

# 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

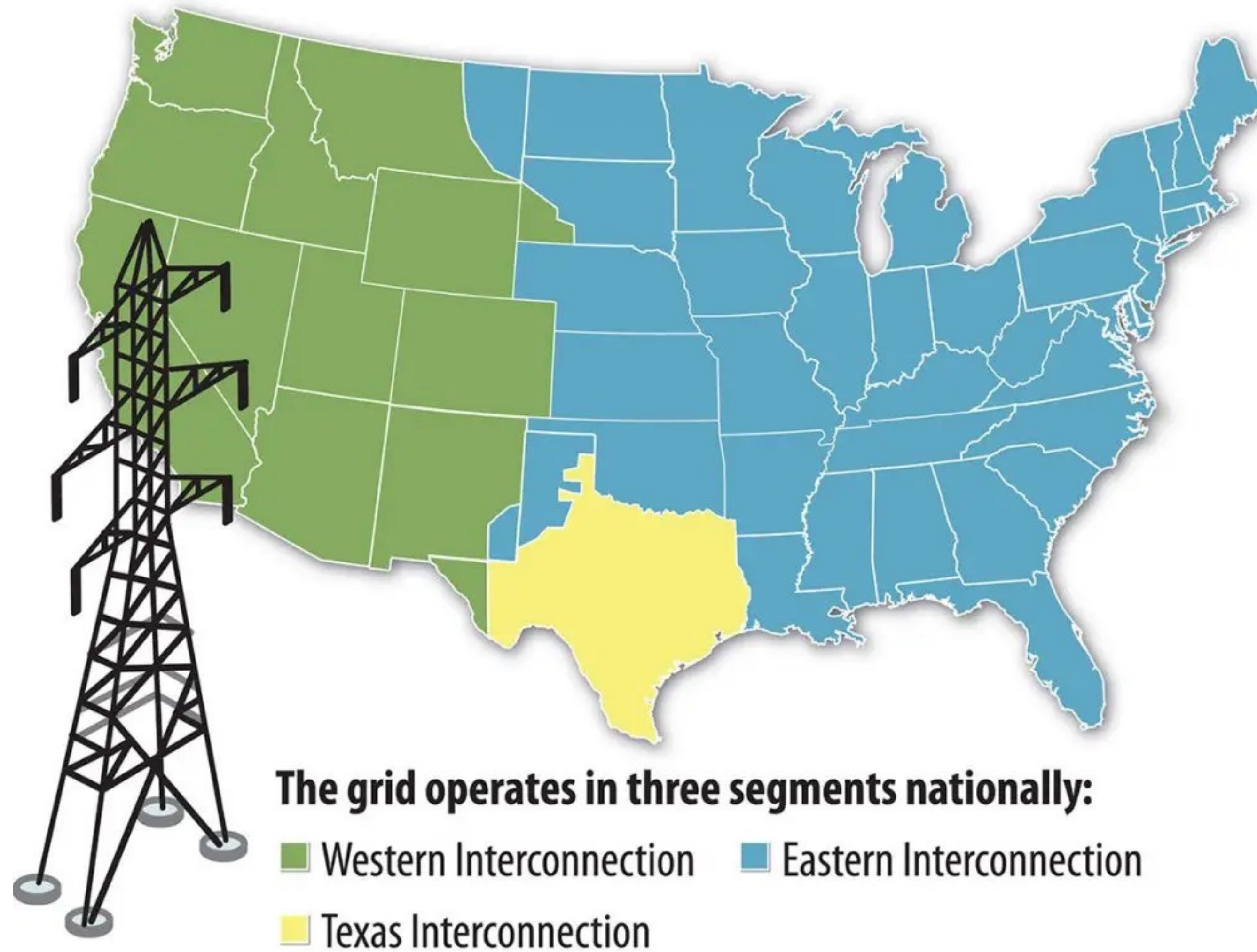


Series of 20 videos



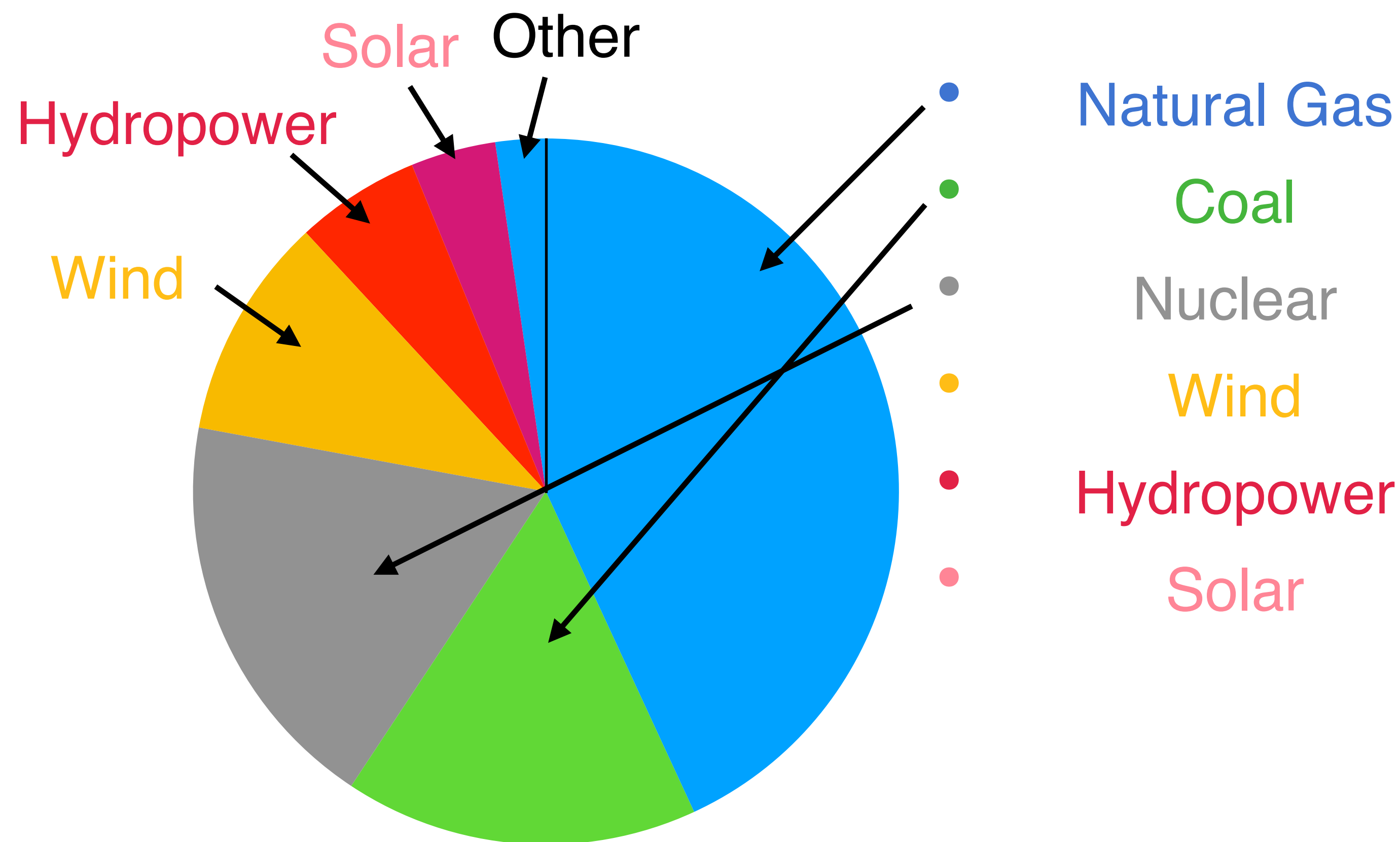


# U.S. Power Grids

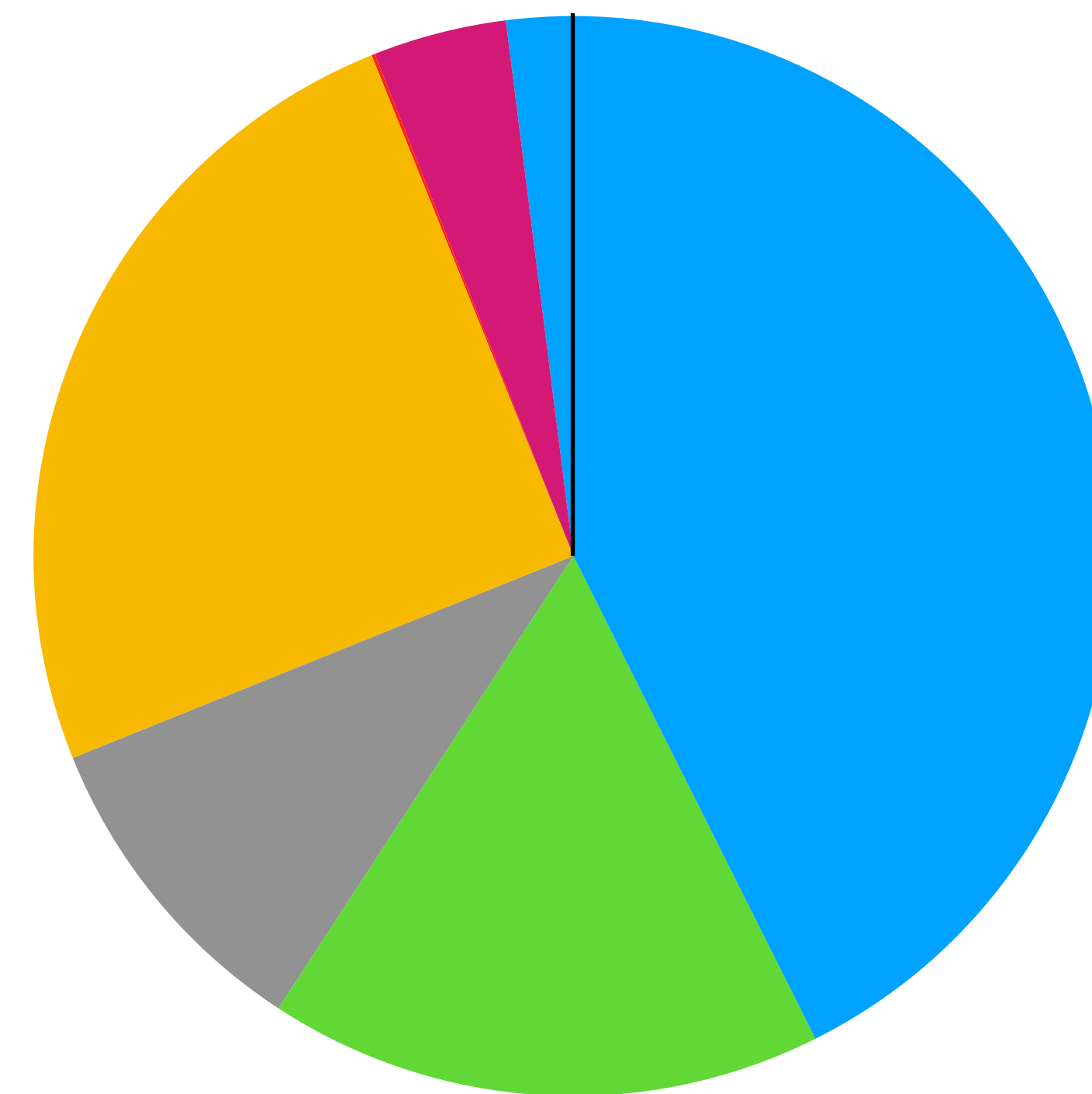


# Overview: Electric Power Sources

# Generation by Energy Source



United States



Texas



# Challenges for our Electric Grid

- Old Age
- Electric Vehicles
