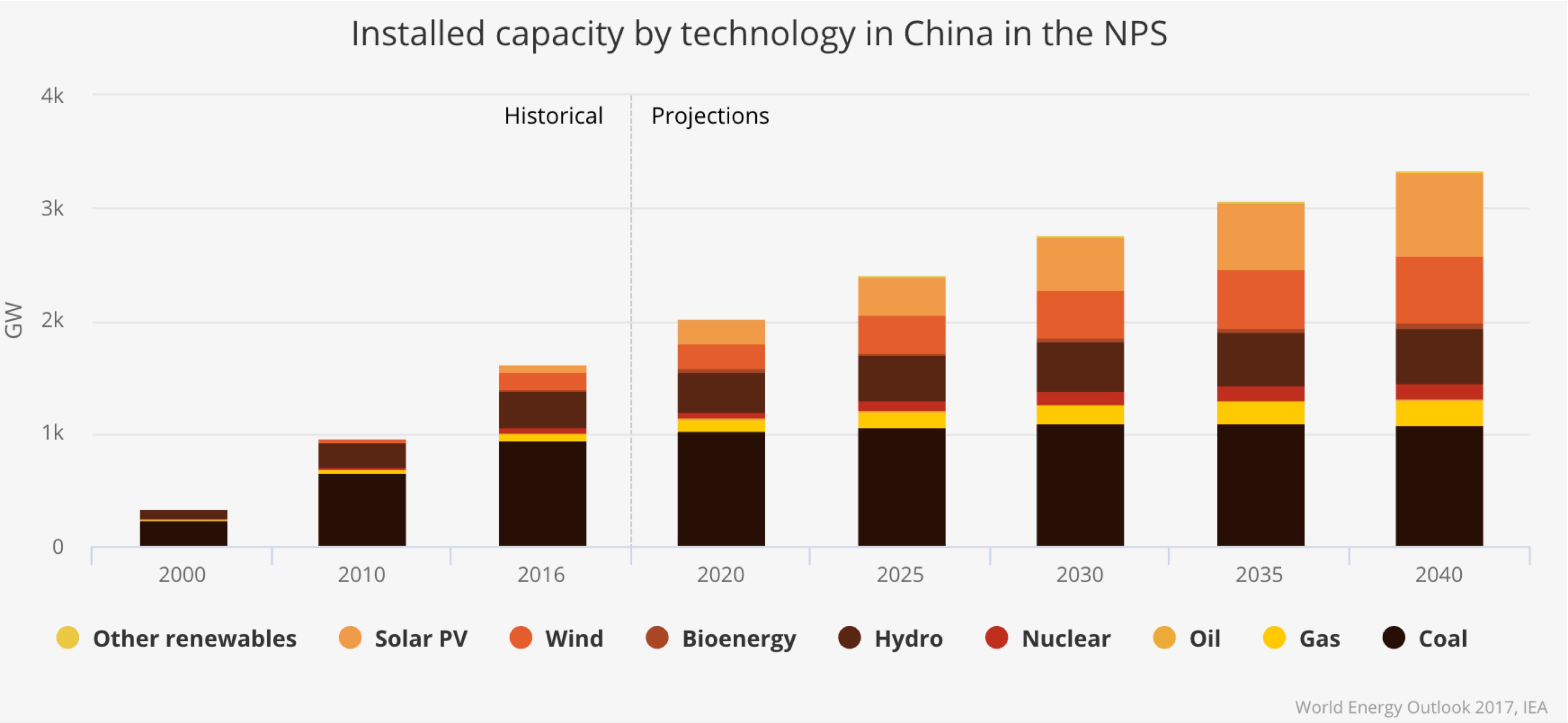
Capacity Growth of Renewables



Bright Future of Renewables

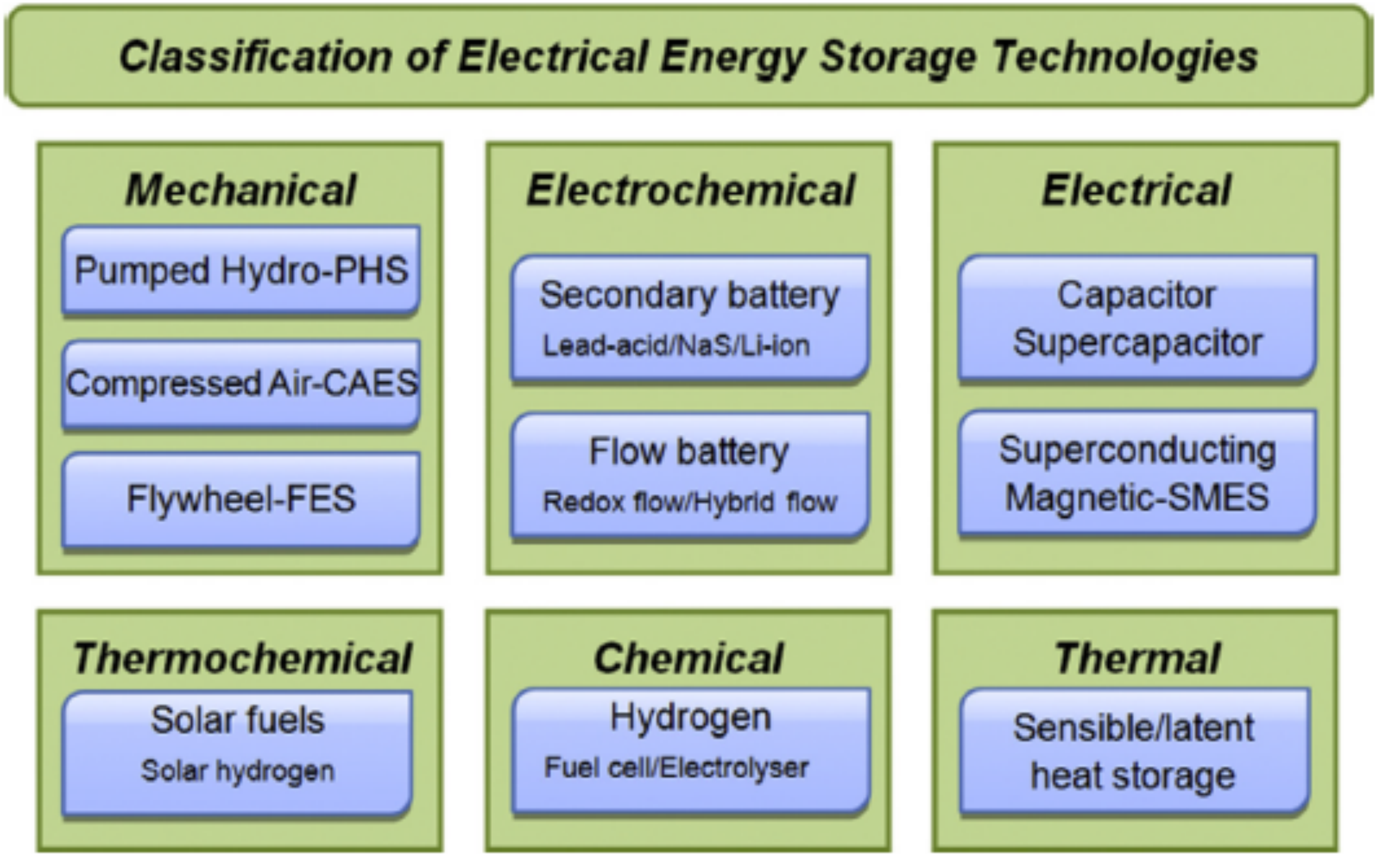


Bright Future of Renewables



Energy Storage

Energy storage: Capture of energy produced at one time for use at a later time. A device that stores energy is called an accumulator or battery. [wiki]

