Cool Science Series

Electric Power Grid

Generation, Transmission, Distribution, Storage

January 2025, Linda Fugate, Ph.D.

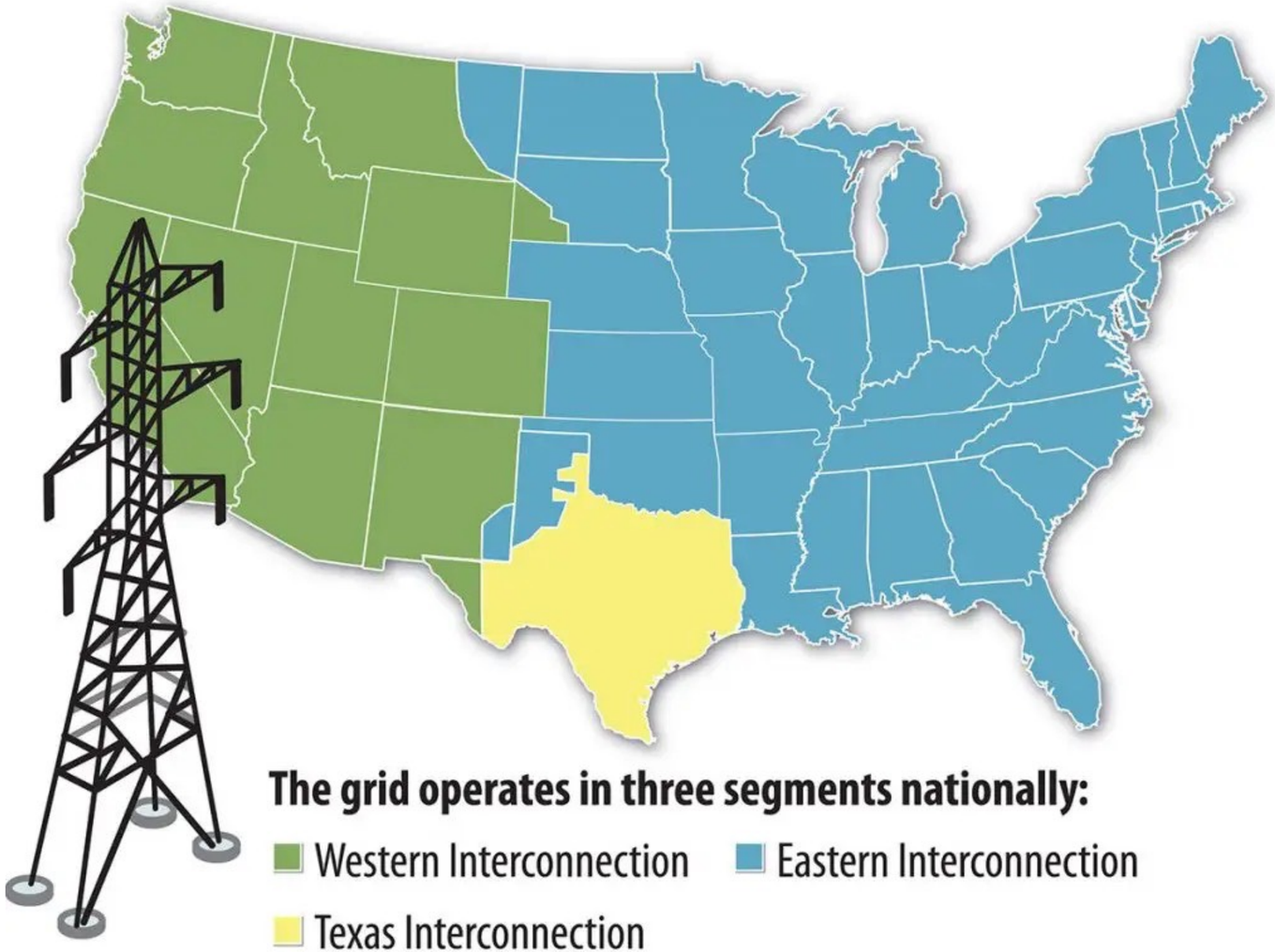
References

- Electrical Power System Analysis and Design, David K. K. Smith, 2024
- The Grid: The Fraying Wires between Americans and our Energy Future, Gretchen Bakke, 2017.
- Web sites for ERCOT, Department of Energy, etc.
- YouTube videos, on next slide

Practical Engineering Series

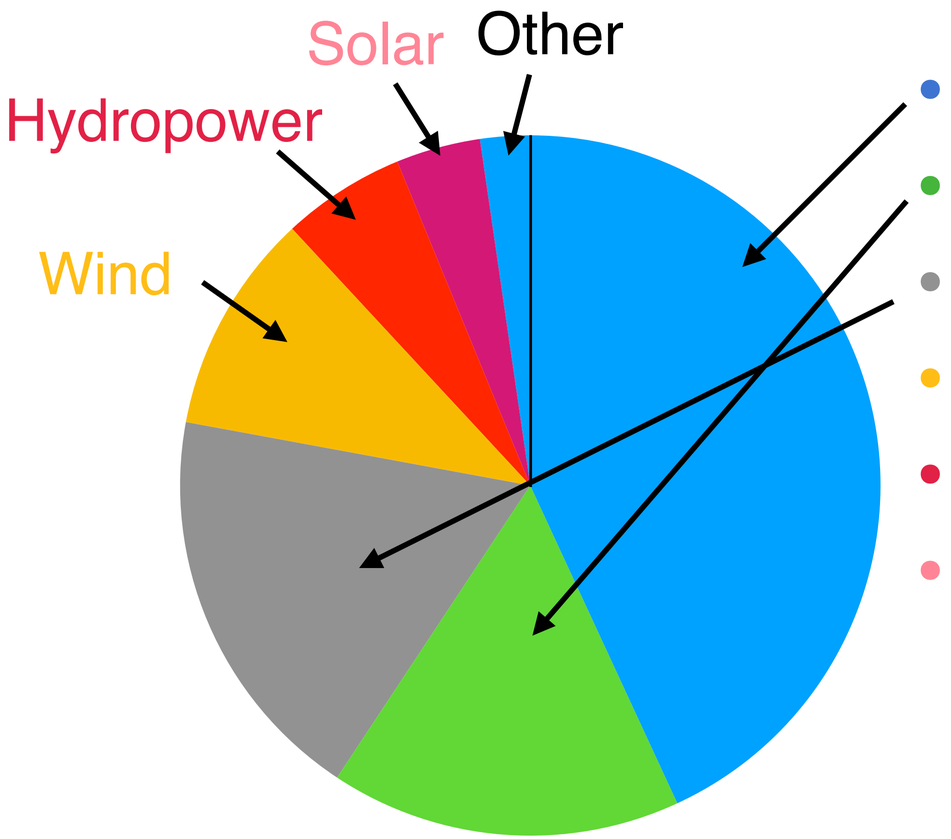
Series of 20 videos

U.S. Power Grids



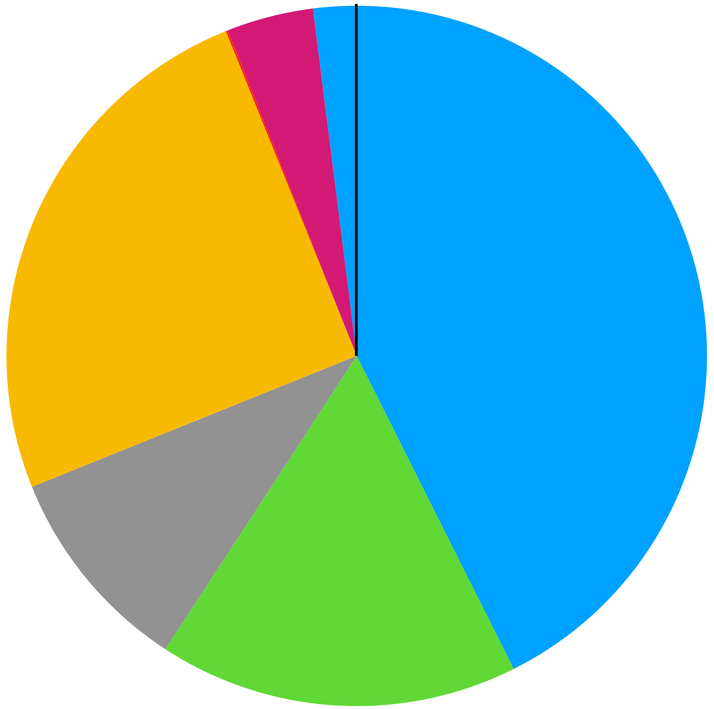
Overview:
Electric Power Sources

Generation by Energy Source



United States

Natural Gas
Coal
Nuclear
Wind
Hydropower
Solar



Texas

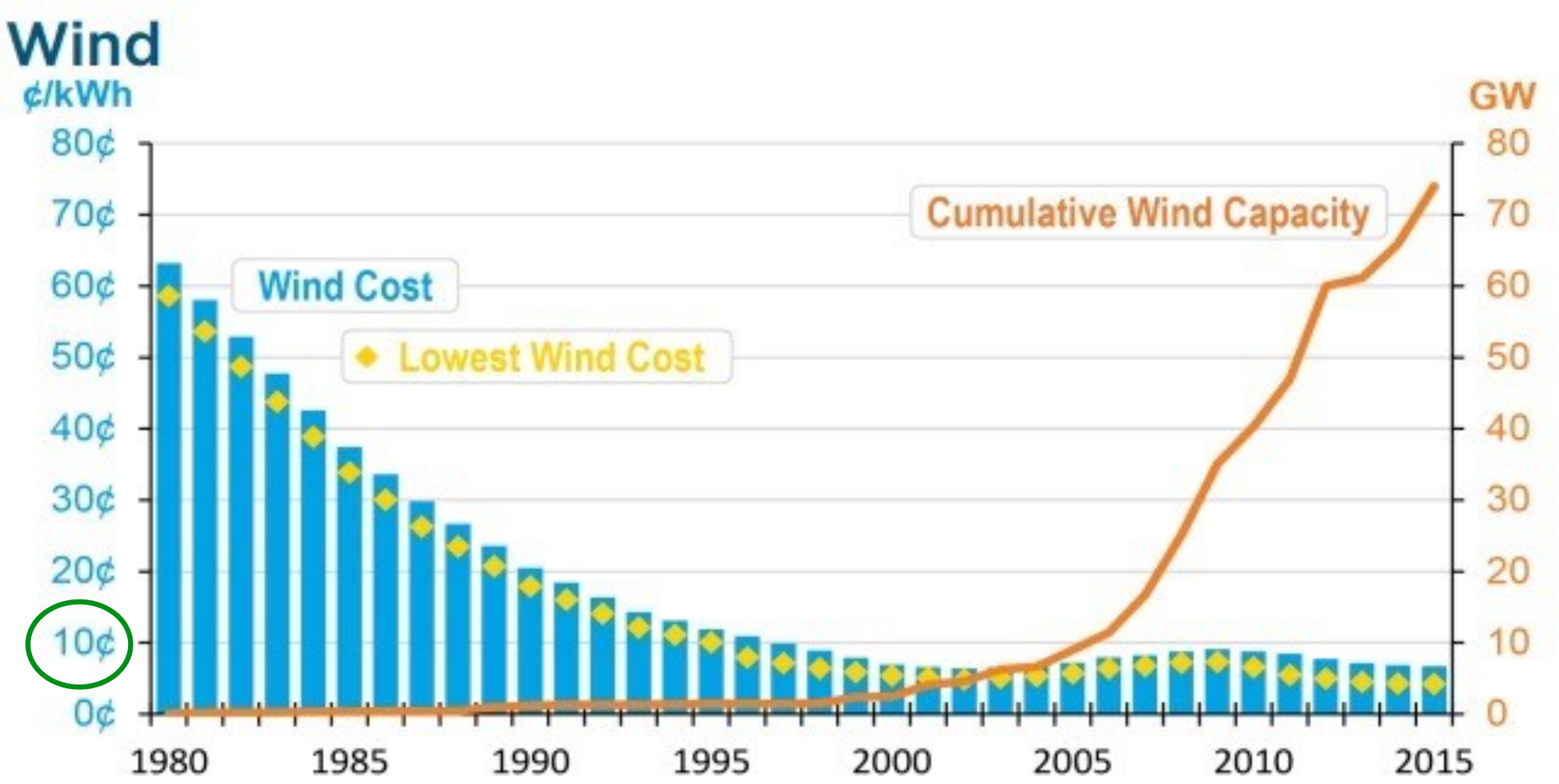
Challenges for our Electric Grid

- Old Age
- Electric Vehicles
- Cryptocurrency
- Artificial Intelligence

Solutions in Development

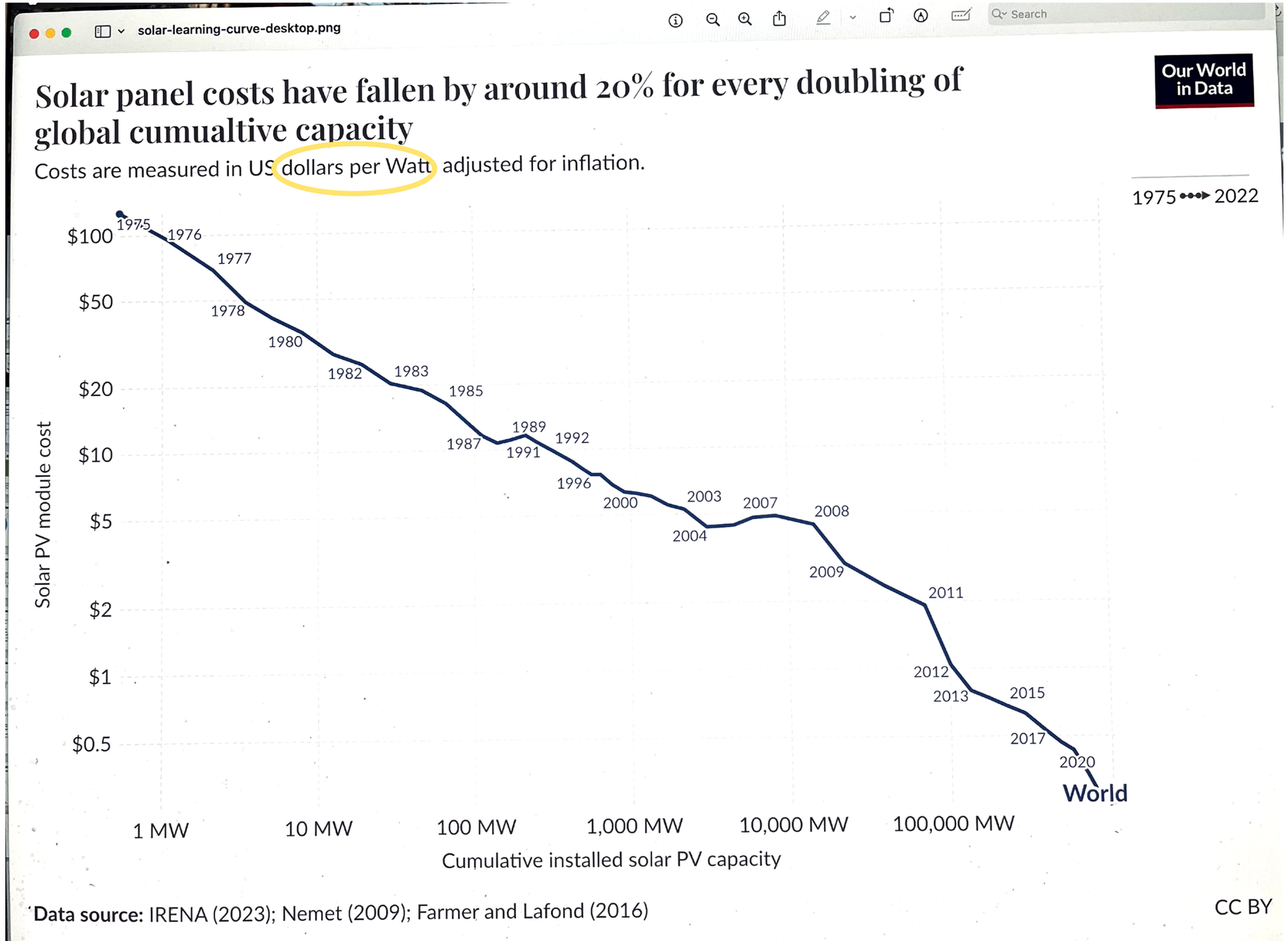
- High and Ultra-High Voltage Direct Current Transmission
- New generation nuclear power plants, including modular designs and thorium reactors
- More renewable, especially wind and solar generation, which require:
- Energy storage:
  - Lithium ion batteries
  - Other batteries (they don’t have to be lightweight at a power plant)
  - Pumped hydro
  - Other gravity storage (massive concrete blocks)
  - Compressed air in caverns
  - Heat storage (sand, salt)
  - Flywheels