- Cryptocurrency
- Artificial Intelligence

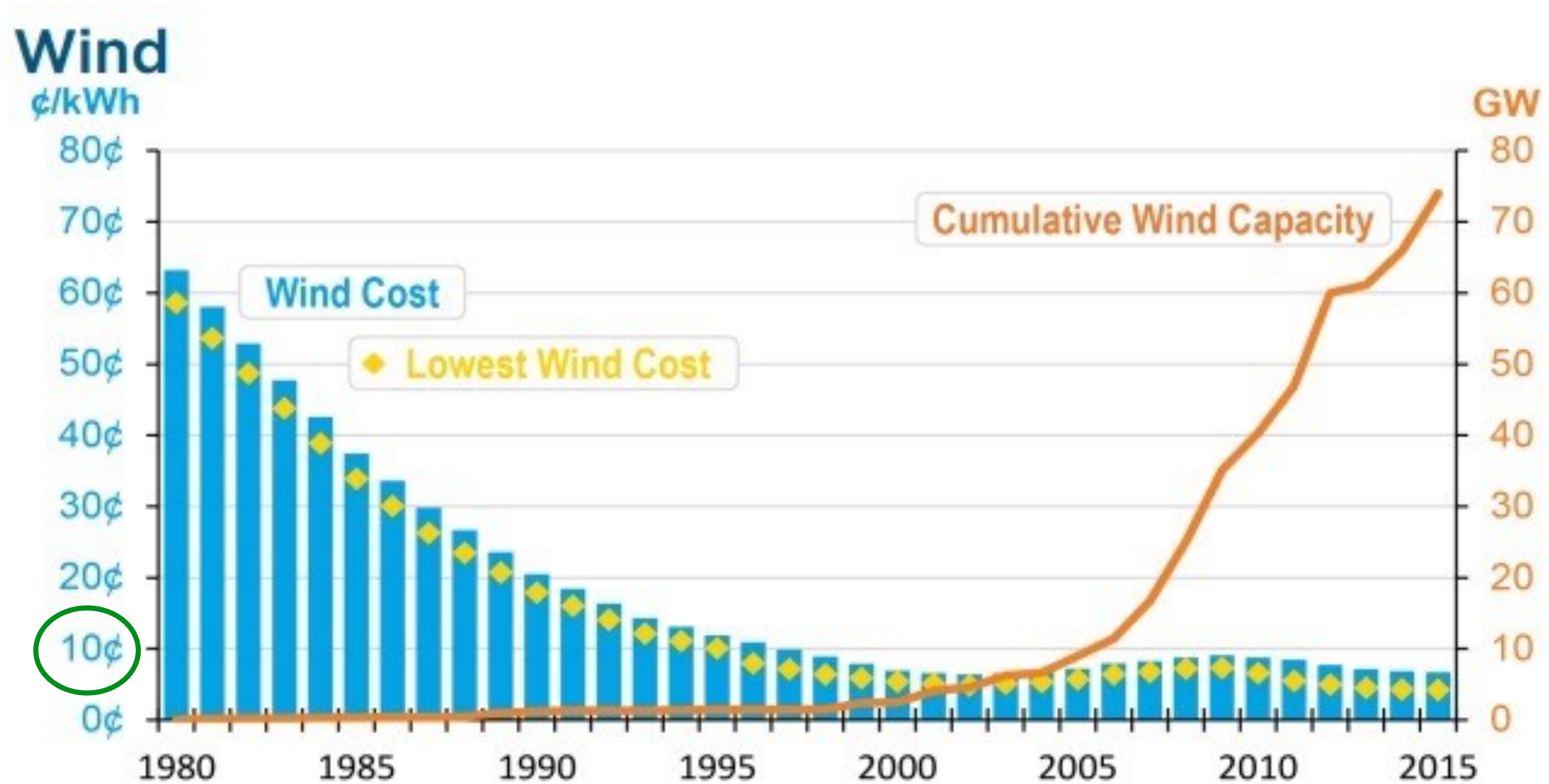




# Solutions in Development

- 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



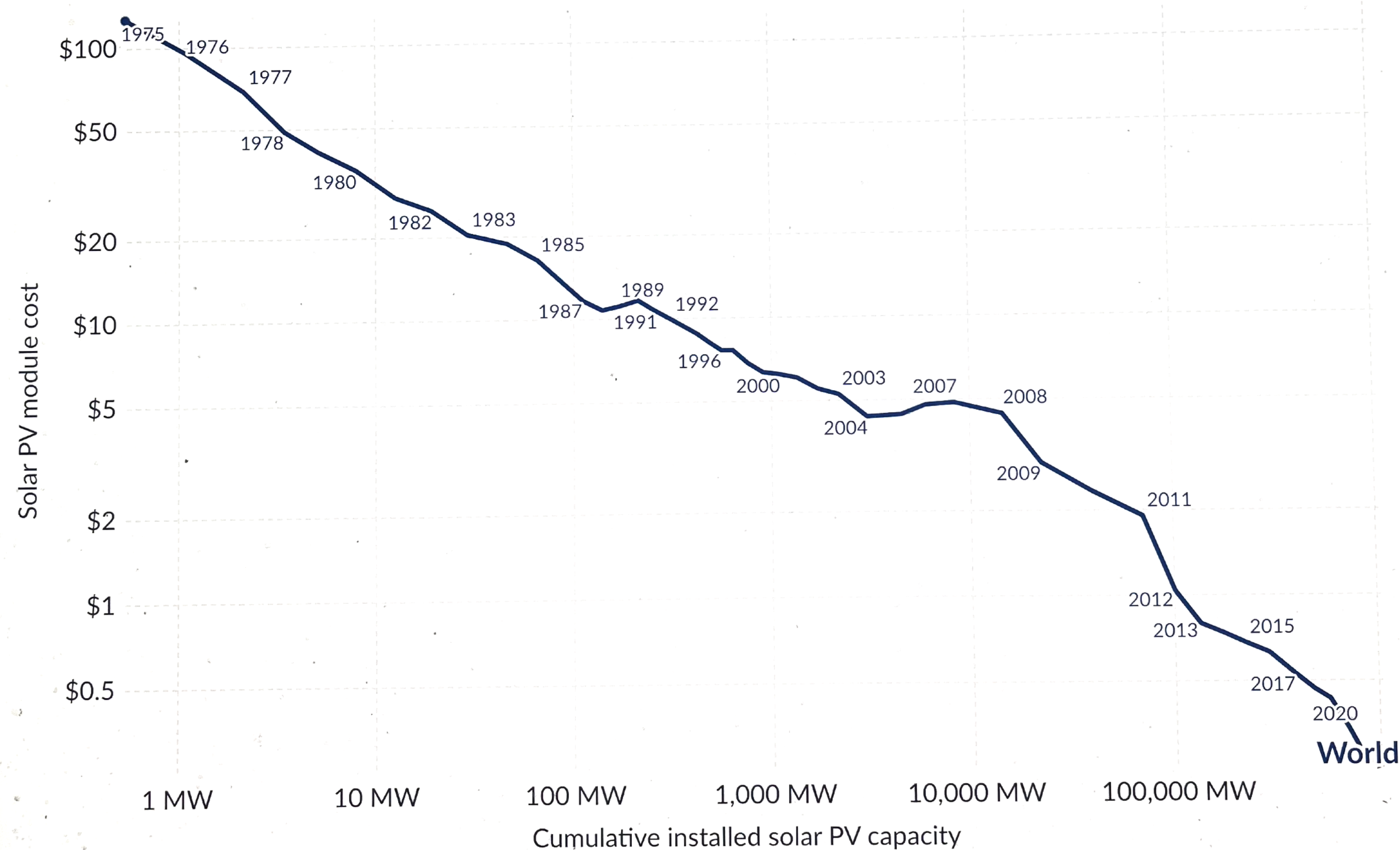
# Solar Panel Costs

Solar panel costs have fallen by around 20% for every doubling of global cumulative capacity

Costs are measured in US dollars per Watt adjusted for inflation.