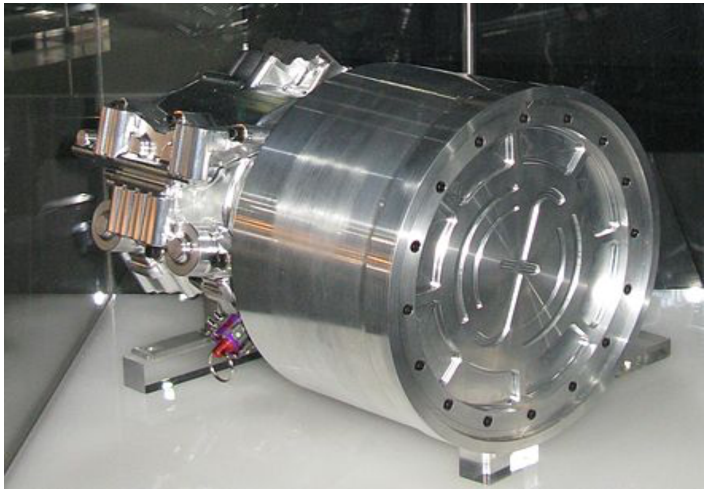


Picture credit: Xing Luo, etc, "Overview of current development in electrical energy storage technologies and the application potential in power system operation."