Wind Energy Costs

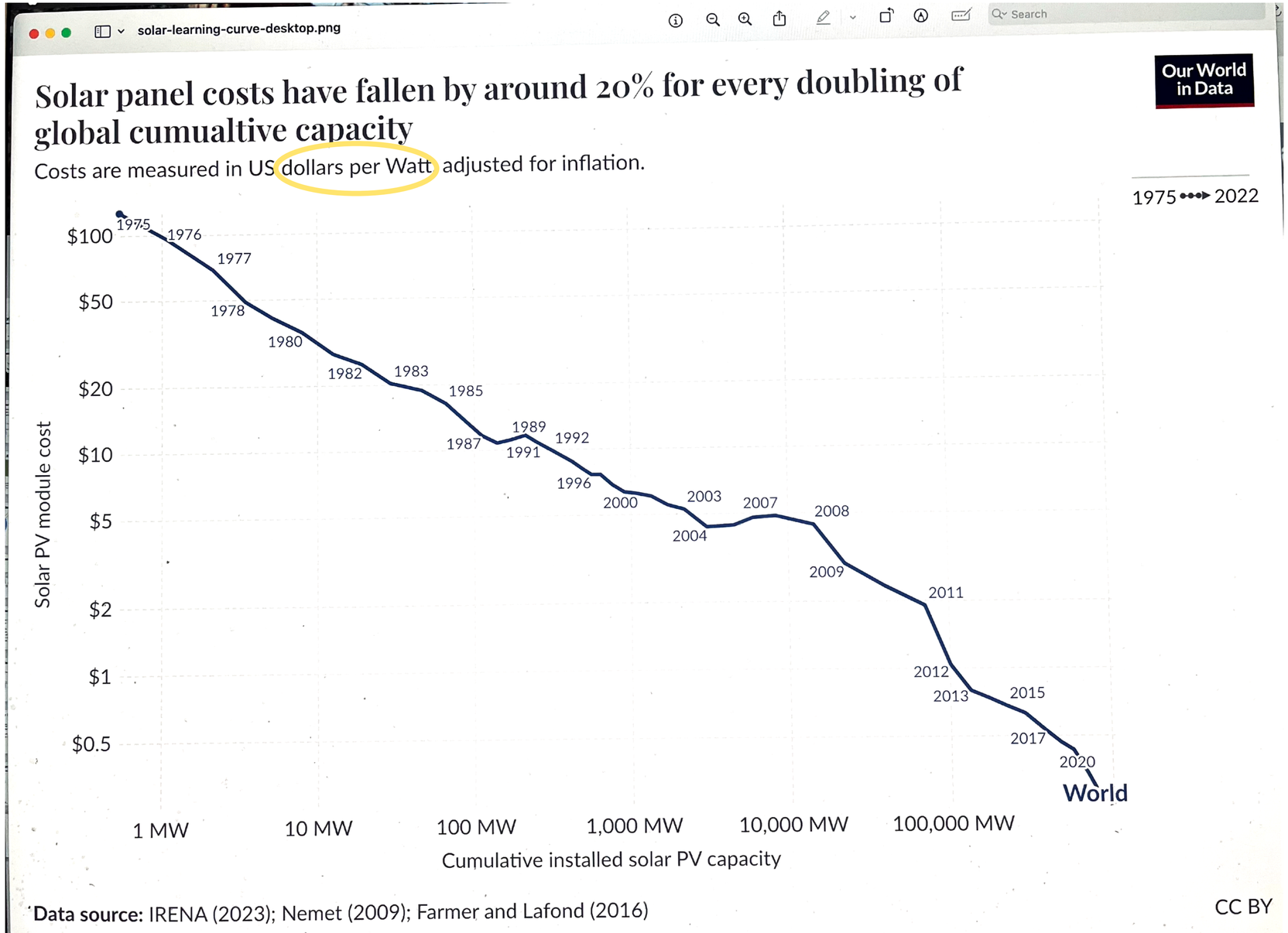


From Department of Energy

Solar Panel Costs



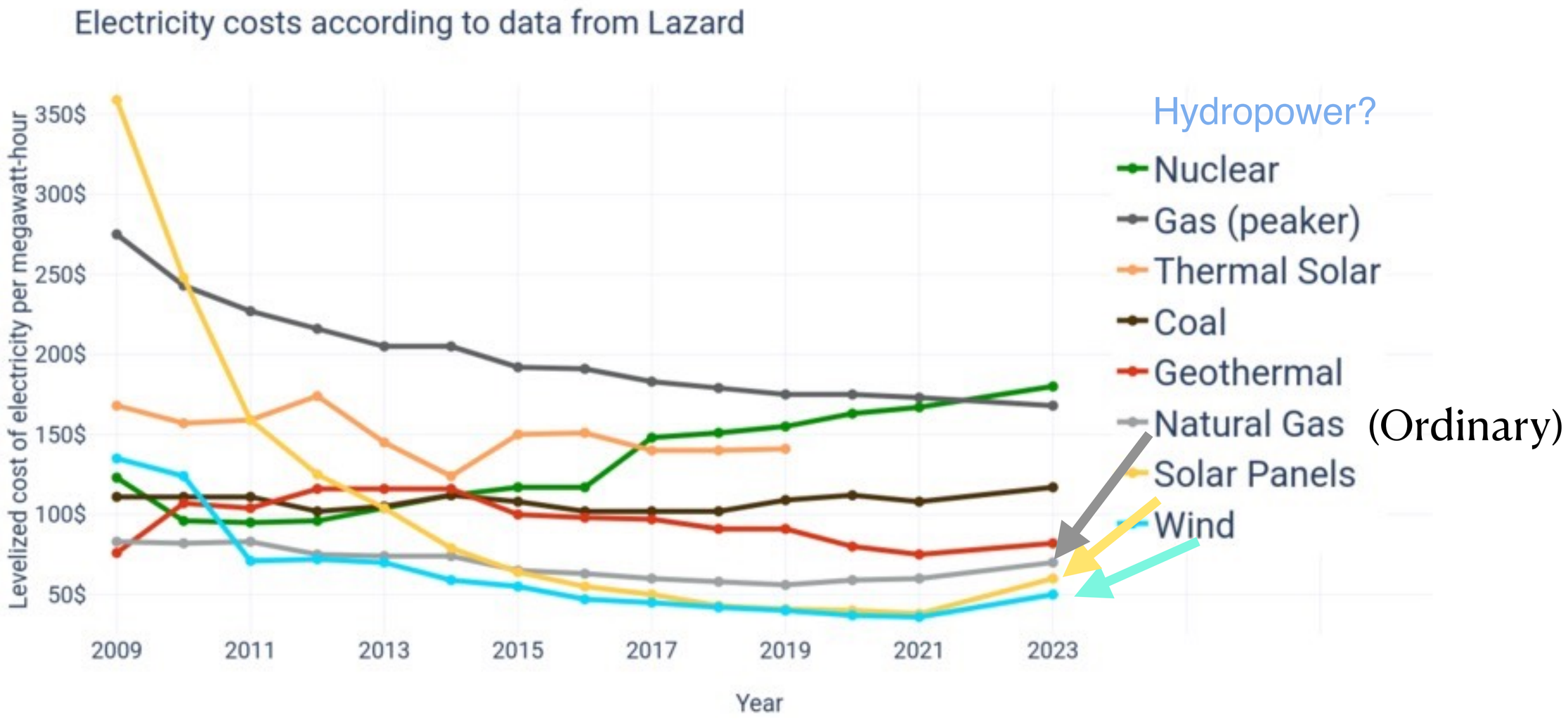
Solar Panel Costs



$$\frac{\$}{\text{Watt}} \times \frac{1000}{1000} \times \frac{1}{\text{hours}} = \frac{\$}{\text{kWh}}$$

Unsubsidized Energy Costs Comparison

Lazard.com, financial advisors

- 

Unsubsidized Energy Costs Comparison

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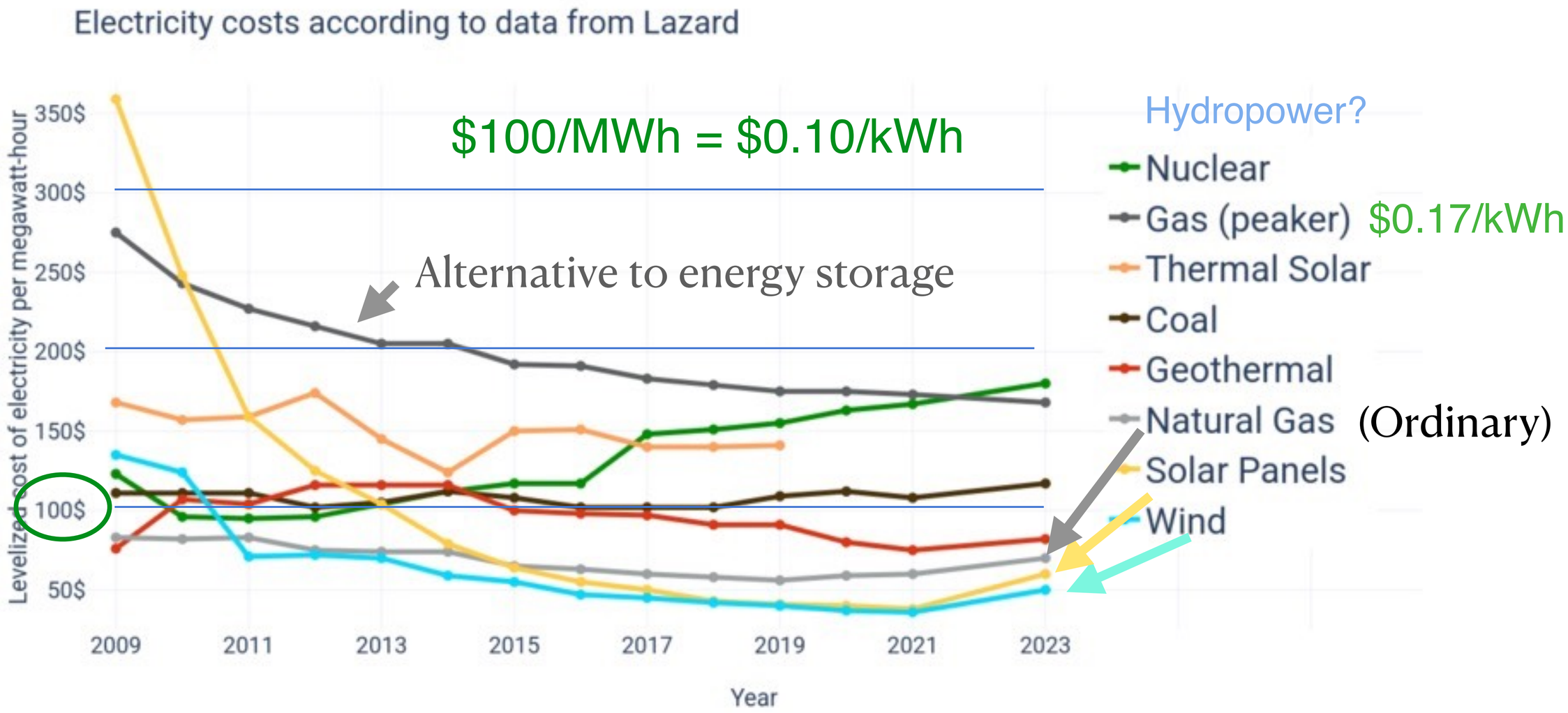
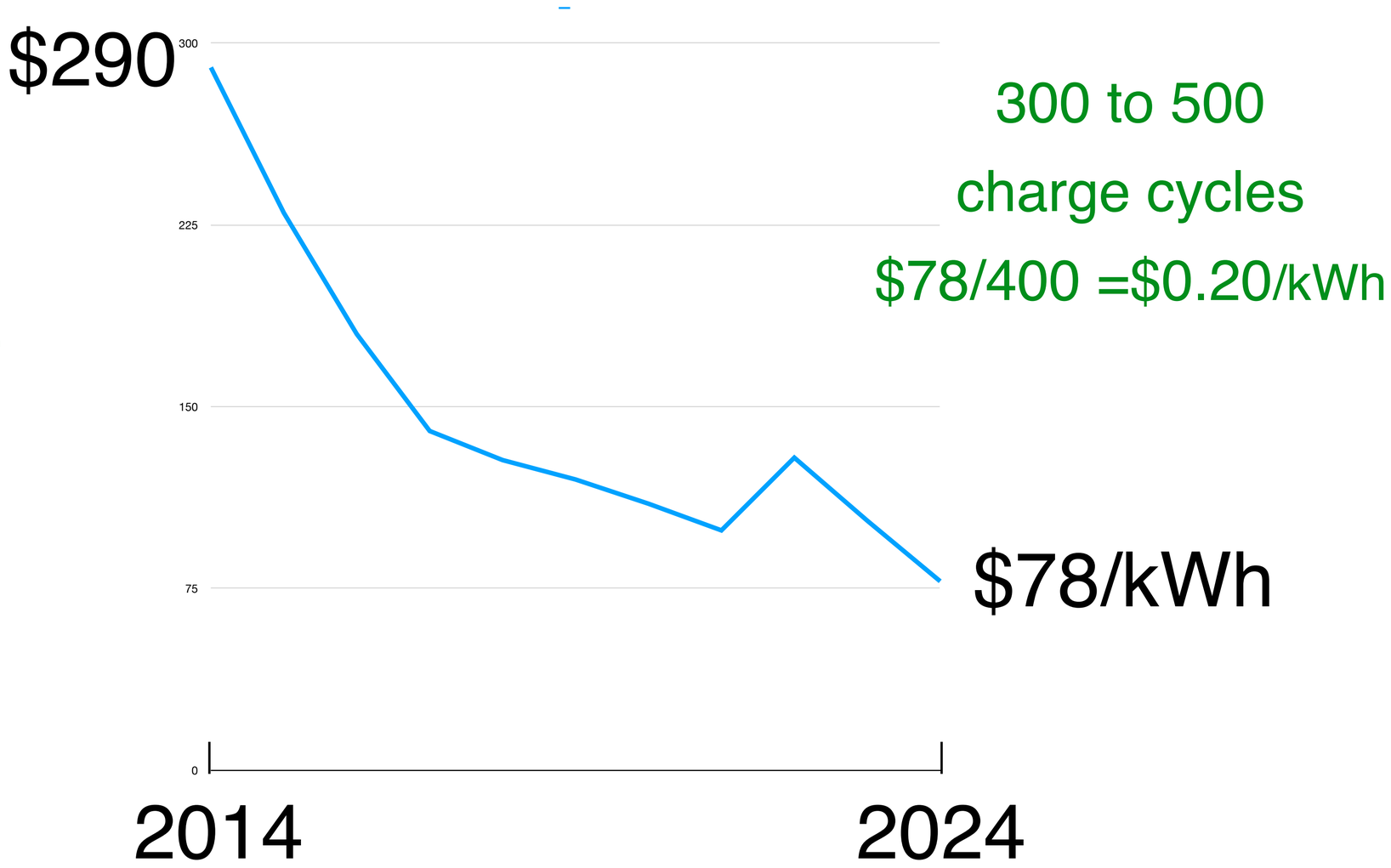