Our World  
in Data

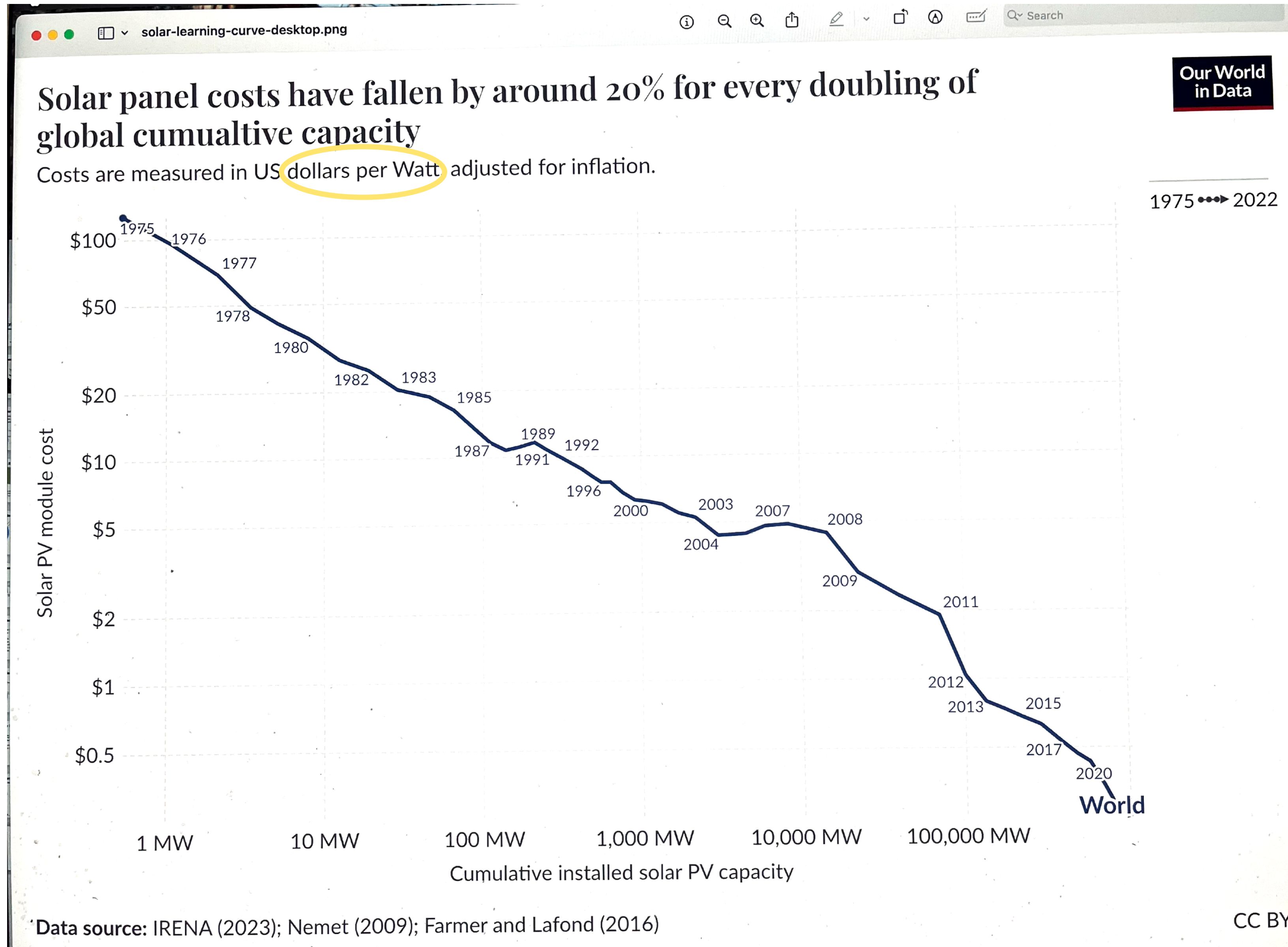
1975 ••••• 2022



Data source: IRENA (2023); Nemet (2009); Farmer and Lafond (2016)

CC BY

# Solar Panel Costs



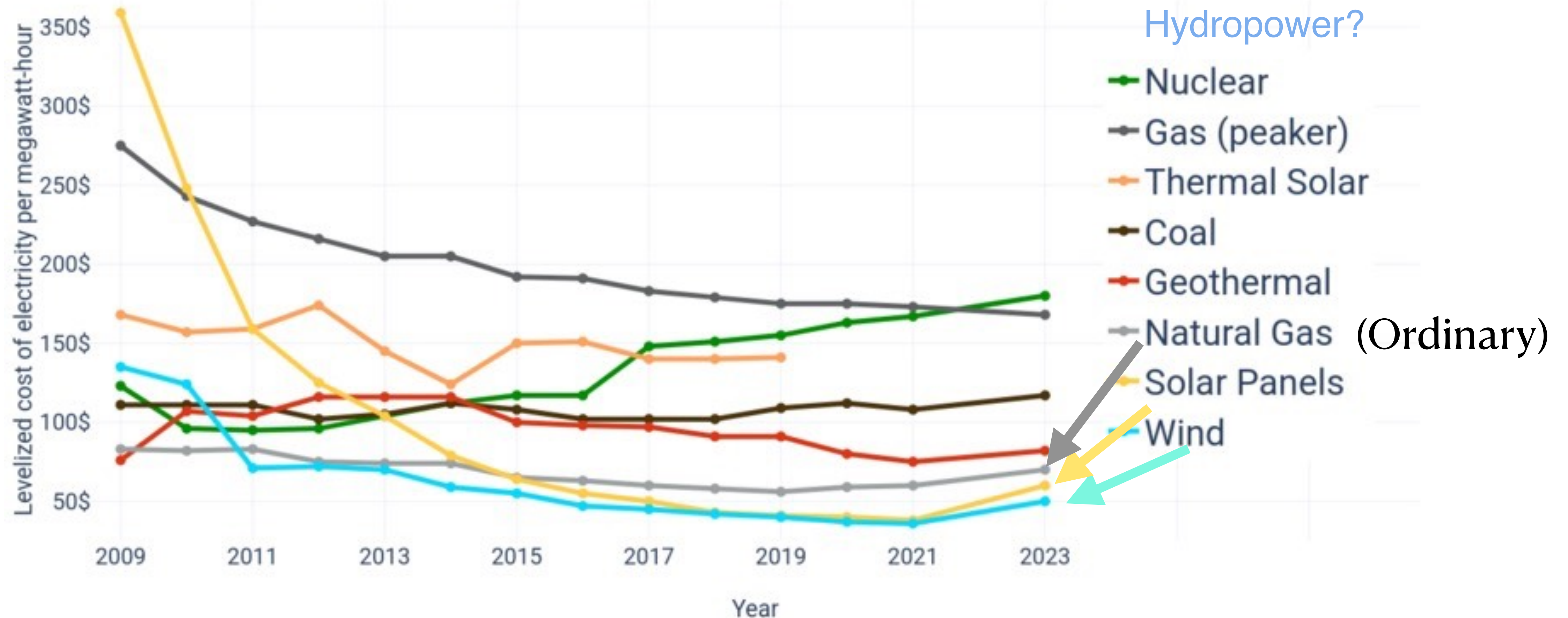
$$\frac{\$}{\text{Watt}} \times \frac{1000}{1000} \times \frac{1}{\text{hours}}$$
$$= \frac{\$}{\text{kWh}}$$