Energy Storage

pumped storage hydroelectricity

Compressed air locomotive

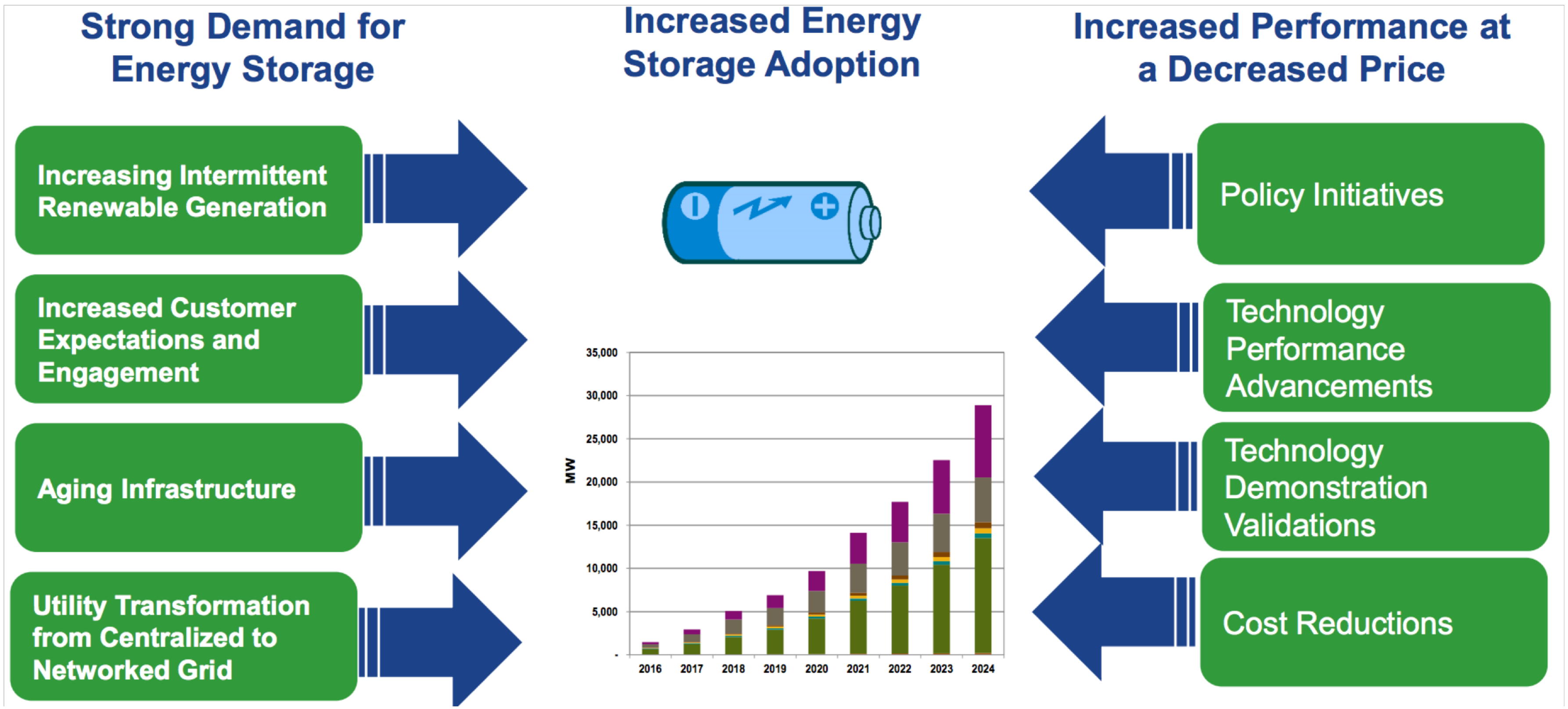


Flywheel

Thermal storage

Why Energy Storage Now

Driving demand: Industry changes, policy, technology, and cost advances



Picture credit: betterbuildingssolutioncenter.energy.gov

Applications of Energy Storage

Electricity cost optimization

- peak/off-peak price management
- demand and power factor charge management

Capacity

- generation resource adequacy (e.g., capacity markets, operating reserves)
- T&D infrastructure adequacy