Lithium Ion Battery Cost

Dollars per kilowatt-hour, https://elements.visualcapitalist.com/charted-lithium-ion-batteries-keep-getting-cheaper/



300 to 500

charge cycles

$78/400 =$0.20/kWh

This makes

wind and solar

energy

more practical

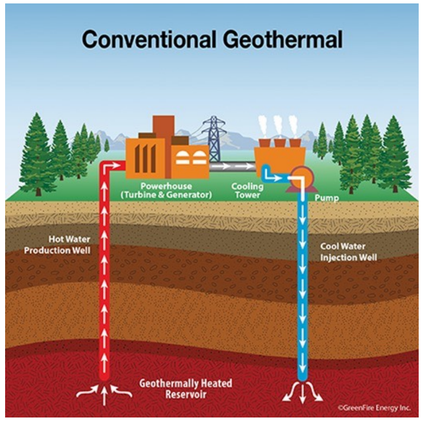
Retail Prices for EV Batteries

https://www.recurrentauto.com/research/tesla-battery-replacement-costs

- BMW 13: $145 to $727 per kWh
- Chevrolet Bolt: $250 to $271 per kWh
- Chevrolet Volt: $152 to $467 per kWh
- Hyundai Ioniq: $1,829 per kWh
- Nissan Leaf: $137 to $187.2 per kWh
- Tesla: $12,000 to $15,000, Battery sizes are 60kWh to 100 kWh
- Tesla Megapack: $1.4 million for 3MWh, $0.47 per Wh = $470 per kWh
- Battery farms get better deals

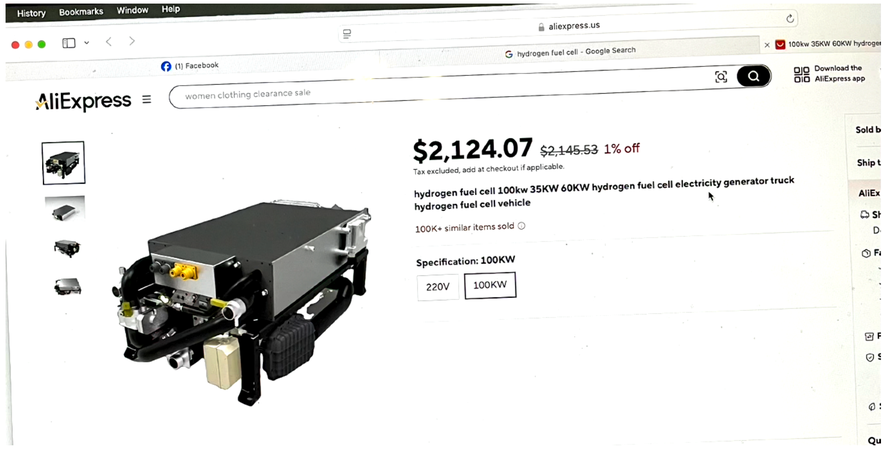
Minor Energy Sources

- Geothermal: 25% of Iceland’s total energy production

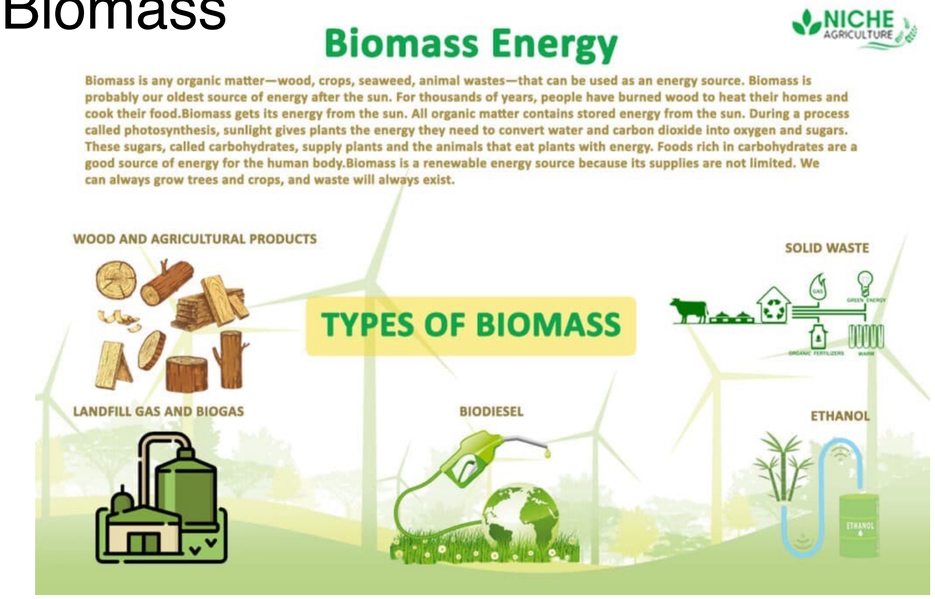


- Wave and Tidal (South Korea)

- Hydrogen fuel cells

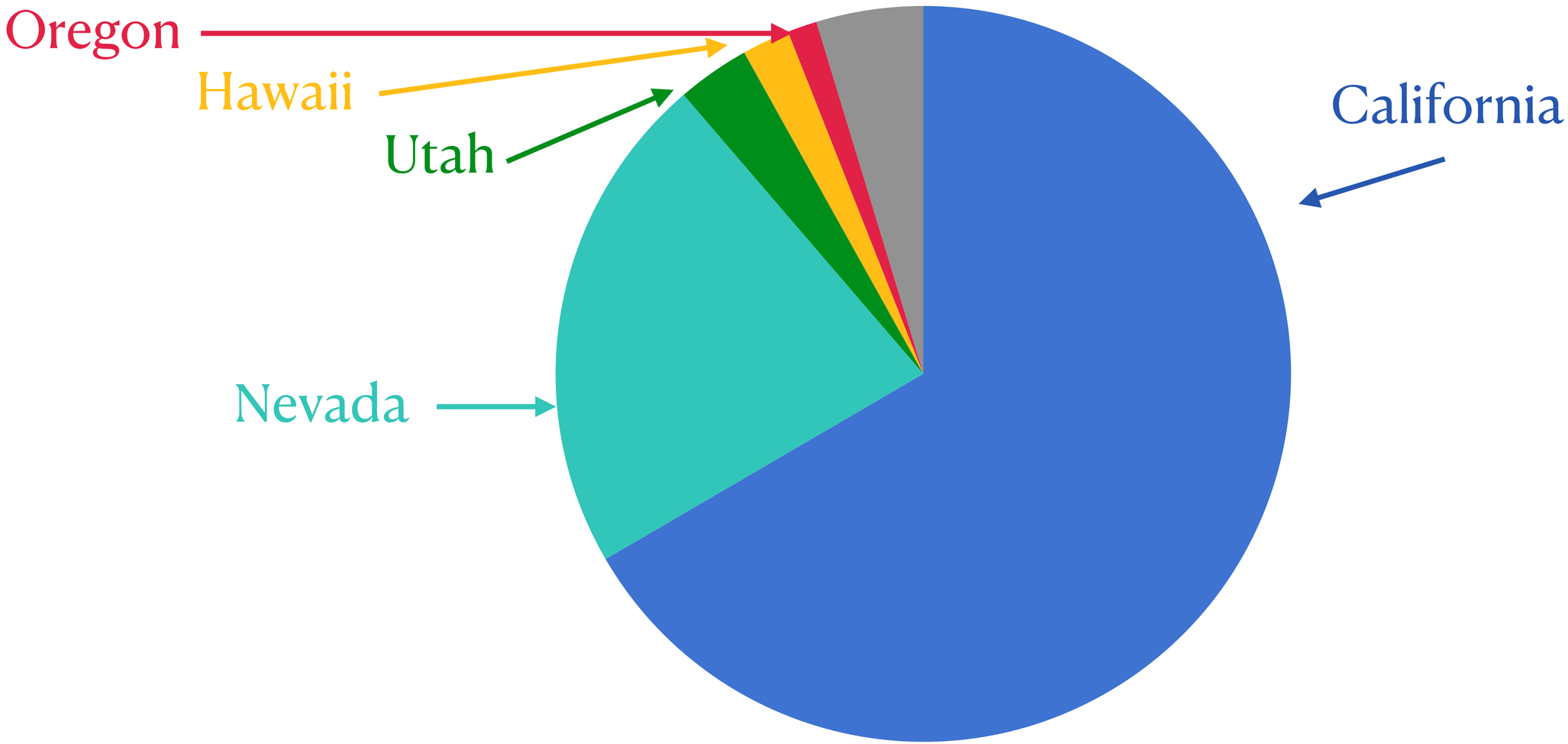


- Biomass



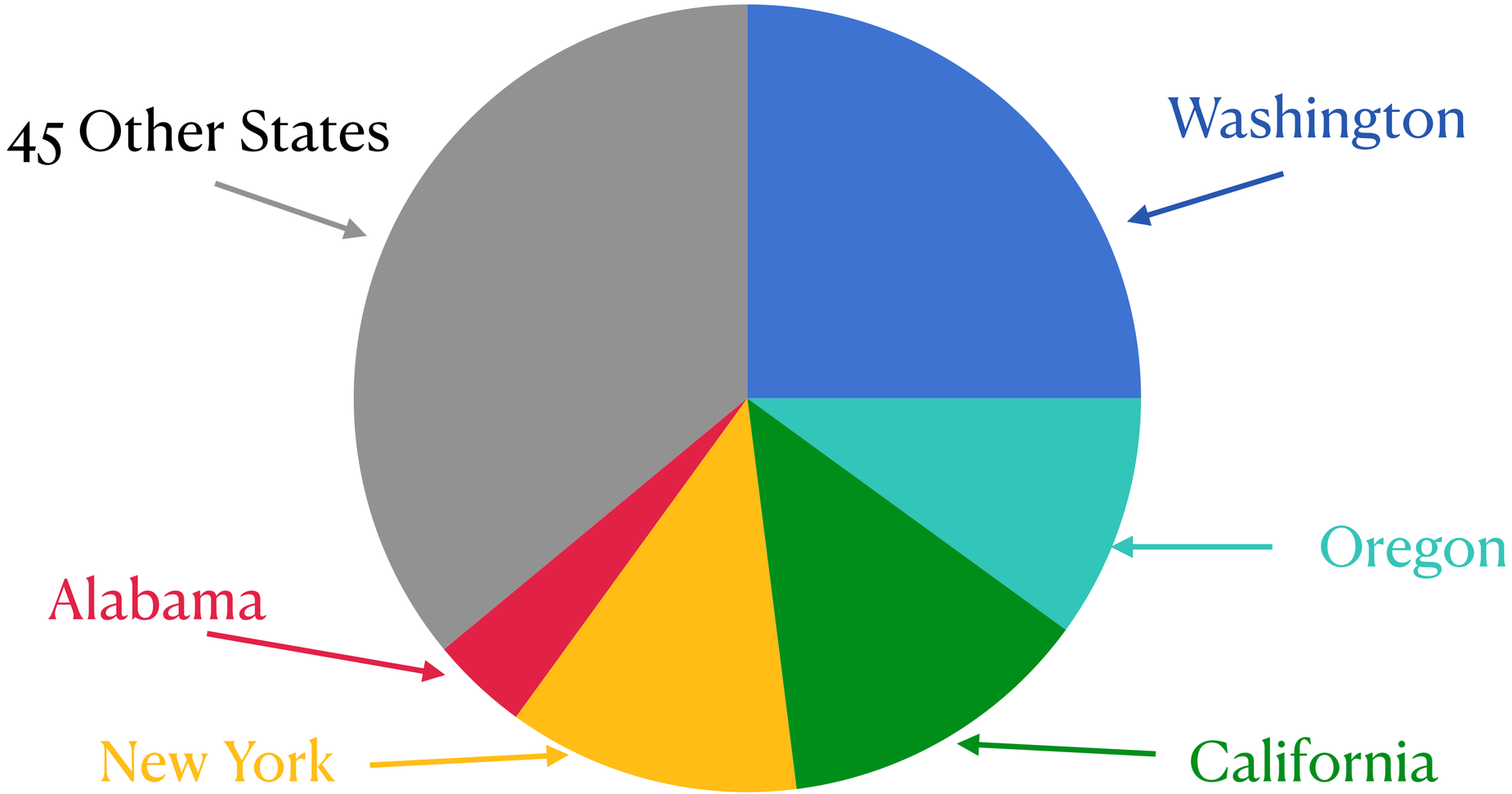
Geothermal Power Generated in U.S.

U.S. Energy Information Administration



Hydroelectric Power Generated in U.S.