# Unsubsidized Energy Costs Comparison

Lazard.com, financial advisors

Electricity costs according to data from Lazard

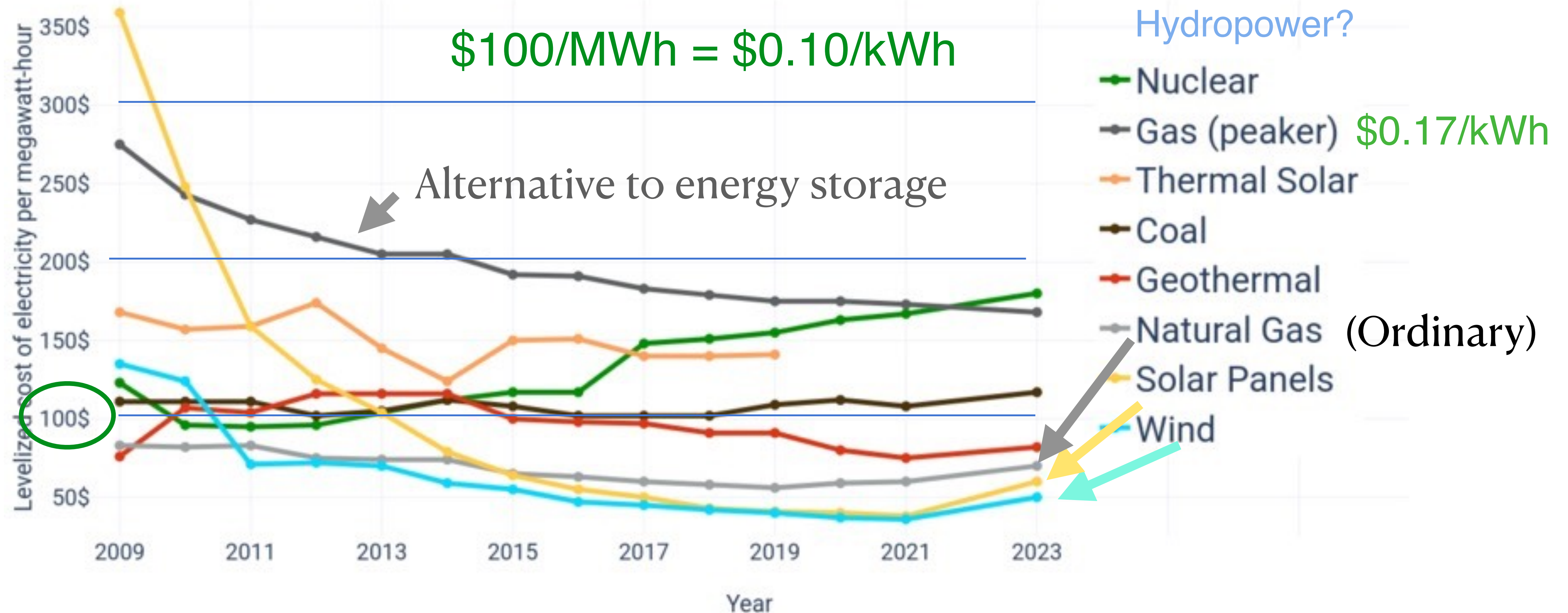




# Unsubsidized Energy Costs Comparison

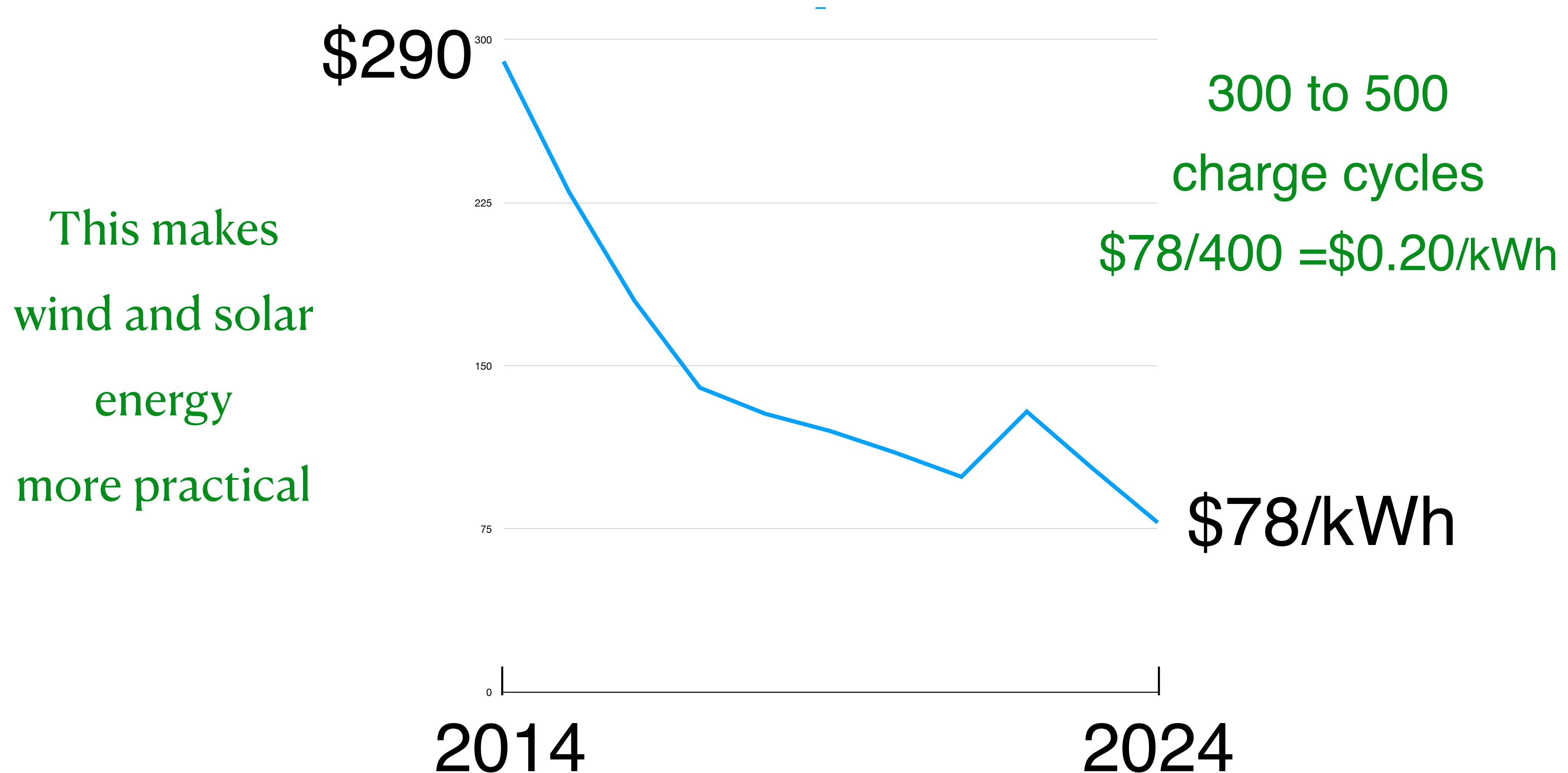
Lazard.com, financial advisors

Electricity costs according to data from Lazard



# Lithium Ion Battery Cost

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



# Retail Prices for EV Batteries

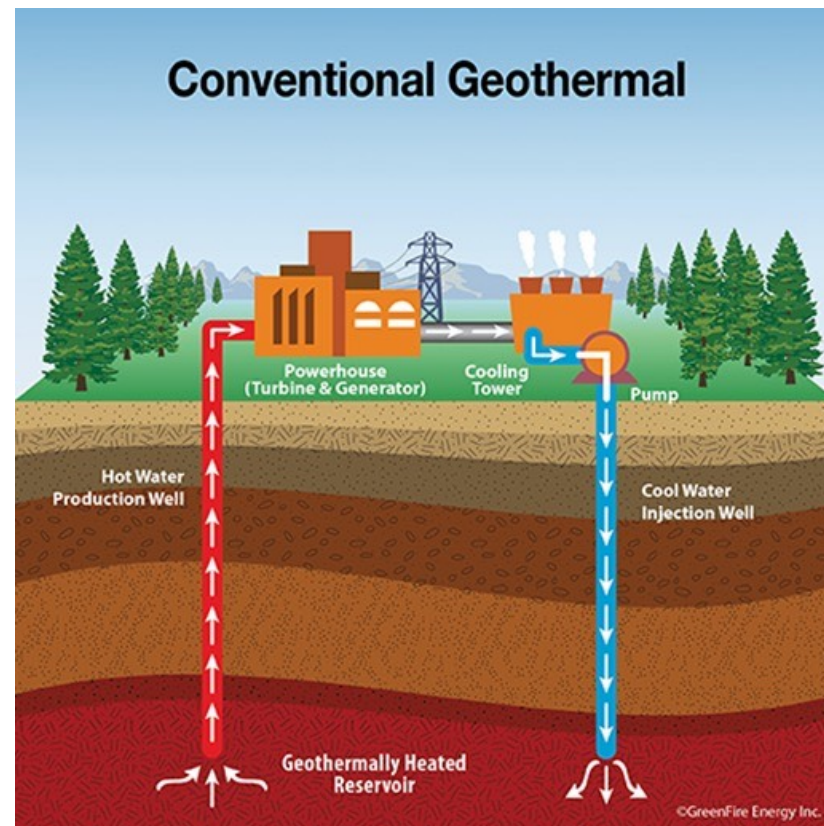
<https://www.recurrentauto.com/research/tesla-battery-replacement-costs>

- 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

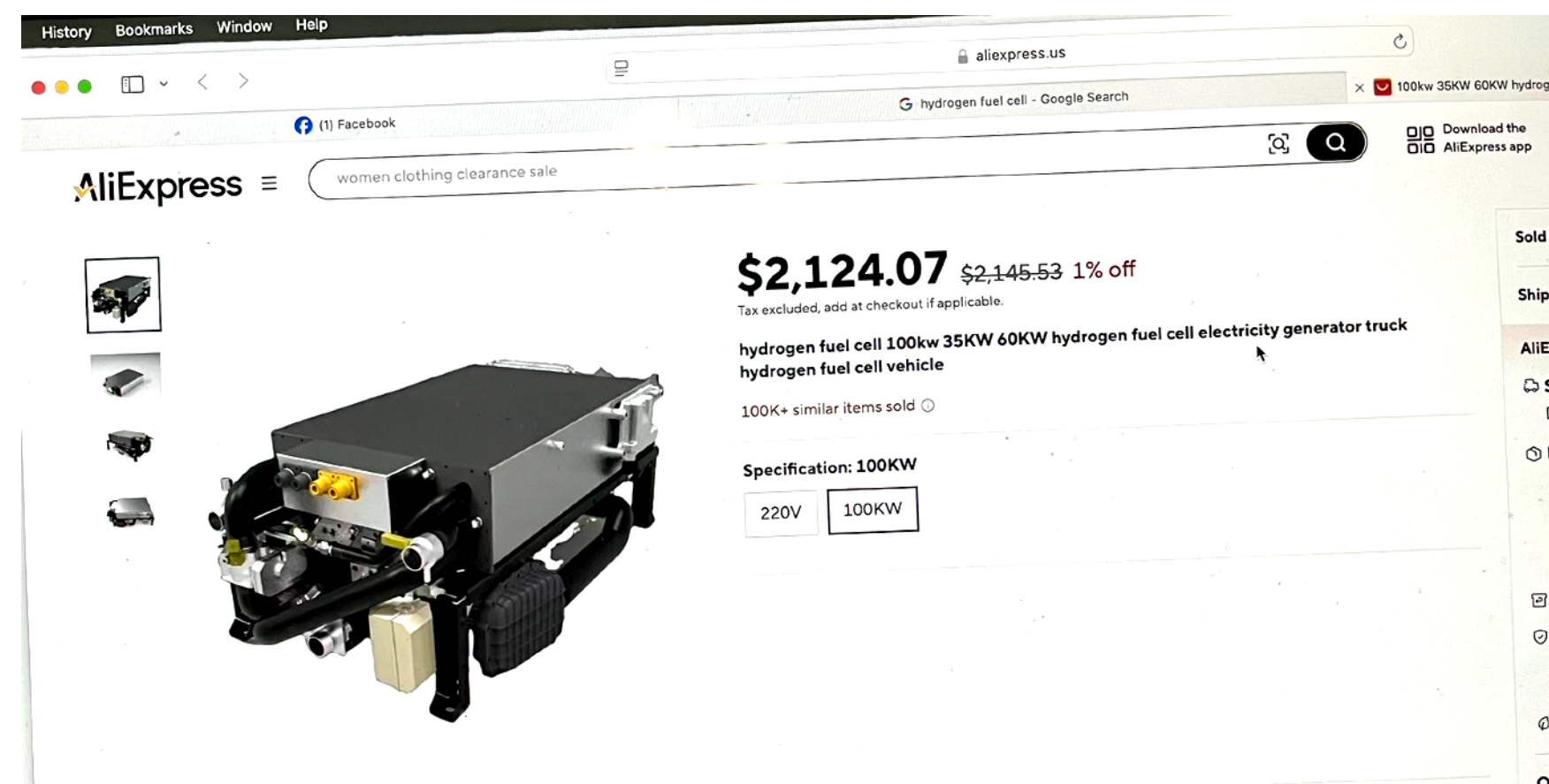


# Minor Energy Sources

- Geothermal: 25% of Iceland's total energy production
- Wave and Tidal (South Korea)