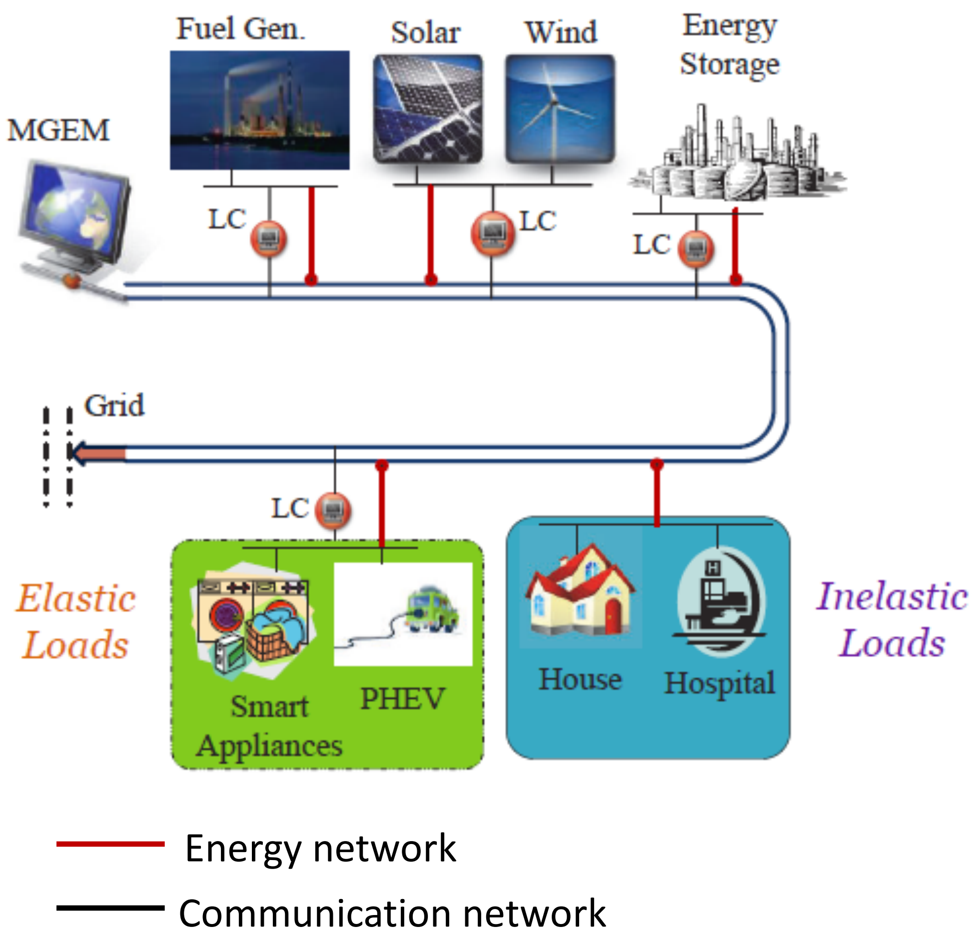
Routine grid operations

- frequency regulation
- voltage/VAR support
- renewable energy ramping/ smoothing/shifting

Contingency Situations

- black start
- sustained/momentary outages

Microgrids and Distributed Energy Resources



Microgrids

- Distributed generation units
  - Fossil fuels
  - Renewables
- Distributed storage (DS)
- Elastic and inelastic loads

Challenges

- Renewable energy sources: high volatility
- Distributed scheduling over the microgrid infrastructure

Energy Management with Renewables

- Economic dispatch

$$\min_{\{P_{G_m}\}} \sum_{m=1}^{M} C_m(P_{G_m})$$

$$\text{s.t.} \quad \text{power generation constraints}$$

$$\sum_{m=1}^{M} P_{G_m} = P_D$$

(supply = demand)