U.S. Energy Information Administration, 6% of total U.S. electricity

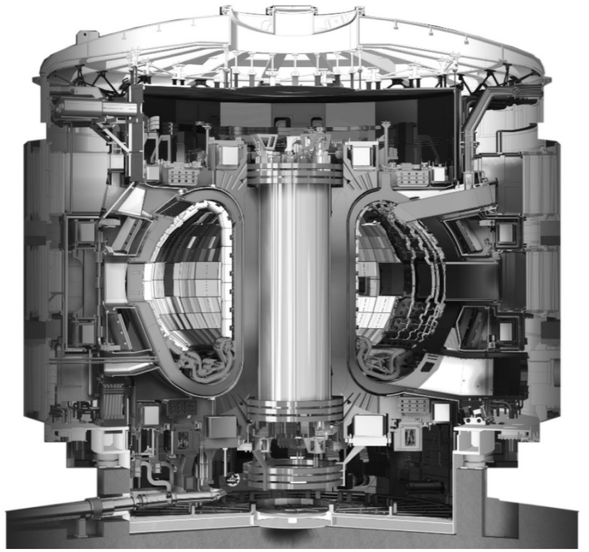


Other Possible Energy Source

- Nuclear Fusion: ITER is a multi-billion dollar project with the goal of making fusion energy practical. ITER members are China, the European Union, India, Japan, Korea, Russia and the United States.

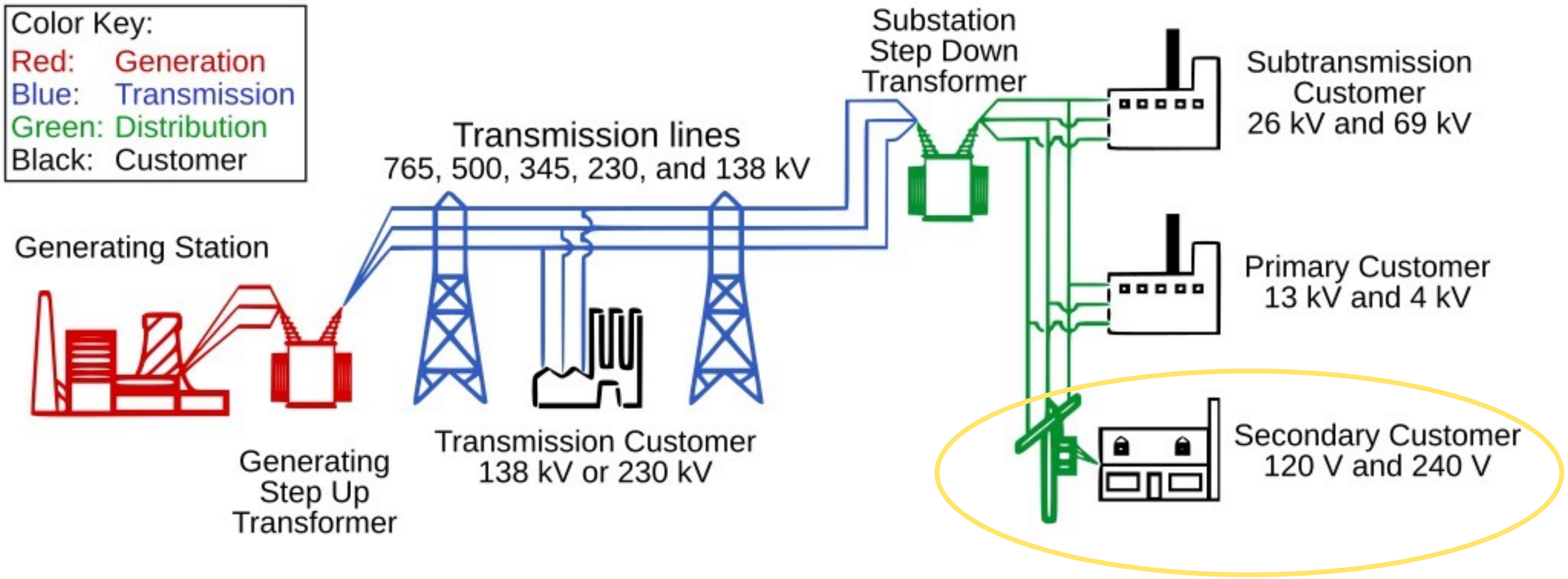
ITER

Tokamak

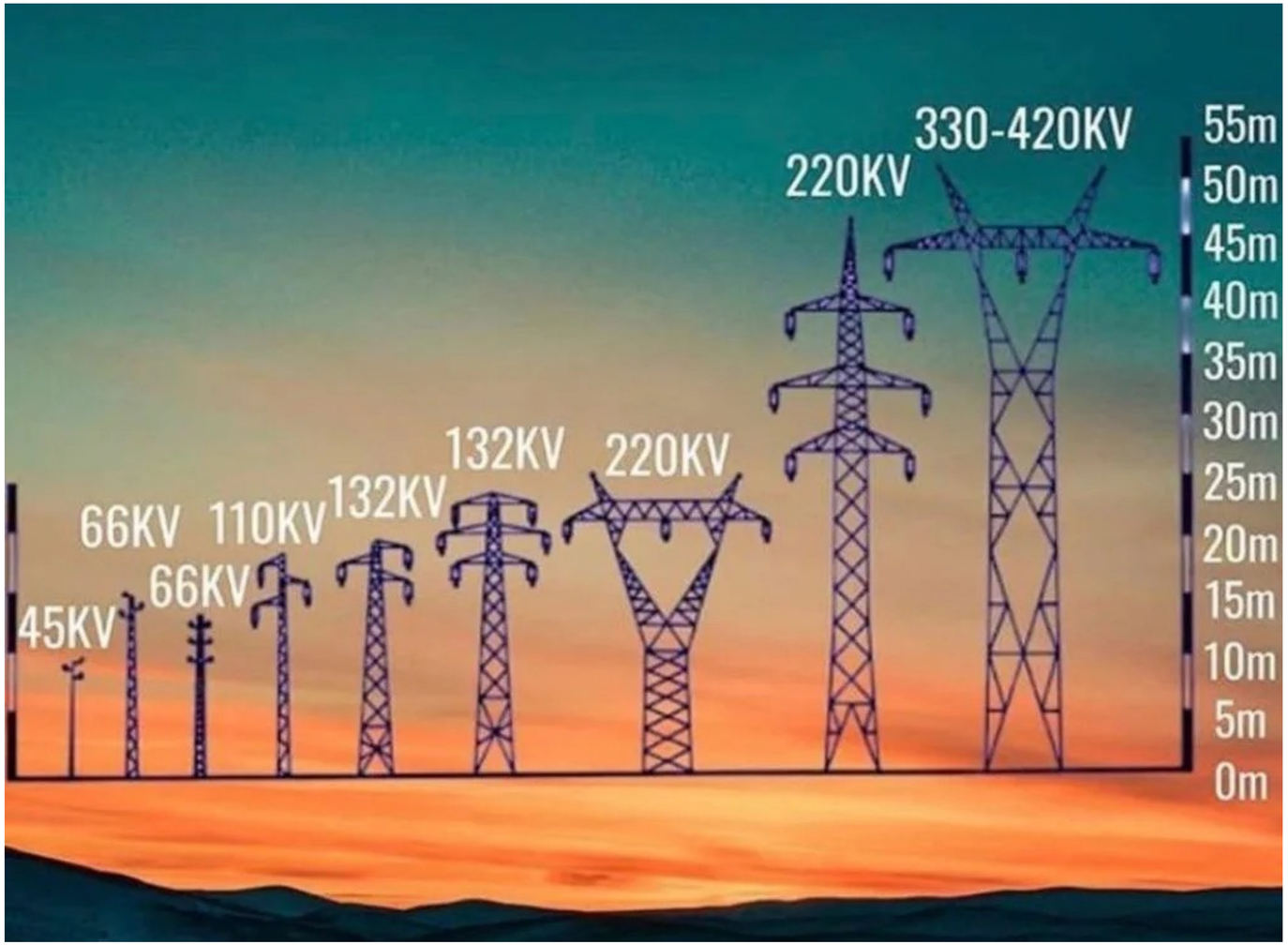


How it works

Transmission and Distribution



Transmission Towers

- 

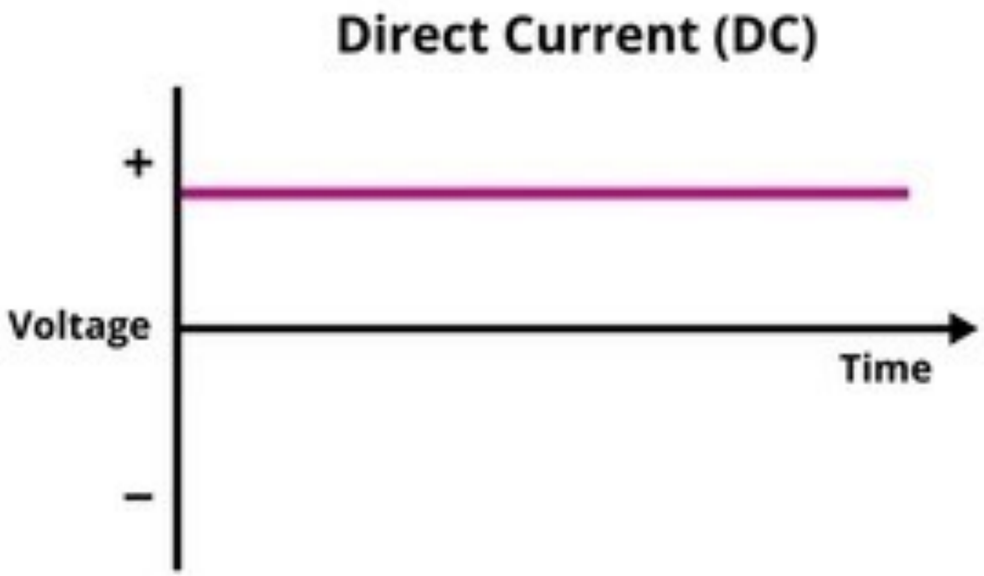
Electricity Basics

- Ohm's law: Voltage = Current x Resistance, $V = IR$
- Power = Energy per unit Time = $VI = I^2R$
- Units:
  - Voltage measured in volts
  - Current measured in amps
  - Resistance measured in ohms
  - Power measured in watts or horsepower
  - Energy measured in joules, calories, B.T.U.s, or kilowatt-hours (kWh)

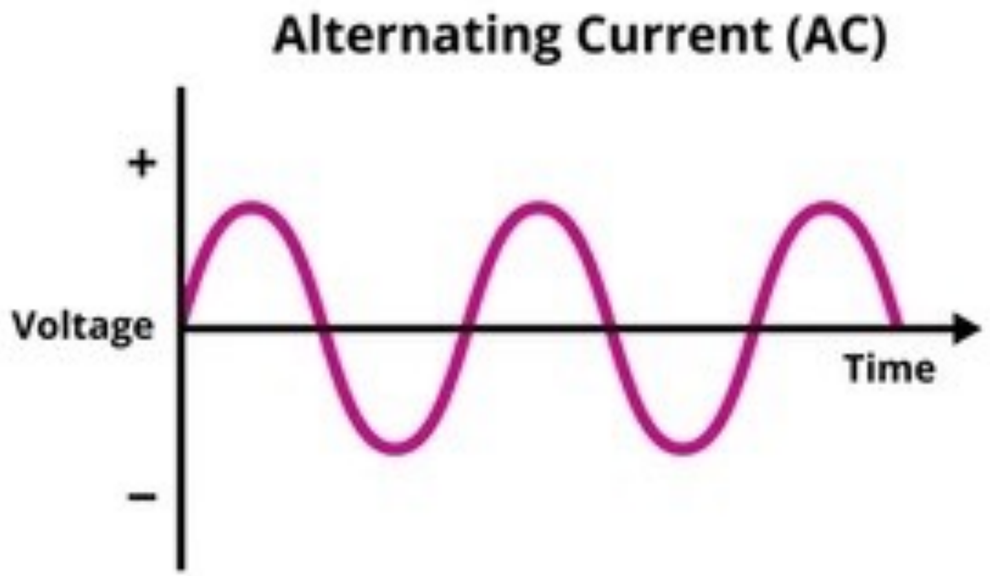
Check your electric bill

Direct and Alternating Current

Almost all grid power is AC



From batteries



From the grid

AC versus DC

Alternating Current

- It’s relatively easy and inexpensive to change the voltage for AC lines. High voltages are used for long-distance transmission to minimize power losses. For transmission lines shorter than 400 miles, the cost of installing the line plus transformers is lower for AC.
- However, AC circuits have inductance and capacitance that produce “reactive power”, which must be accommodated on the grid but does no useful work.

Direct Current

- High voltage DC has less power loss per mile than AC. For lines longer than 400 miles, the cost of installing the line plus voltage step up and step down equipment is lower for DC.
- DC is simpler, because it doesn’t produce reactive power.

Above Ground versus Underground

Distribution power lines are often buried in new subdivisions, where they can be installed before the houses are built. This makes the cost reasonable.

Above Ground

- Subject to frequent damage, mostly by weather, vegetation
- Can be repaired in hours
- Can be uprated easily
- Average life 80 years
- Possible hazard to aircraft and wildlife
- Risk of fire

Underground

- Subject to damage by earthquakes, lightning, roots of falling trees, floods, people digging
- Takes days or weeks to repair.
- Considered more beautiful
- Average life 40 years
- Much more expensive, after the land is developed.
- High reactive power makes grid stabilization more difficult

Grid Operator Challenge

Electric Reliability Council of Texas, ERCOT

- All the power generating plants have to produce AC at the same frequency (60 Hz in the U.S., 50 Hz in Europe)

- And they all have to be IN PHASE.

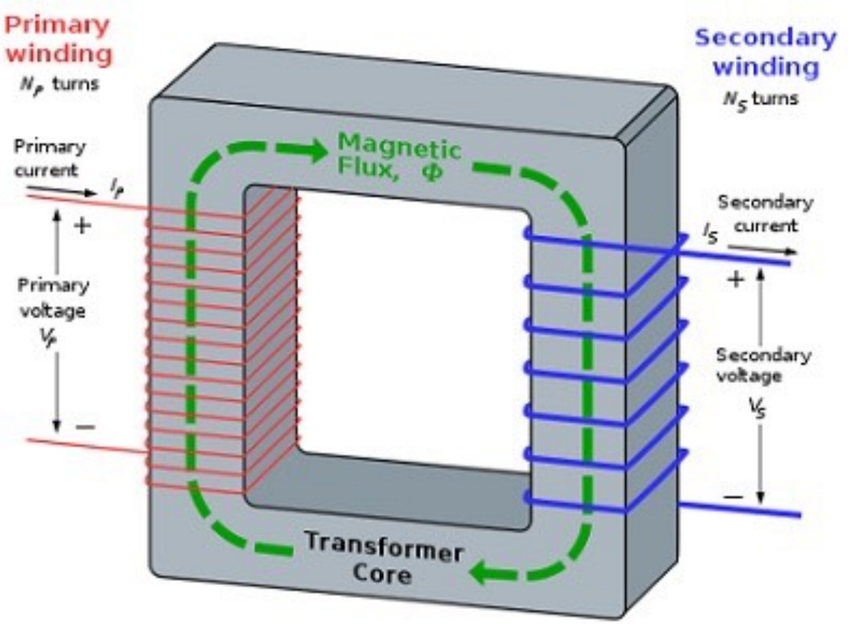
- Plus, the generators use electromagnets instead of permanent magnets. This means it takes energy to make energy.