- Hydrogen fuel cells

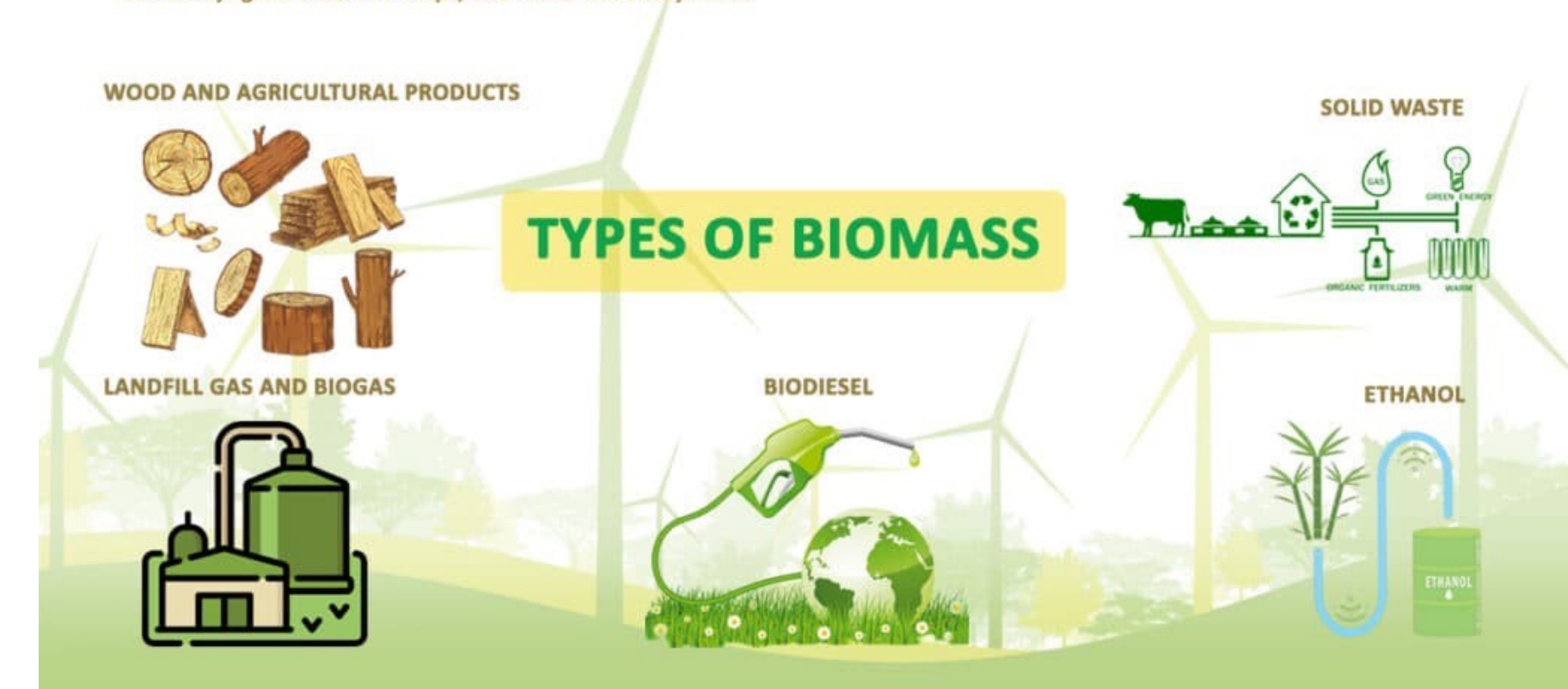


- Biomass

## Biomass Energy



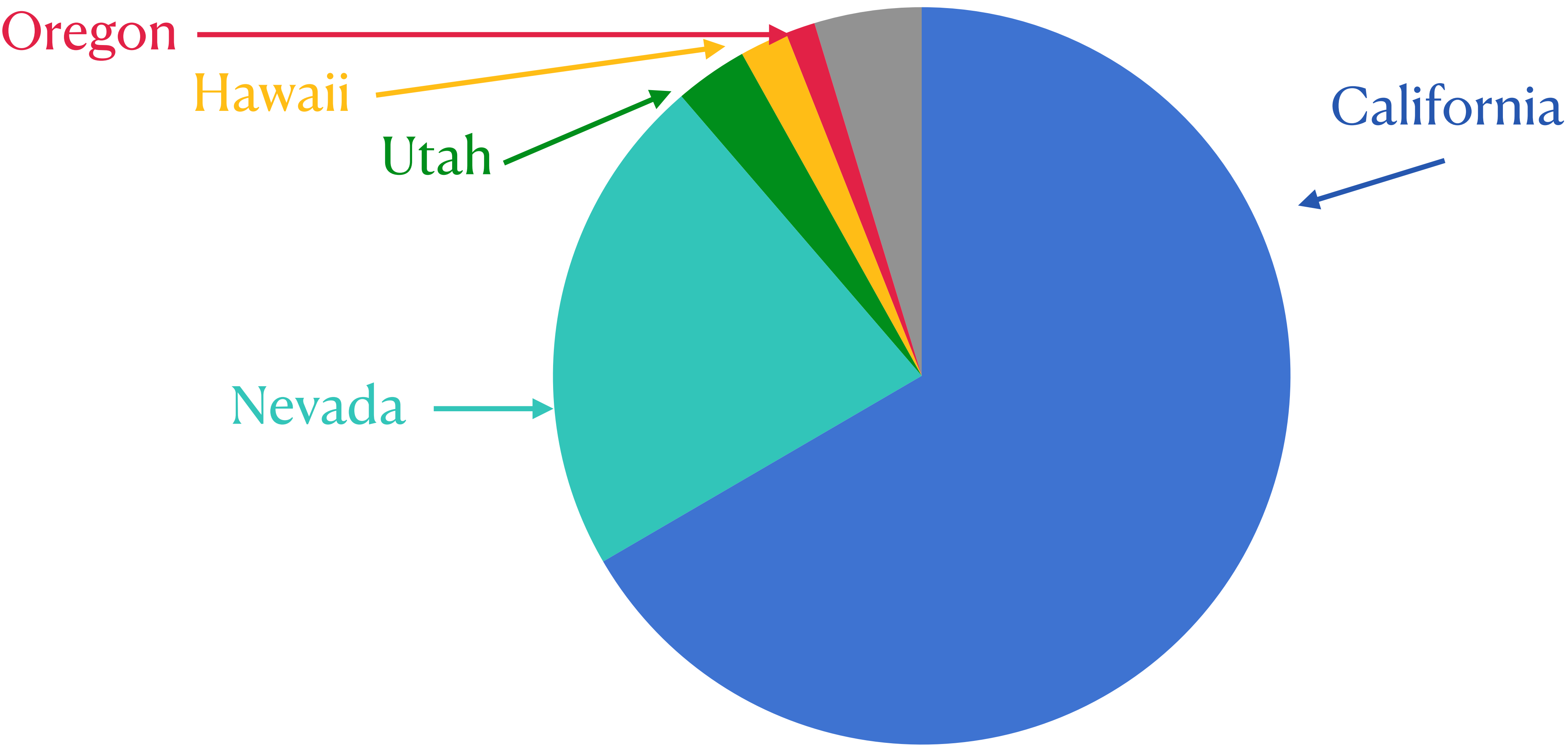
Biomass is any organic matter—wood, crops, seaweed, animal wastes—that can be used as an energy source. Biomass is probably our oldest source of energy after the sun. For thousands of years, people have burned wood to heat their homes and cook their food. Biomass gets its energy from the sun. All organic matter contains stored energy from the sun. During a process called photosynthesis, sunlight gives plants the energy they need to convert water and carbon dioxide into oxygen and sugars. These sugars, called carbohydrates, supply plants and the animals that eat plants with energy. Foods rich in carbohydrates are a good source of energy for the human body. Biomass is a renewable energy source because its supplies are not limited. We can always grow trees and crops, and waste will always exist.