$$\min_{\{P_{G_m}\}} \sum_{m=1}^{M} C_m(P_{G_m})$$

$$\text{s.t.} \quad \text{power generation constraints}$$

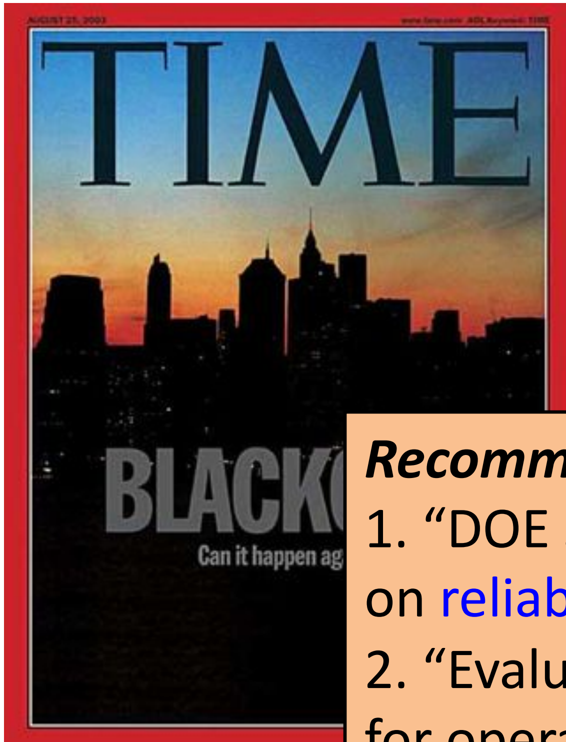
$$\sum_{m=1}^{M} P_{G_m} + W = P_D$$

W: stochastic resource

P_{G_m}: Power output of generator m

$C_m(\cdot)$: Cost of generator m

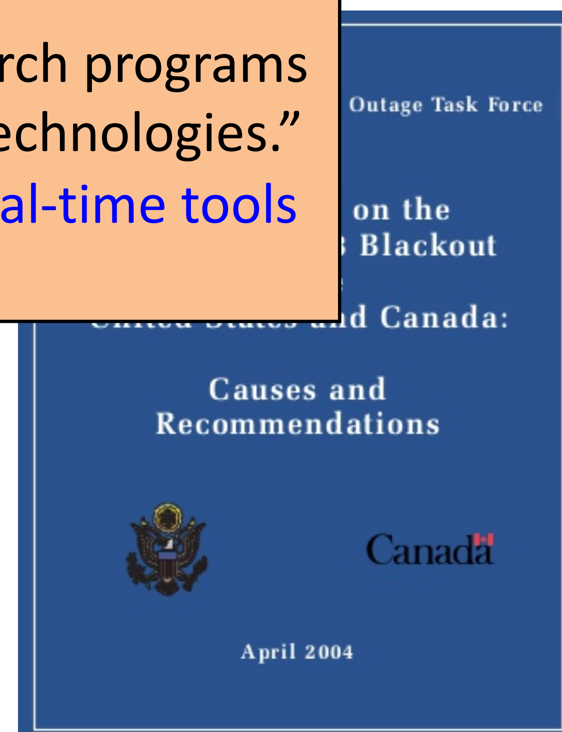
Remember …



Time: August 14, 2003
Location: Midwest/Northeast US & Ontario, CAN

Costs: 50 million people, 61,800 MWs of load lost. $4~10 billion in the US and Canada's GDP was down 0.7%

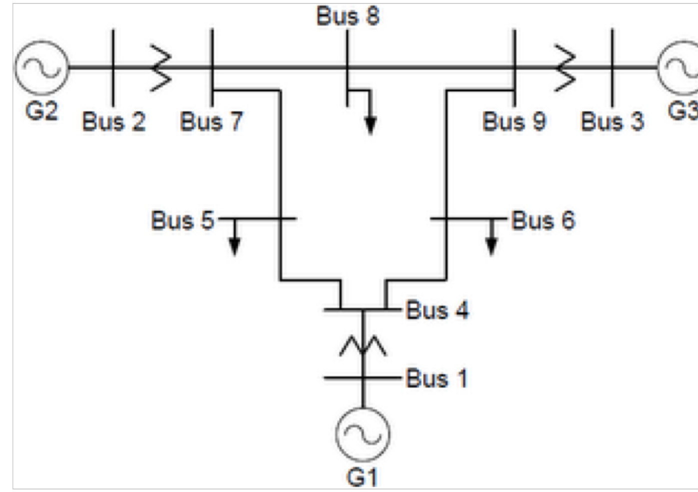
Recommendations:
1. "DOE should expand its research programs on reliability-related tools and technologies."
2. "Evaluate and adopt better real-time tools for operators..."



"**Key phase events:** MISO's state estimator (SE) software solution was compromised…"
"The failure of its SE contributed to the lack of situational awareness."

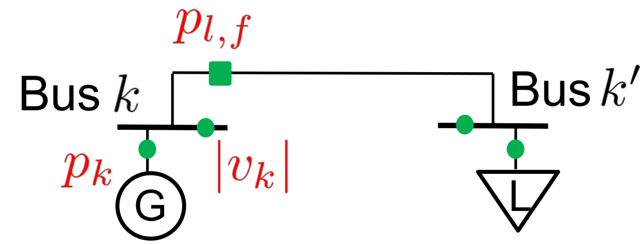
System Modeling

- A power system $\mathcal{G} = (\mathcal{N}, \mathcal{L})$
  - Transmission lines, buses, and transformers



- Complex voltage: $\mathbf{v} = [v_1, \ldots, v_n]^\top \in \mathbb{C}^n$
- Nodal current injection: $\mathbf{i} = \mathbf{Y}\mathbf{v}$
- Net injected complex power: $\mathbf{p} + \mathbf{q}j = \mathrm{diag}(\mathbf{v}\mathbf{i}^*)$

Nodal and Line Quantities



- Voltage magnitude and nodal power injections:

$$|v_k|^2 = \mathrm{Tr}(\mathbf{E}_k \mathbf{v}\mathbf{v}^*), \;\; p_k = \mathrm{Tr}(\mathbf{Y}_{k,p} \mathbf{v}\mathbf{v}^*), \;\; q_k = \mathrm{Tr}(\mathbf{Y}_{k,q} \mathbf{v}\mathbf{v}^*)$$

- Branch active and reactive powers:

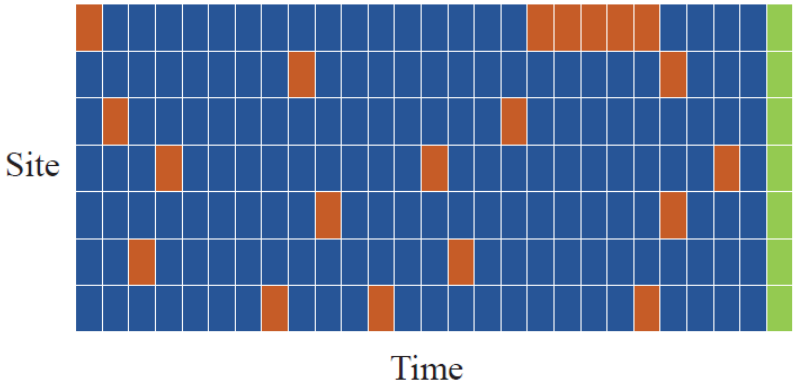
$$p_{l,f} = \mathrm{Tr}(\mathbf{Y}_{l,p_f} \mathbf{v}\mathbf{v}^*), \quad p_{l,t} = \mathrm{Tr}(\mathbf{Y}_{l,p_t} \mathbf{v}\mathbf{v}^*)$$
$$q_{l,f} = \mathrm{Tr}(\mathbf{Y}_{l,q_f} \mathbf{v}\mathbf{v}^*), \quad q_{l,t} = \mathrm{Tr}(\mathbf{Y}_{l,q_t} \mathbf{v}\mathbf{v}^*)$$

- All quantities are quadratic functions of the complex voltage $\mathbf{v}$

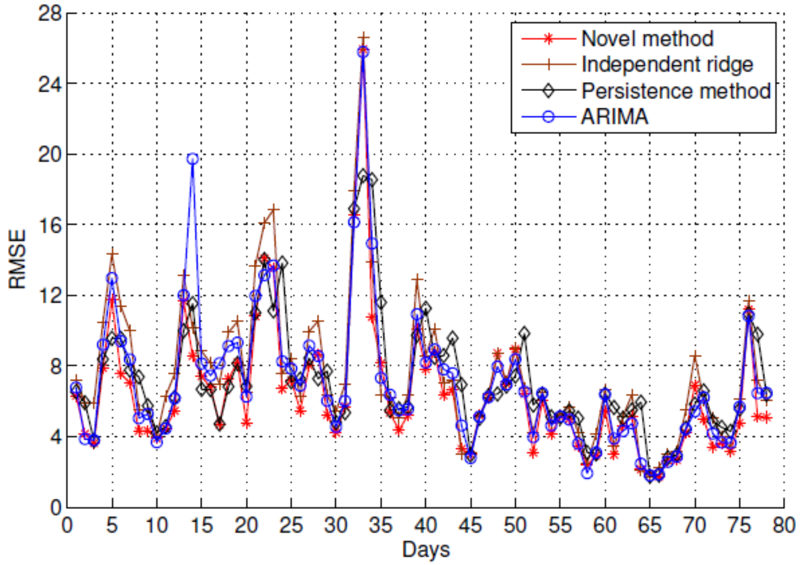
$$\mathbf{v} = \text{state of the system}$$

Energy Data Analytics

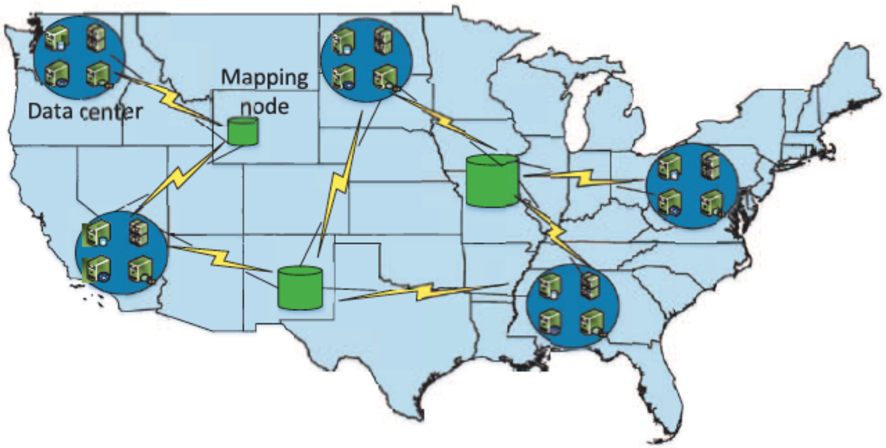
Wind power inference:
Given historical wind power outputs, infer missing and future values.