- If the load is too high, the frequency drops, and they have to “shed load” = blackouts

Innovations in Transmission

AC versus DC

- AC can be converted to higher or lower voltage easily with transformers.
- DC has lower transmission losses, about half those of AC, but requires more expensive equipment to change voltages.
- For more than about 400 miles, the total cost is lower for DC transmission.



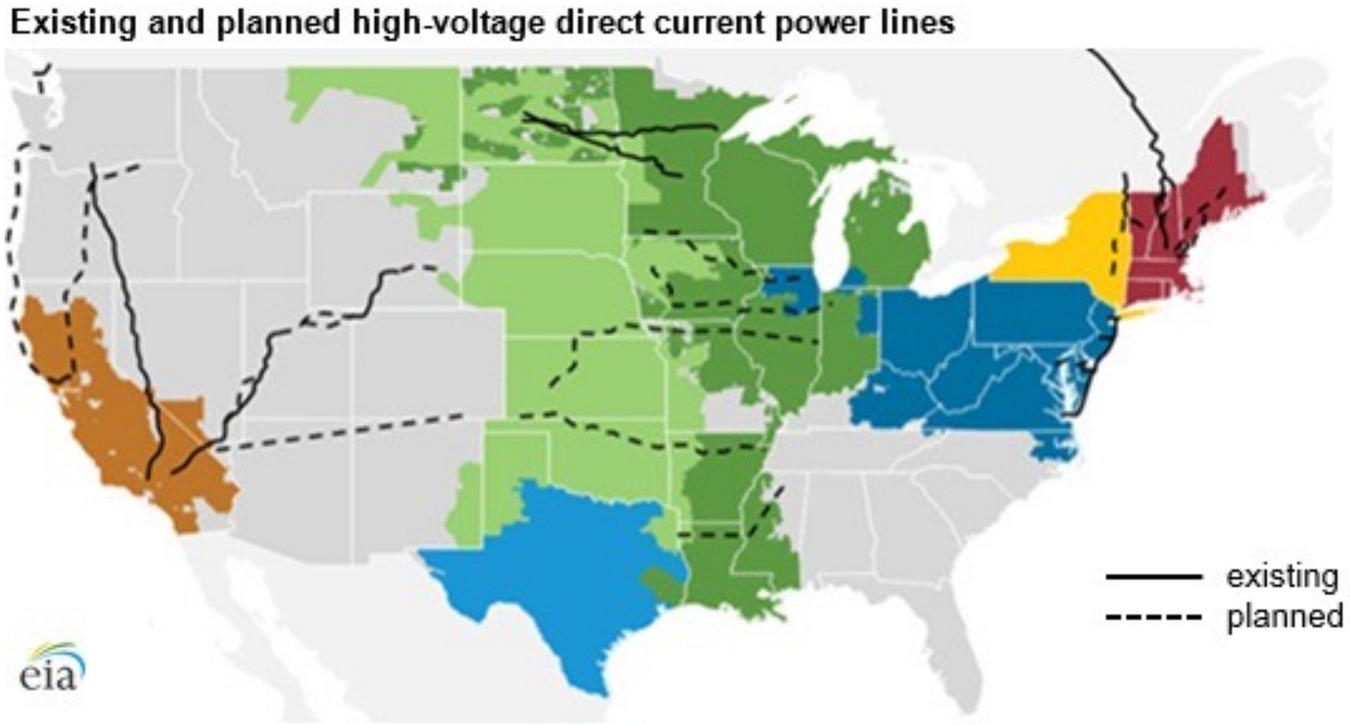
Exception: the Pacific DC Intertie

Also called Path 65

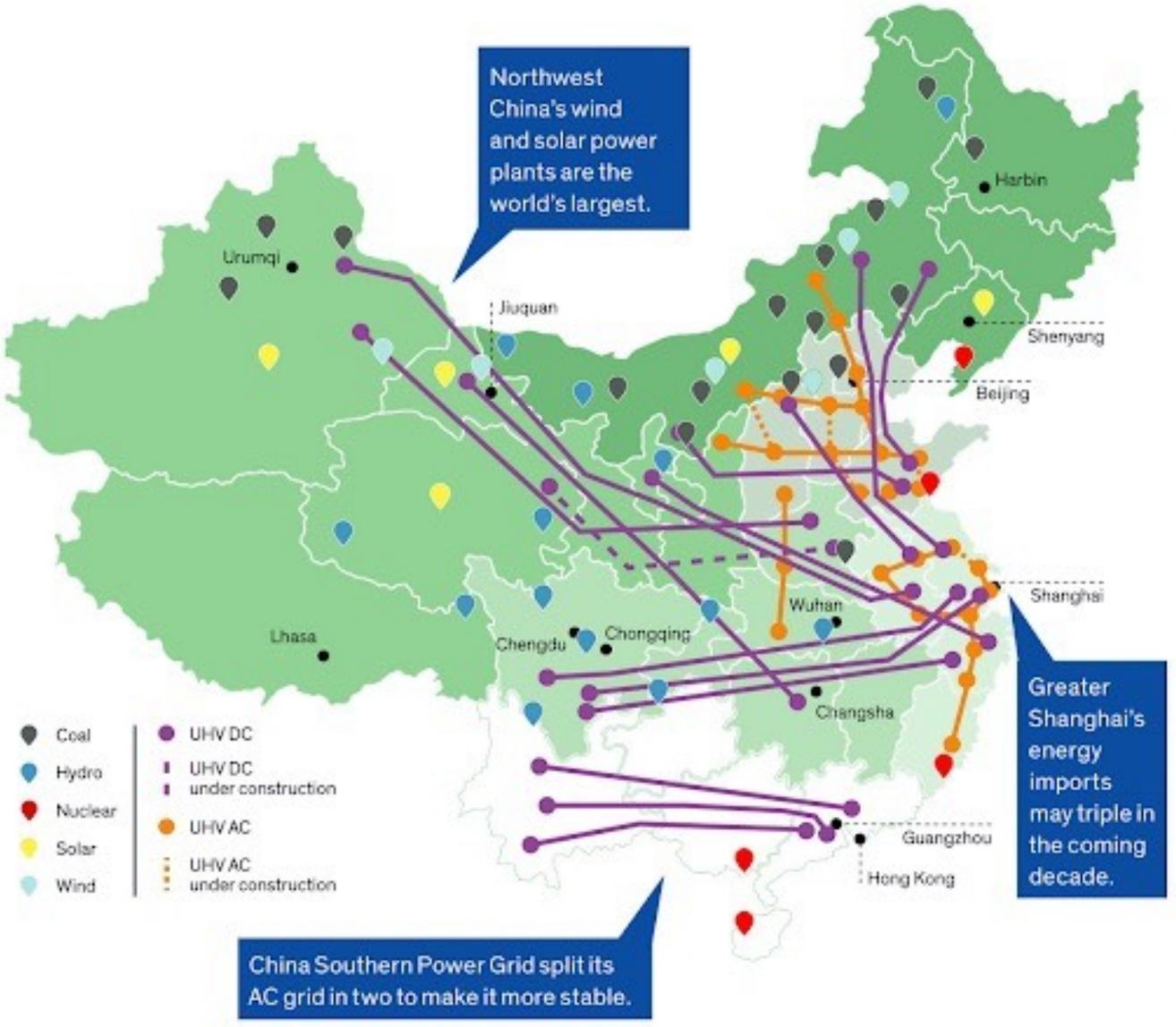
- Runs from dams on the Columbia River in Oregon to Los Angeles, CA
- Delivers up to 3.1 gigawatts to California in summer for air conditioning, or to Oregon in winter for heating
- In operation since 1970
- 846 miles long
- 500 kV

Existing and Planned U.S. HVDC

U.S. Energy Information Administration



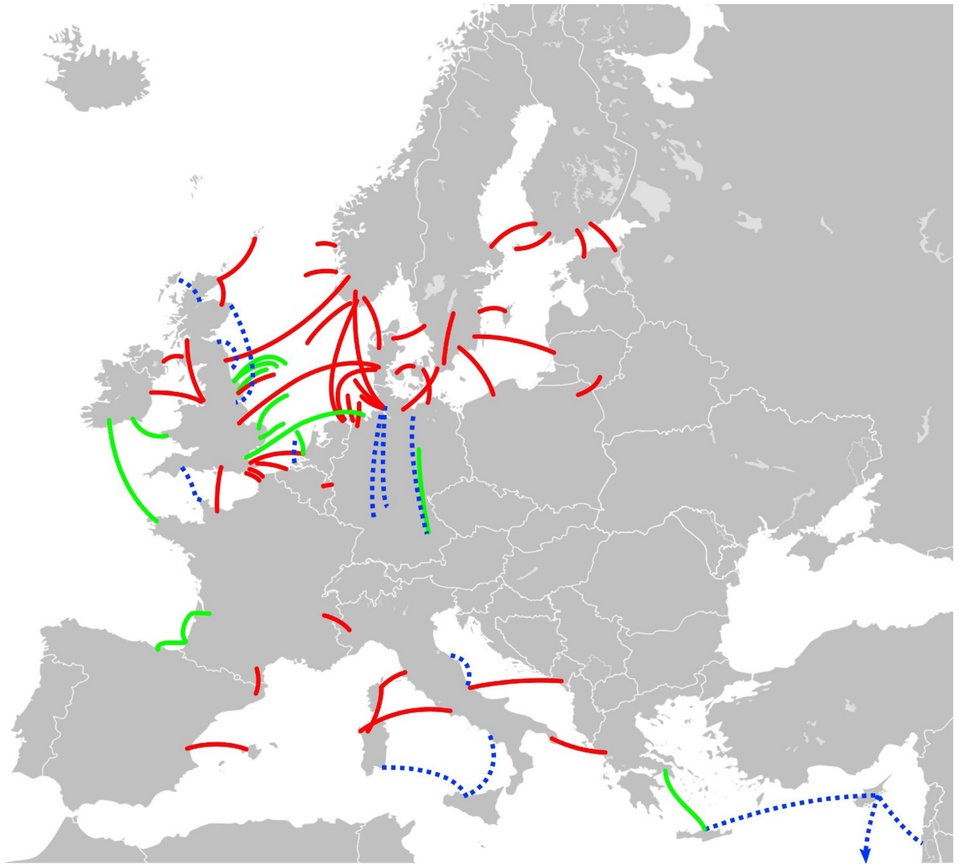
China’s Ultra-High Voltage Transmission



HVDC Links in Europe

- Red = existing
- Green = under construction
- Blue = proposed

- From Wikipedia



Challenges for building transmission lines in U.S.

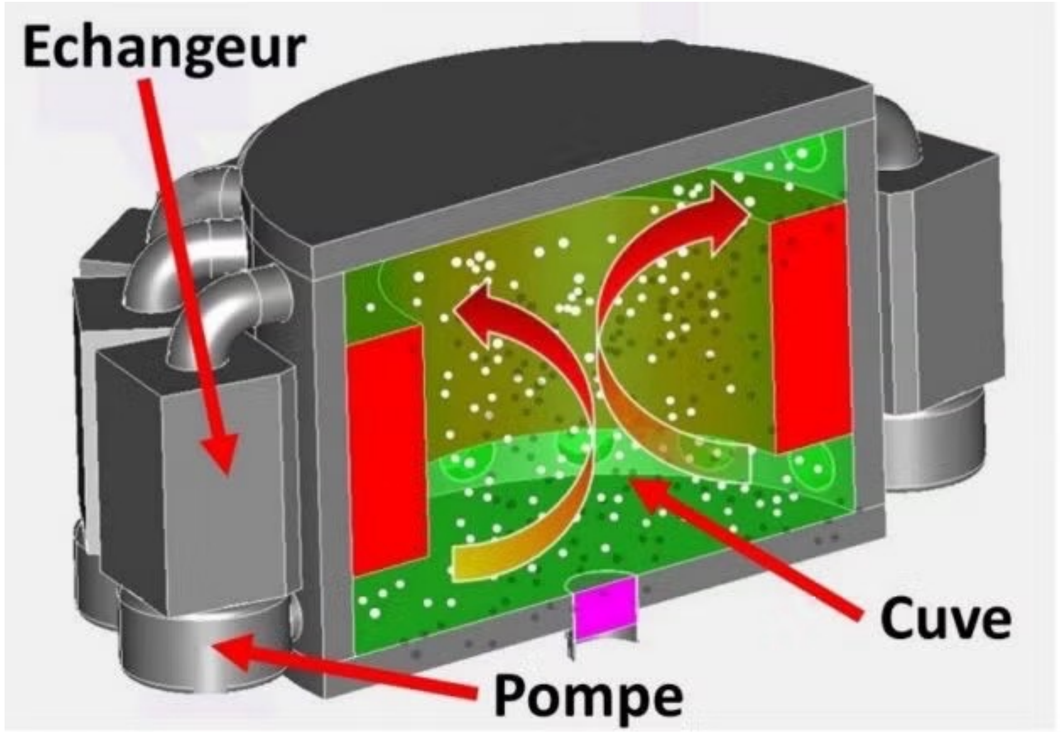
- Technological: easy. We have been doing this for over a century.
- Political: almost impossible. Long distance lines have to pass through so many cities, counties, and utility districts with building permit requirements (NIMBY).