# Geothermal Power Generated in U.S.

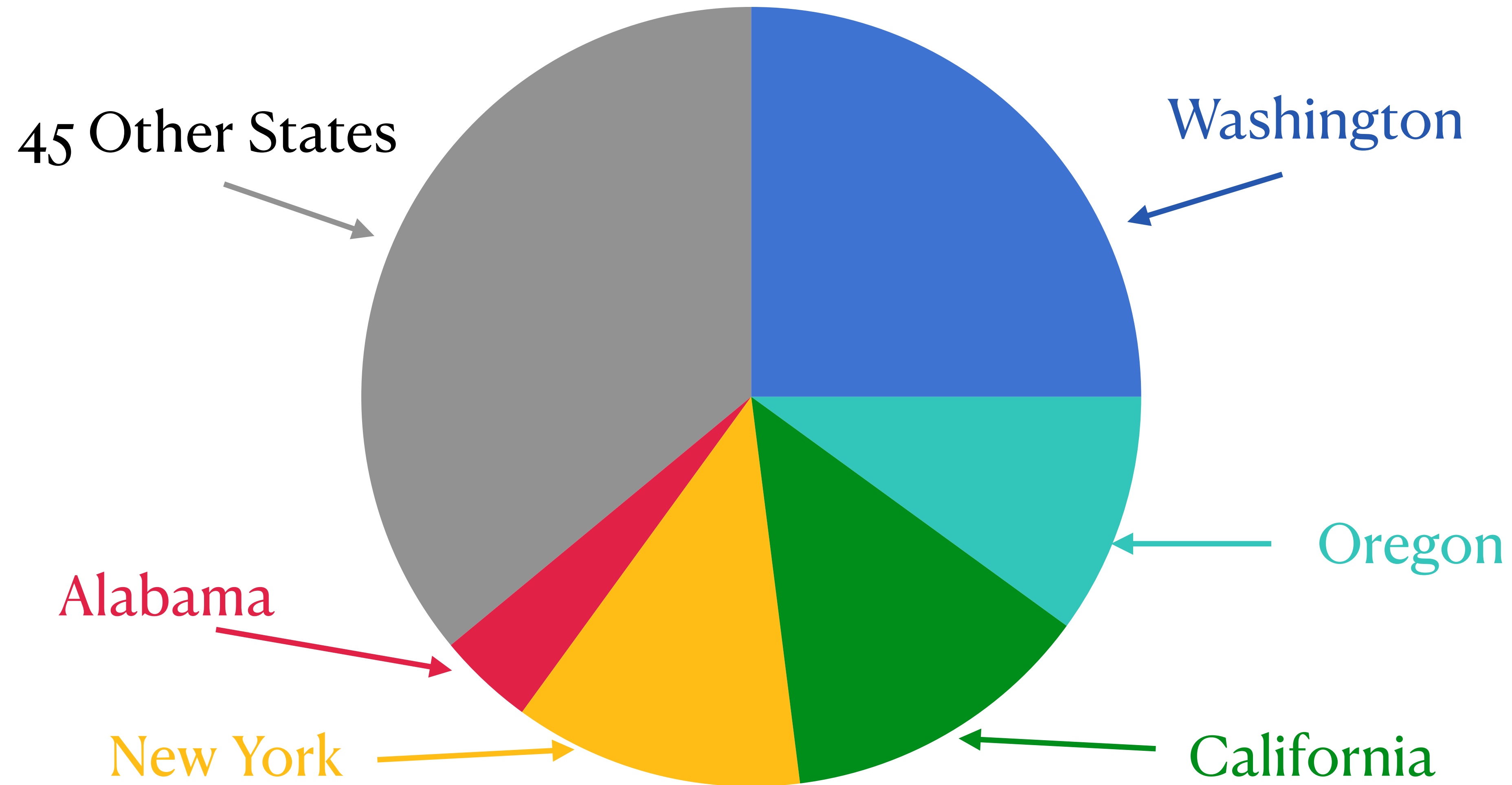
U.S. Energy Information Administration





# Hydroelectric Power Generated in U.S.

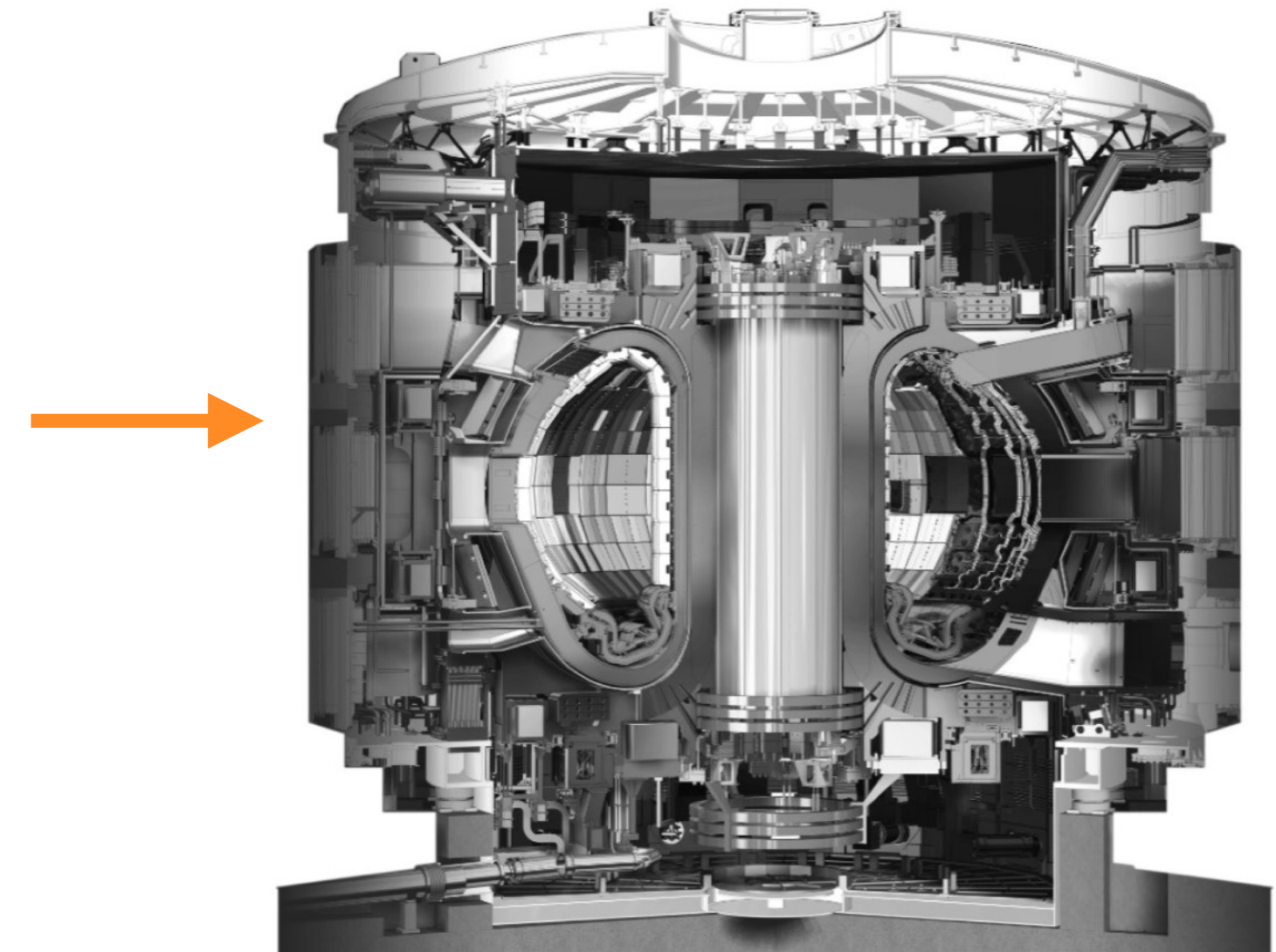
U.S. Energy Information Administration, 6% of total U.S. electricity



# Other Possible Energy Source

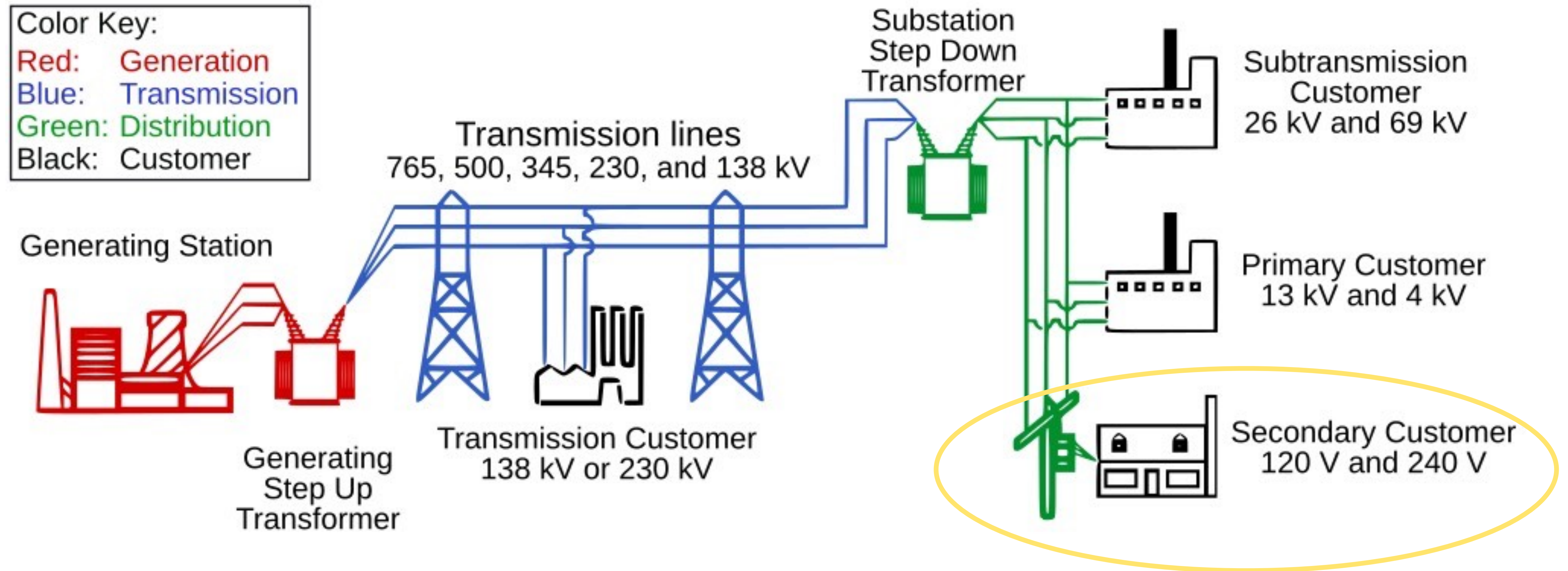
- Nuclear Fusion: ITER is a multi-billion dollar project with the goal of making fusion energy practical. ITER members are China, the European Union, India, Japan, Korea, Russia and the United States.