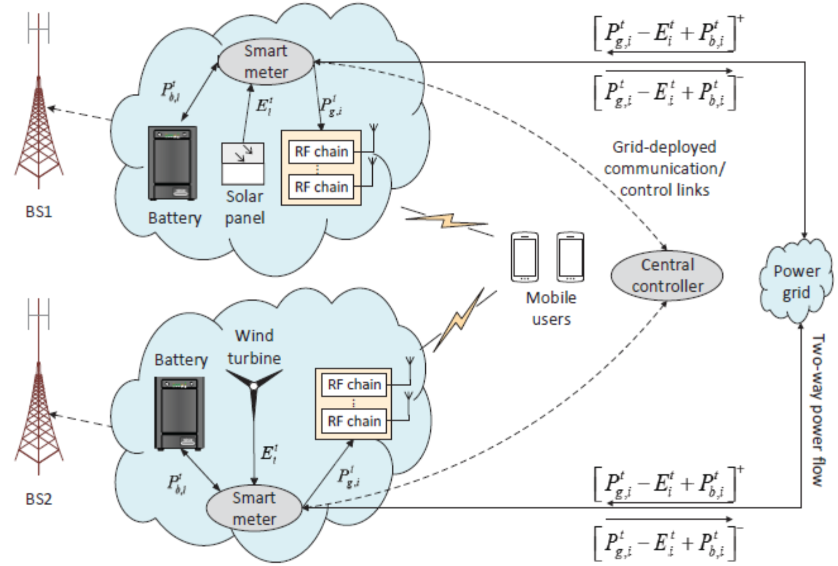
Electricity price forecasting:
Given historical electricity prices and features (e.g., temperature, humidity, load), infer future values.



Renewable Powered Cyber-Physical Systems



Geo-distributed data centers



Cellular networks

System features:

- Locally supported by renewables and storage units
- Two-way energy trading

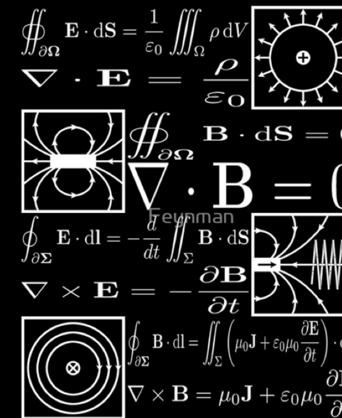
Challenges:

- Uncertainties from renewables, prices, and service requests
- Distributed resource allocation

EE Professor in Power Systems

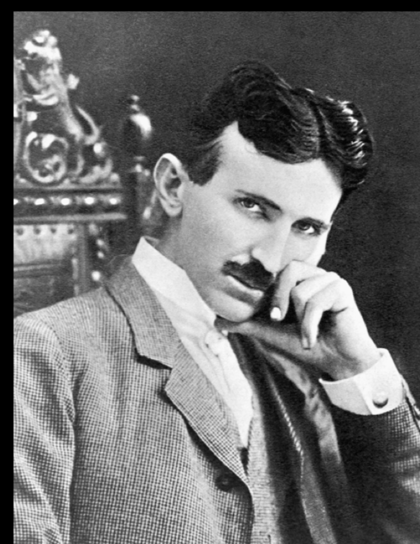
What my friends think I do

What my mom thinks I do



What students think I do

What society thinks I do



What I think I do

What I really do

Q & A

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Thank You!