Innovations in Generation

China’s Thorium Molten Salt Reactor

If all goes as planned:

- Safer
- Cheaper
- Much less long-lived radioactive waste



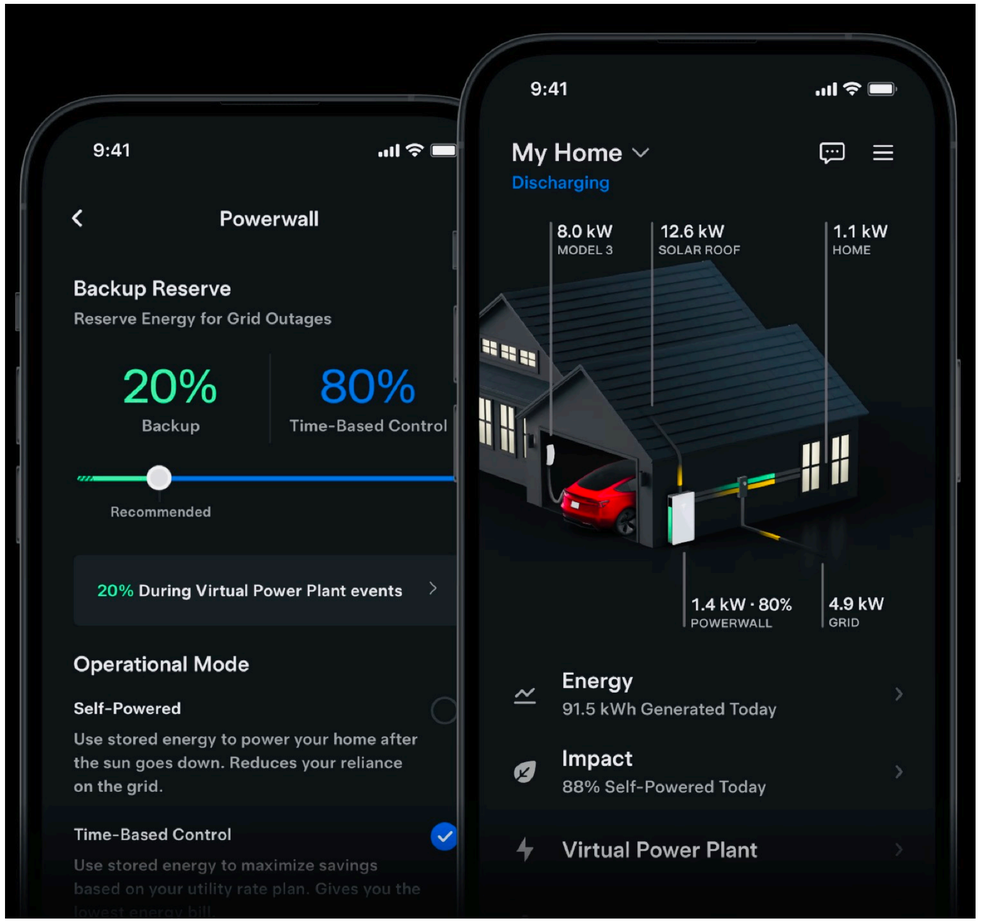
Advanced Solar Panels

- Bifacial
- Perovskite solar cells
- Flexible, lightweight options
- Improved efficiency

Innovations in Energy Storage

Battery Storage for Homes

- Small portable power stations (batteries) start at $169 for 293 Wh
- Ford 150-Lightning and Nissan Leaf offer bi-directional charging so you can use your car to power your home during a power failure.
- Tesla offers a Powerwall system with home solar panels and battery, 13.5 kWh energy capacity per Powerwall unit.
- Tesla Megapack batteries store 3.9 MWh per unit for communities or industry

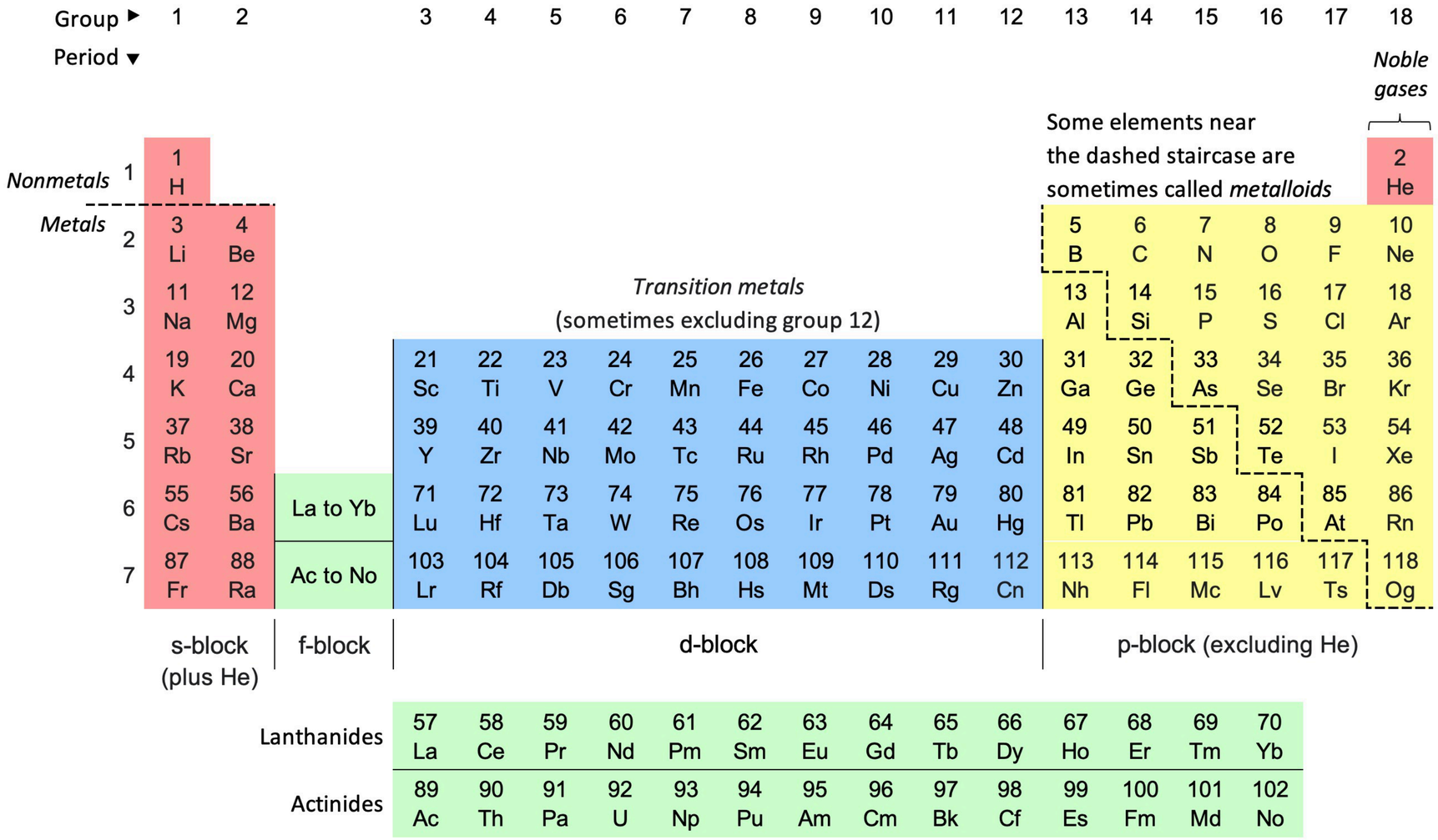


Battery Farms

Battery Energy Storage Systems (BESS)

- Photo from Florida Power & Light Co.
- Buy low, sell high
- Stabilize grid
- Some object to lithium ion batteries as a fire hazard. Other battery types are in development.
- These batteries don’t need to be light weight.

Periodic Table of the Elements



Battery Types (from Wikipedia)

Primary cells or non-rechargeable batteries

- Alkaline battery
- Aluminium–air battery
- Bunsen cell
- Chromic acid cell (Poggendorff cell)
- Clark cell
- Daniell cell
- Dry cell
- Earth battery
- Frog battery
- Galvanic cell
- Grove cell
- Leclanché cell
- Lemon/potato battery
- Lithium metal battery
- Lithium–air battery
- Magnesium battery
- Mercury battery
- Molten salt battery
- Nickel oxyhydroxide battery
  - Oxyride battery
- Organic radical battery
- Paper battery
- Pulvermacher's chain
- Smee cell
- Silver-oxide battery
- Solid-state battery
- Sugar battery
- Voltaic pile
  - Penny battery
  - Trough battery
- Water-activated battery
- Weston cell
- Zinc–air battery
- Zinc–carbon battery
- Zinc–chloride battery
- Zamboni pile

12 types

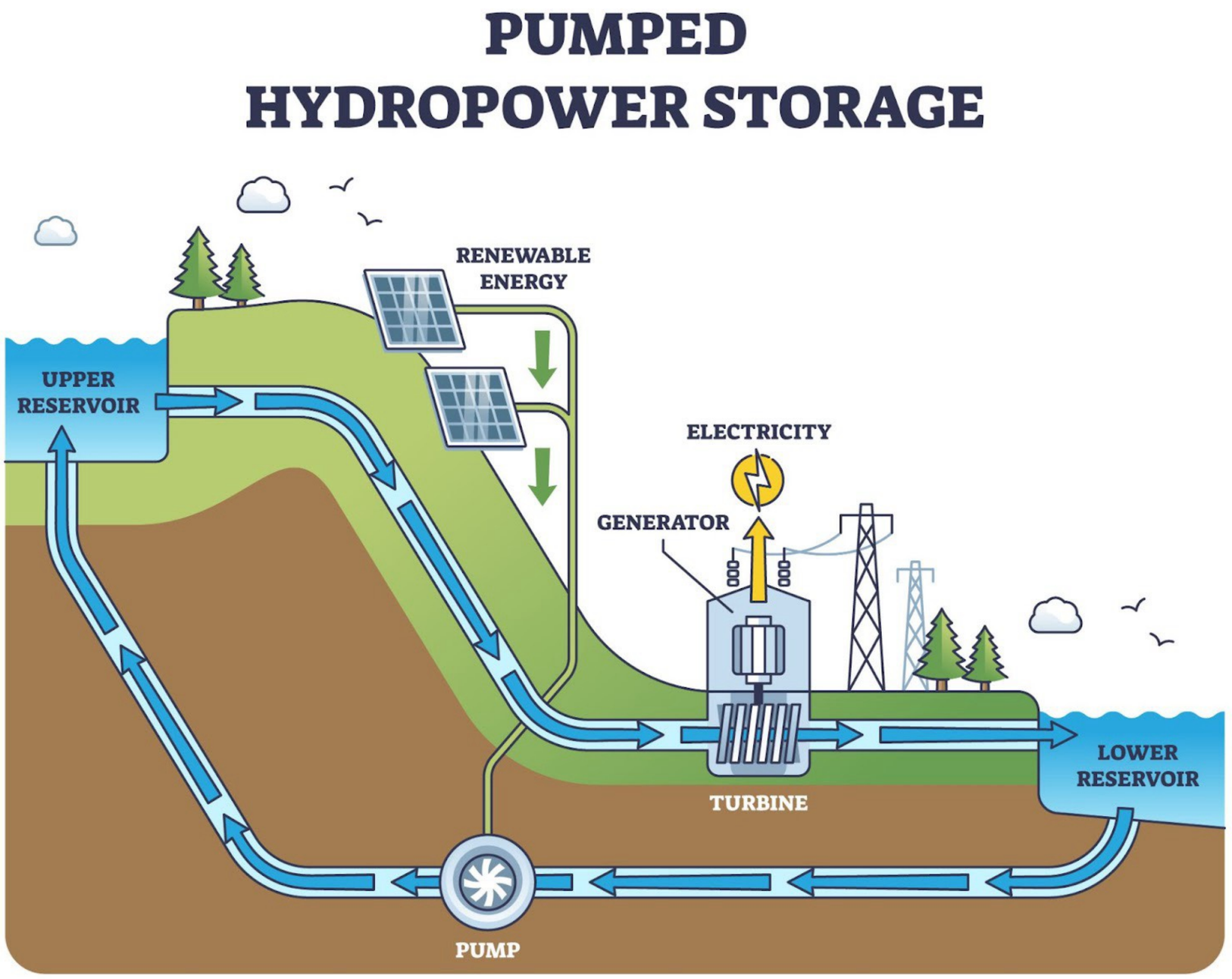
Li ion

Rechargeable batteries

- Aluminium-ion battery
- Calcium battery[1]
- Flow battery
  - Iron redox flow battery
  - Vanadium redox battery
  - Zinc–bromine battery
  - Zinc–cerium battery
  - Hydrogen–bromine battery
- Lead–acid battery
  - Deep-cycle battery
  - Flooded battery
  - VRLA battery
    - AGM battery
    - Gel battery
  - UltraBattery
- Glass battery
- Lithium-ion battery
  - Lithium-ion lithium cobalt oxide battery (ICR)
  - Lithium–silicon battery
  - Lithium-ion manganese iron phosphate battery
  - Lithium-ion manganese-oxide battery (LMO)
  - Lithium-ion polymer battery (LiPo)
  - Lithium–iron–phosphate battery (LFP)
  - Lithium–nickel–manganese–cobalt oxides (NMC)
  - Lithium–nickel–cobalt–aluminium oxides (NCA)
  - Lithium–sulfur battery
  - Lithium–titanate battery (LTO)
  - Thin-film lithium-ion battery
  - Lithium–ceramic battery[2][3]
- Rechargeable lithium–metal battery
- Magnesium-ion battery

Rechargeable batteries

- Metal–air electrochemical cells
  - Lithium–air battery
  - Germanium–air battery
  - Calcium–air battery
  - Iron–air battery
  - Potassium-ion battery
  - Silicon–air battery
  - Zinc–air battery
  - Tin–air battery
  - Sodium–air battery
  - Beryllium–air battery
- Molten-salt battery
- Microbial fuel cell
- Nickel–cadmium battery
  - Nickel–cadmium battery vented cell type
- Nickel–hydrogen battery
- Nickel–iron battery
- Nickel–lithium battery
- Nickel–metal hydride battery
  - Low self-discharge NiMH battery
- Nickel–zinc battery
- Organic radical battery
- Polymer-based battery
- Polysulfide–bromide battery
- Rechargeable alkaline battery
- Rechargeable fuel battery
- Sand battery
- Silver–zinc battery
- Silver–calcium battery
- Silver–cadmium battery
- Sodium-ion battery
- Sodium–sulfur battery
- Solid-state battery[4]
- Super iron battery
- Wet cell
- Zinc ion battery



Currently 96% of utility-scale energy storage.

First used in U.S. in 1930.

U.S. has 43 pumped storage hydropower plants, and potential to double this capacity.