ITER  
Tokamak



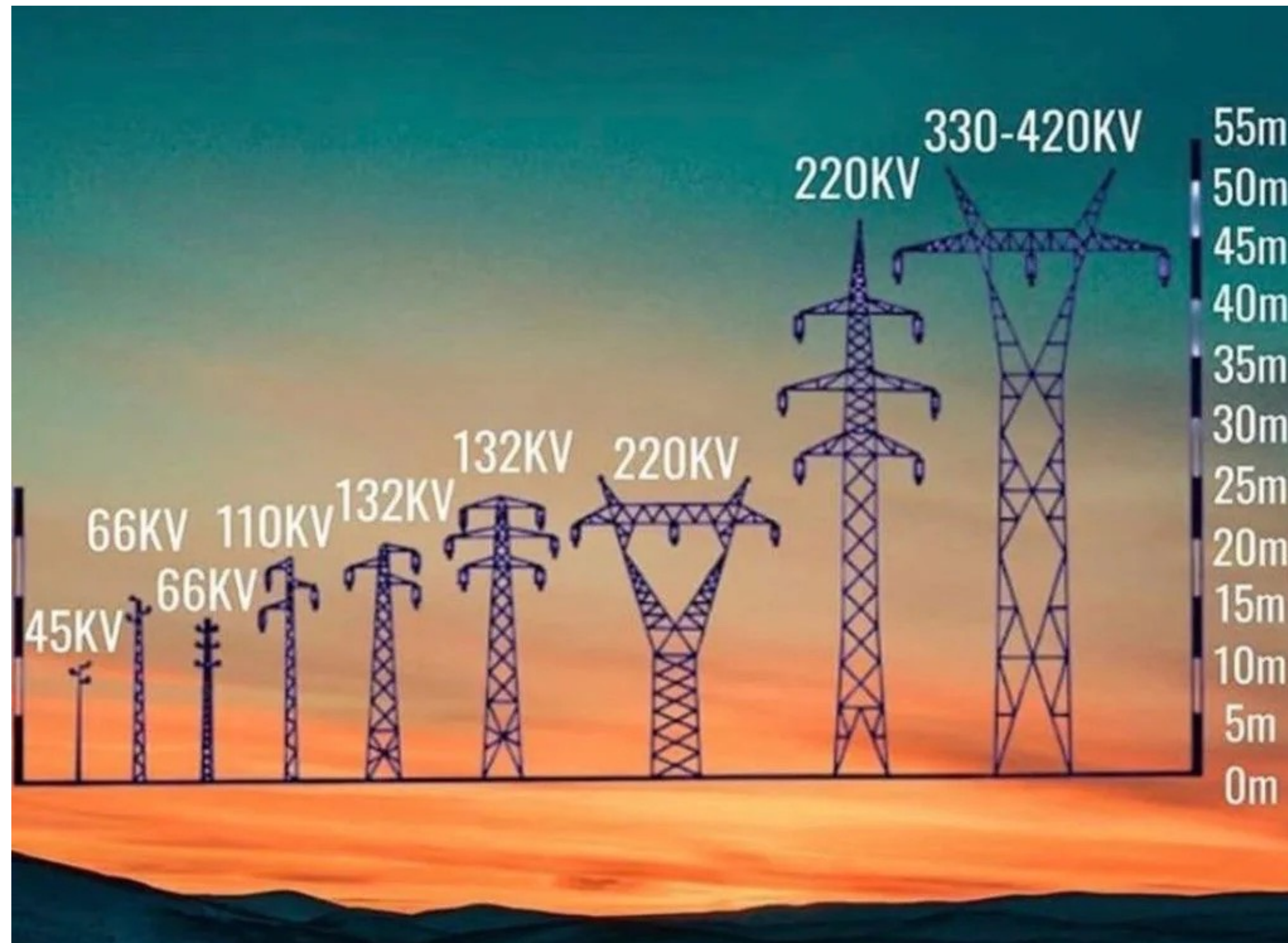
**How it works**

# 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

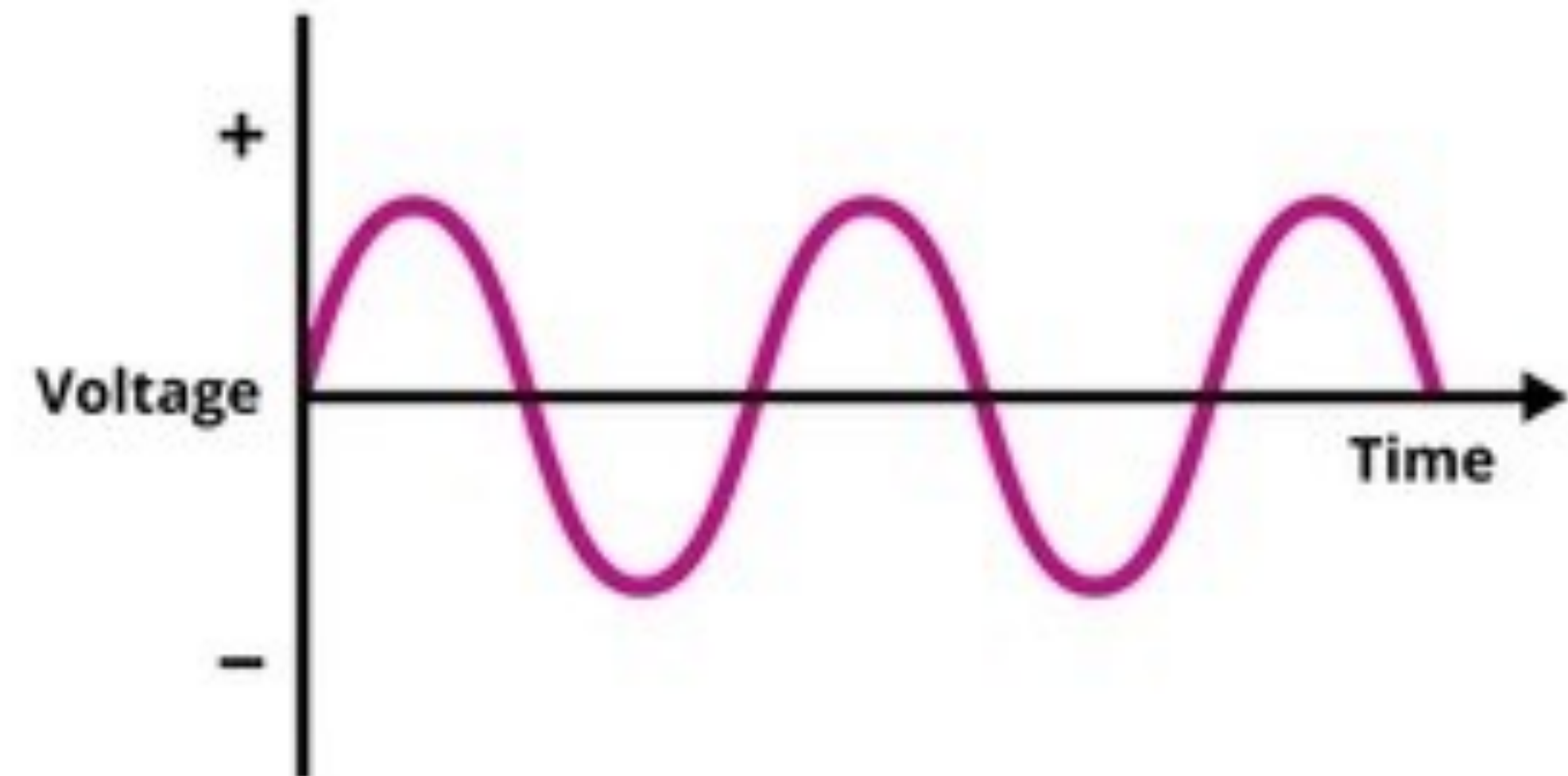
Almost all grid power is AC

Direct Current (DC)



From batteries

Alternating Current (AC)



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

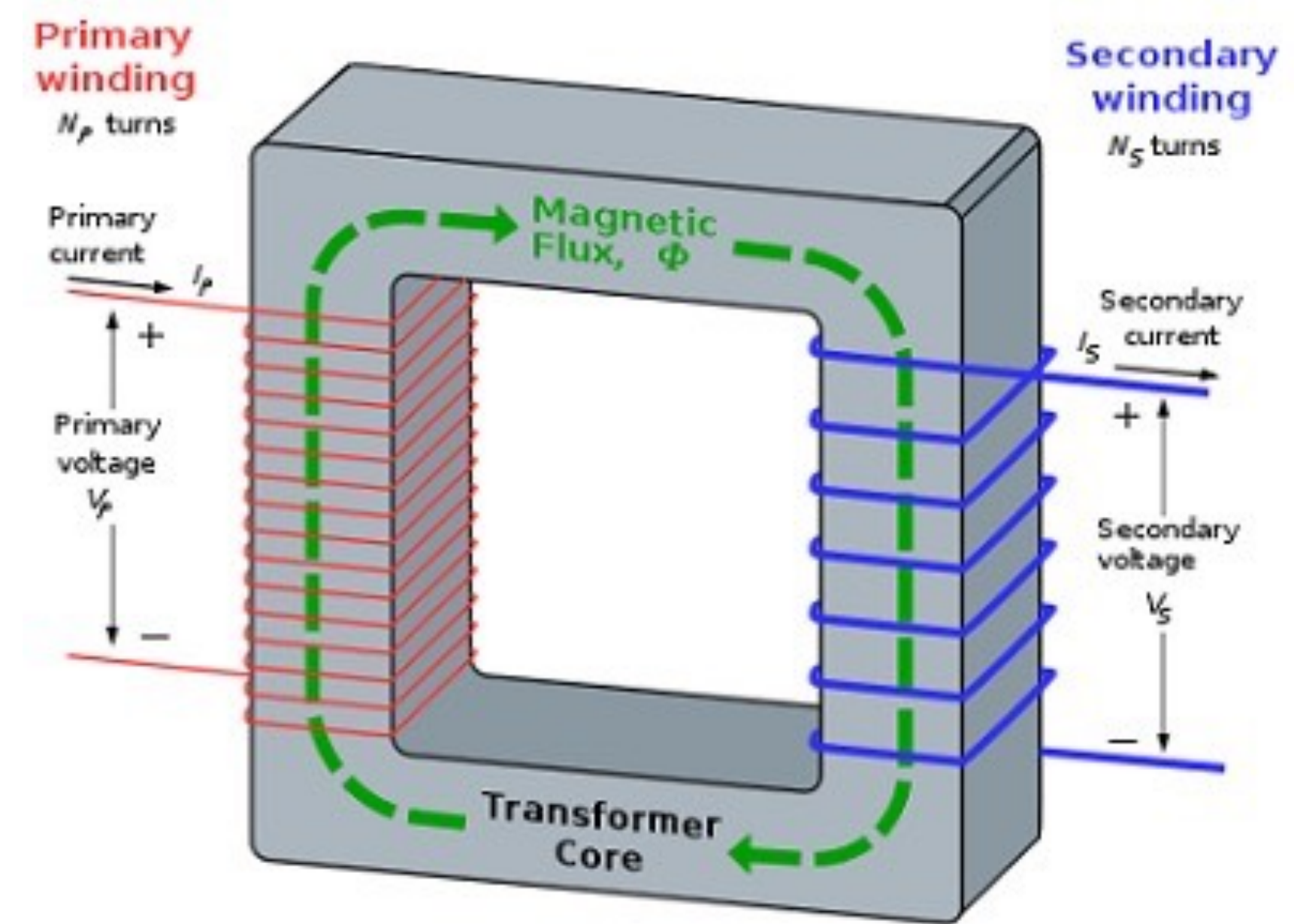
## Electric Reliability Council of Texas, ERCOT