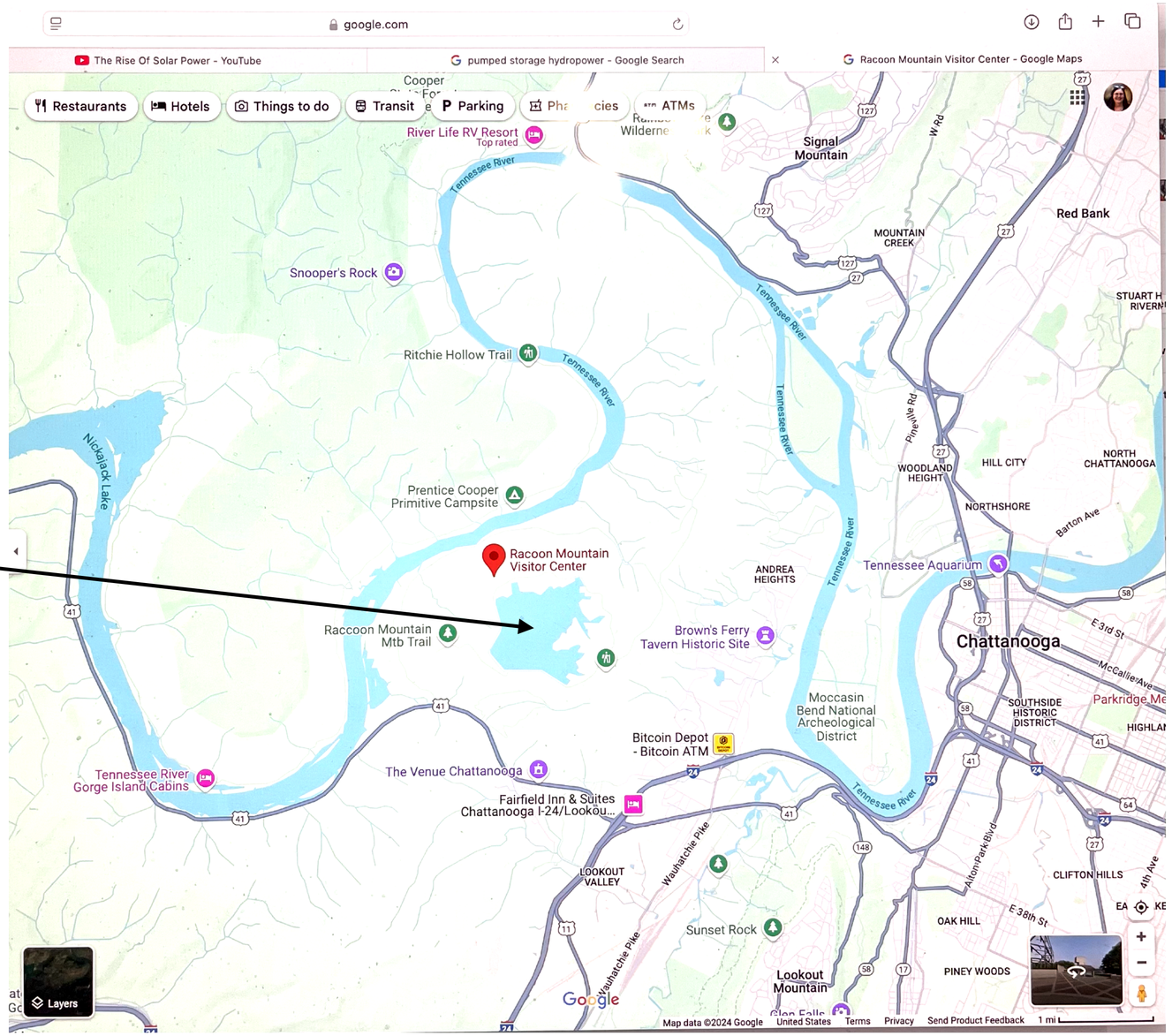
- U.S. Department of Energy

Raccoon Mountain TVA Visitor Center

Pumped Storage Hydropower near Chattanooga, Tennessee

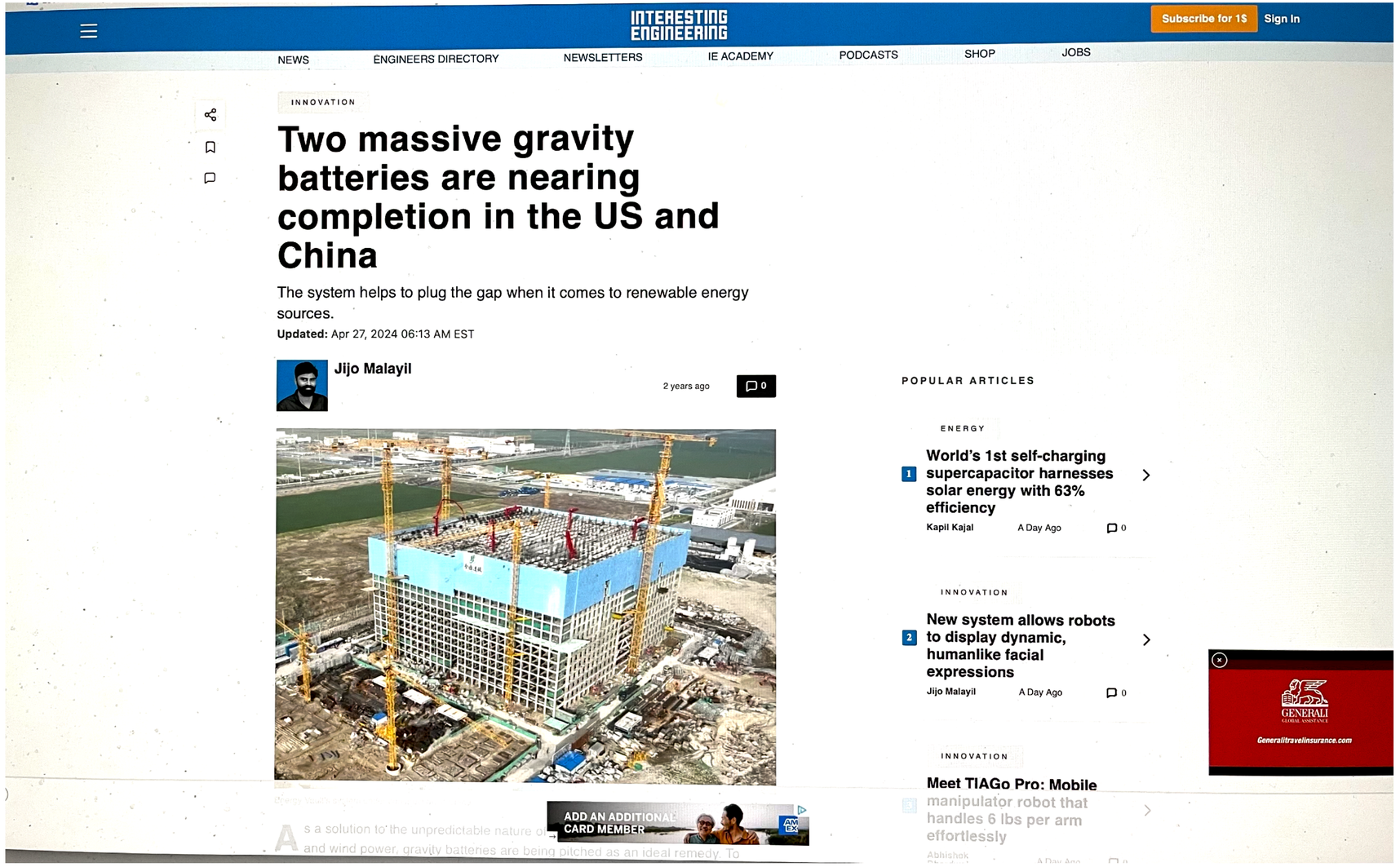
Raccoon Mountain

Pumped hydro Reservoir

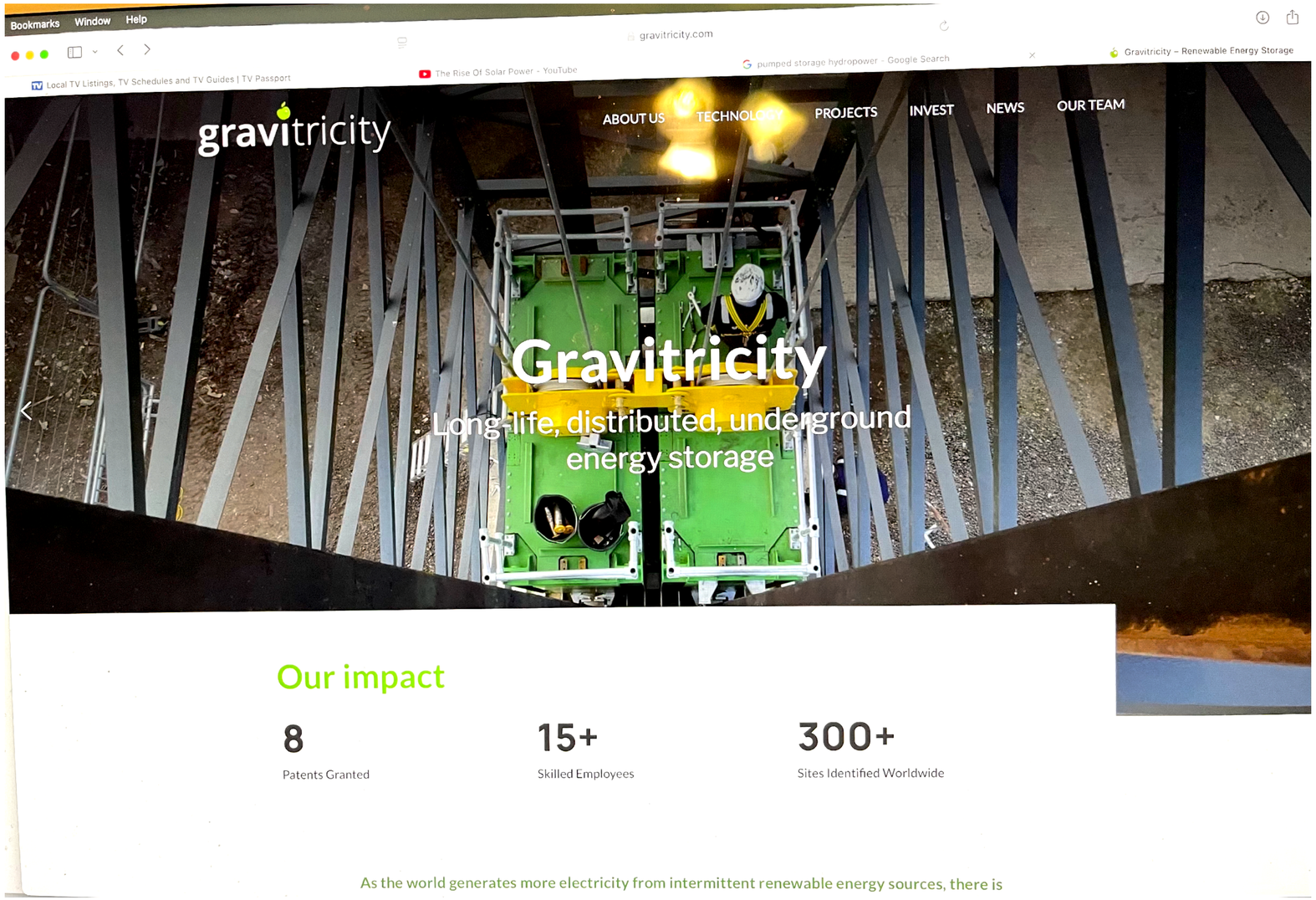


Factory scale energy storage

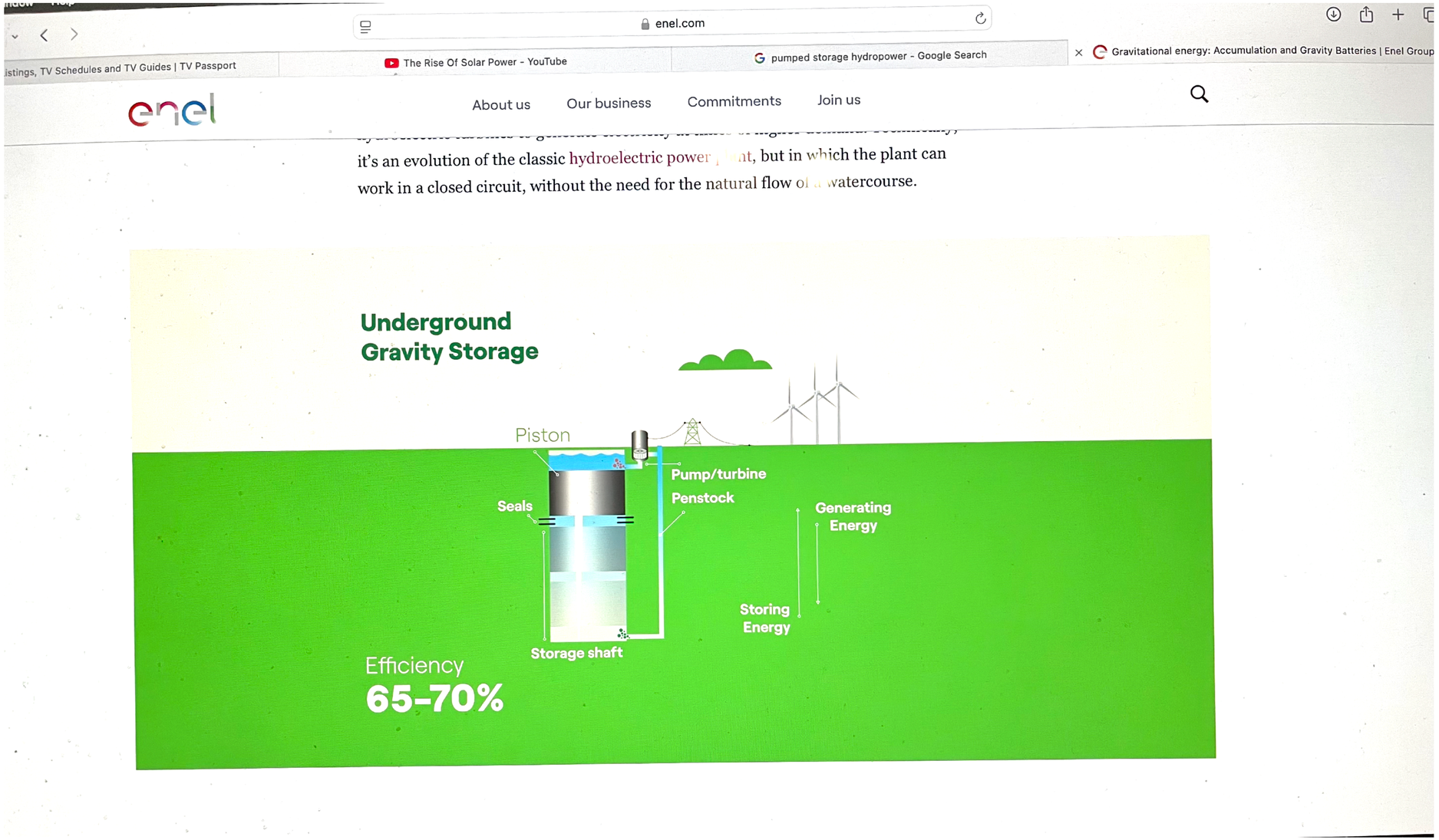
Other Gravity Energy Storage Systems



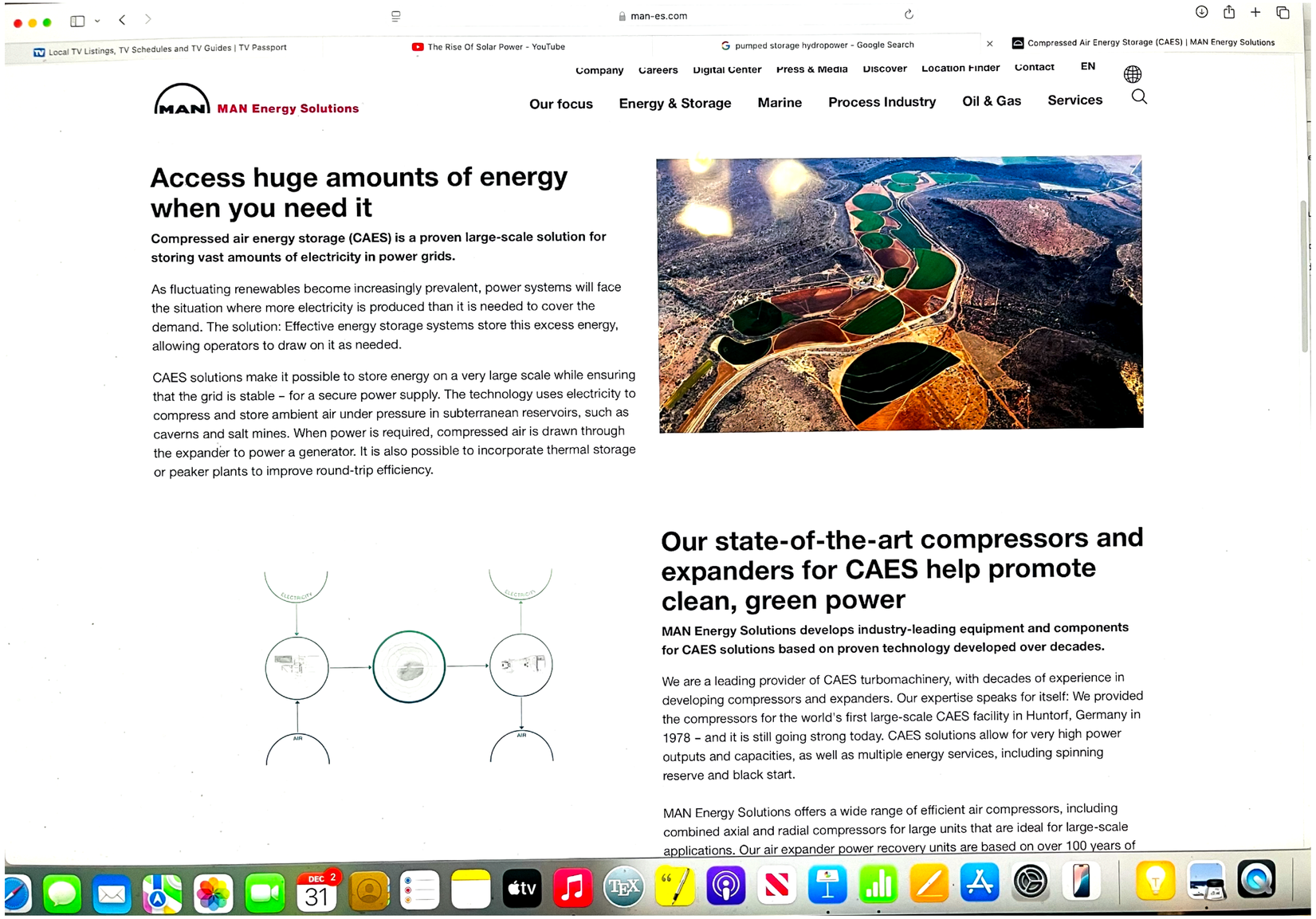
Other Gravity Energy Storage Systems

- 

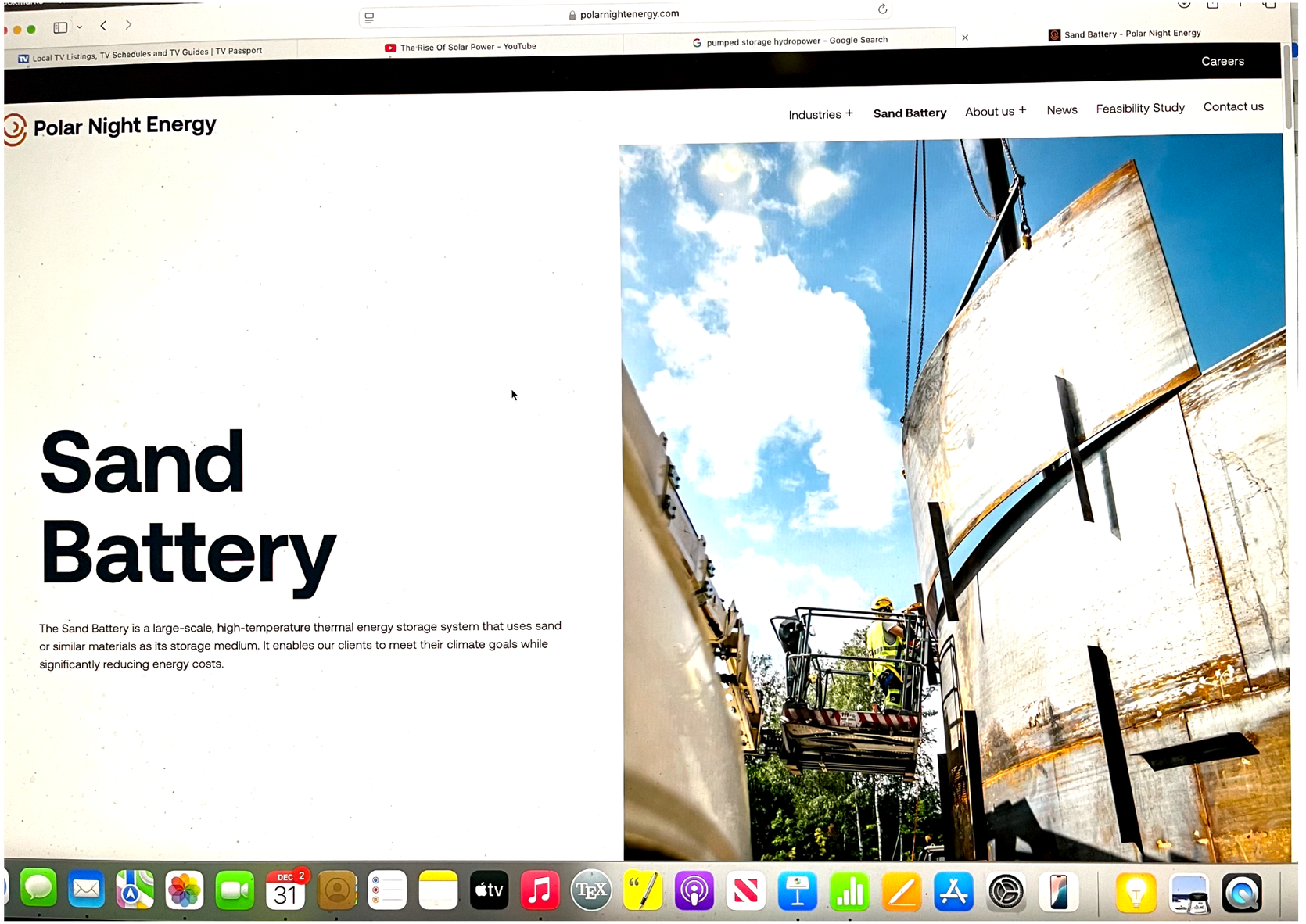
Other Gravity Energy Storage Systems



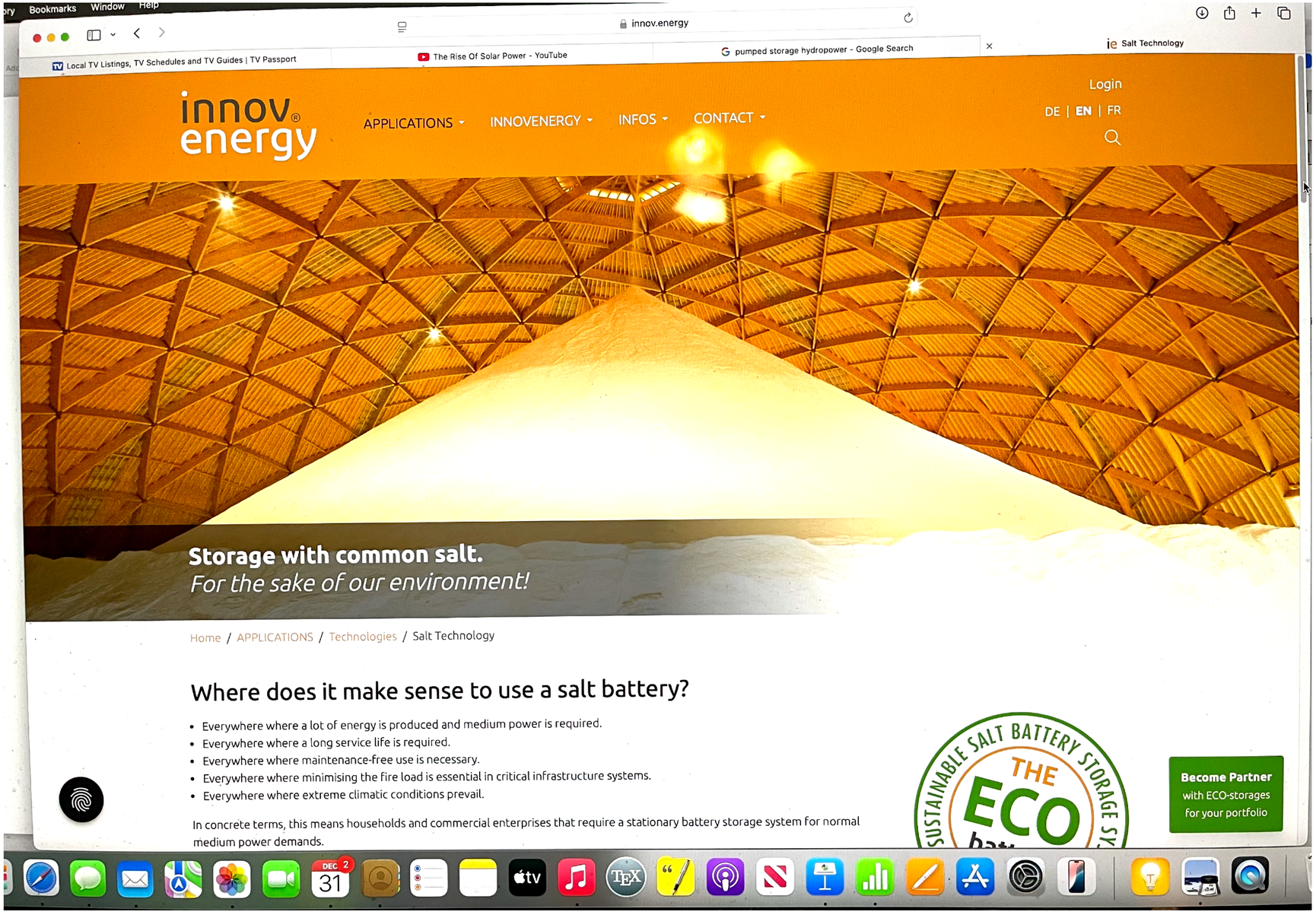
Compressed Air Energy Storage



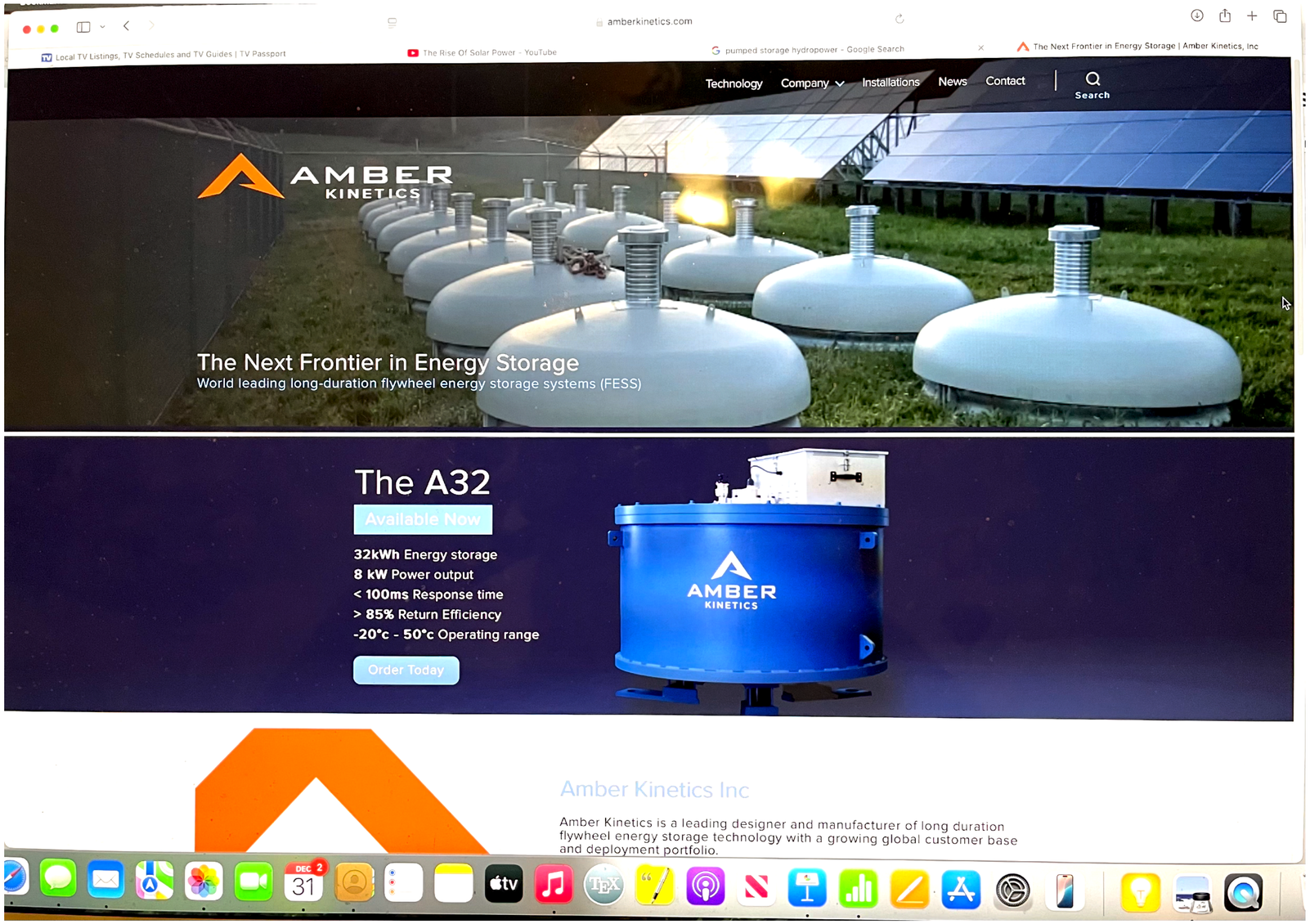
Heat Storage: Sand Battery



Heat Storage: Salt Battery



Flywheels: Kinetic Energy Storage



Microgrids

Full Circle

- Thomas Edison sold light bulbs with their own electricity generators, until Tesla took over with his AC power grid.

- Today many communities and factories set up their own microgrids with power generation (usually solar), storage, and consumption.

- Commonly they have the option to connect to the larger grid, or disconnect and run independently when the larger grid has a power failure.