- 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

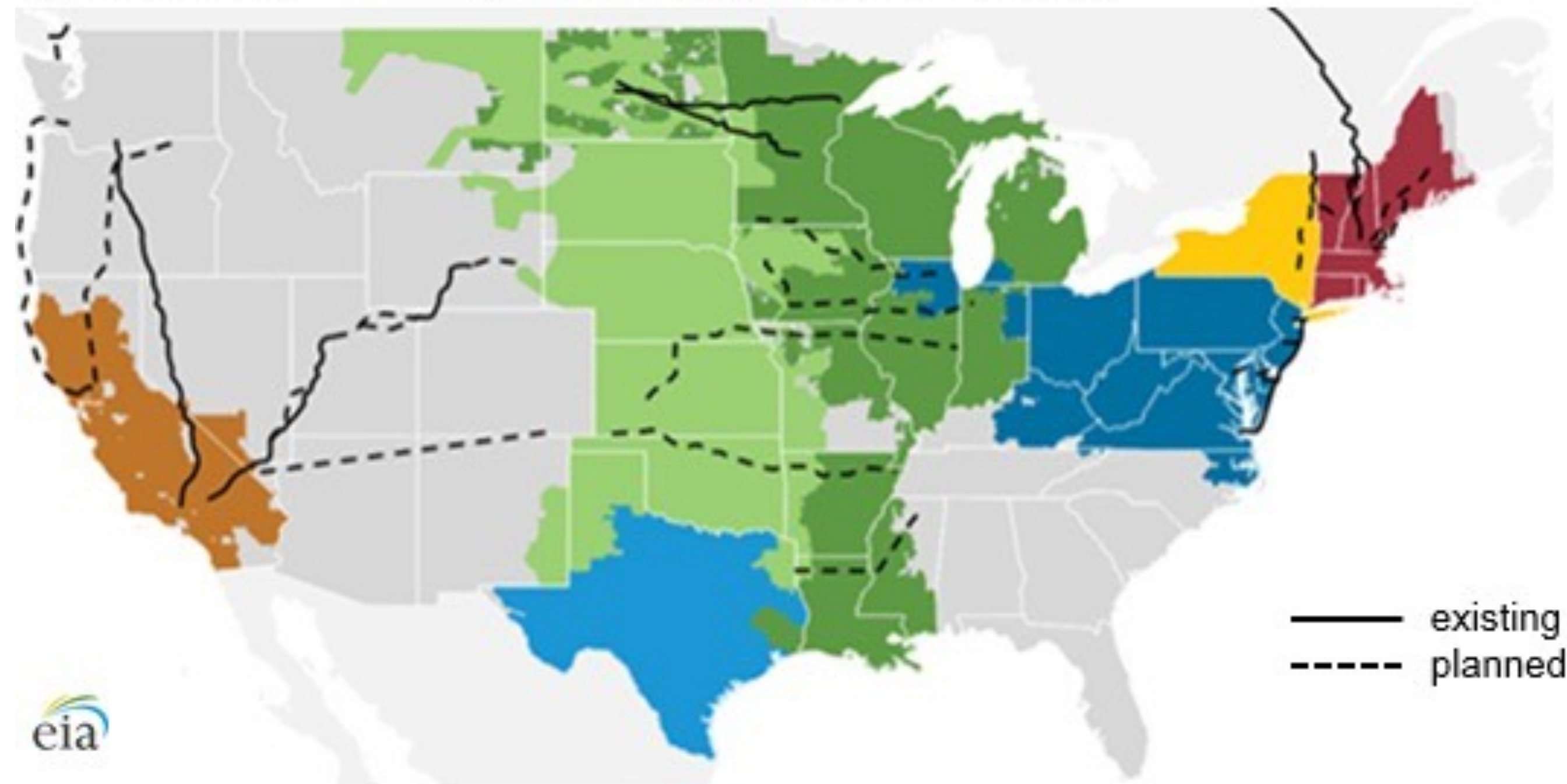




# Existing and Planned U.S. HVDC

U.S. Energy Information Administration

Existing and planned high-voltage direct current power lines





# China's Ultra-High Voltage Transmission

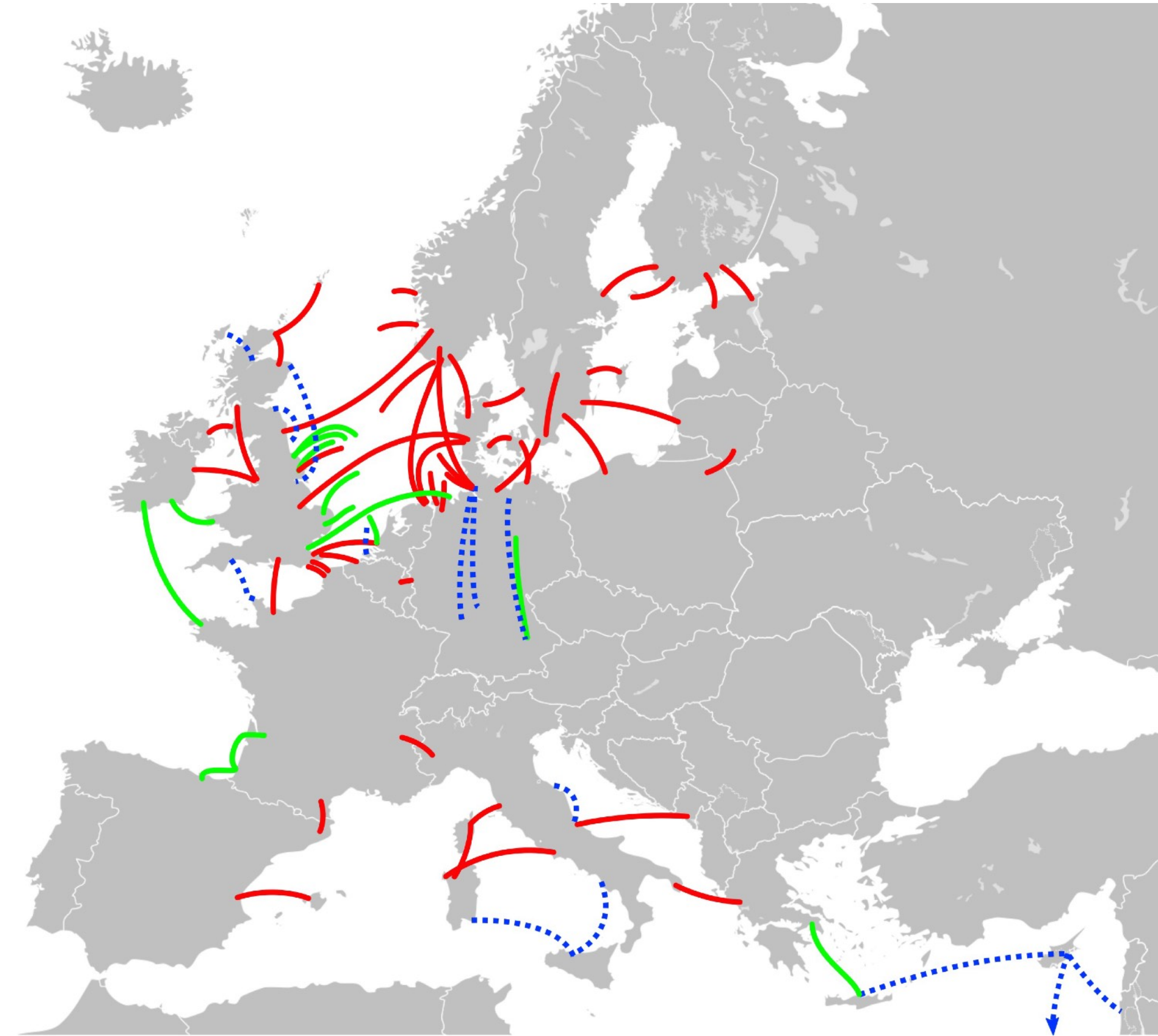




# HVDC Links in Europe

By J JMesserly and those stated in source. - Blank map of Europe.svg by Maix, which is based on Europe countries.svg by Tintazul, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=5553728>

- 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).



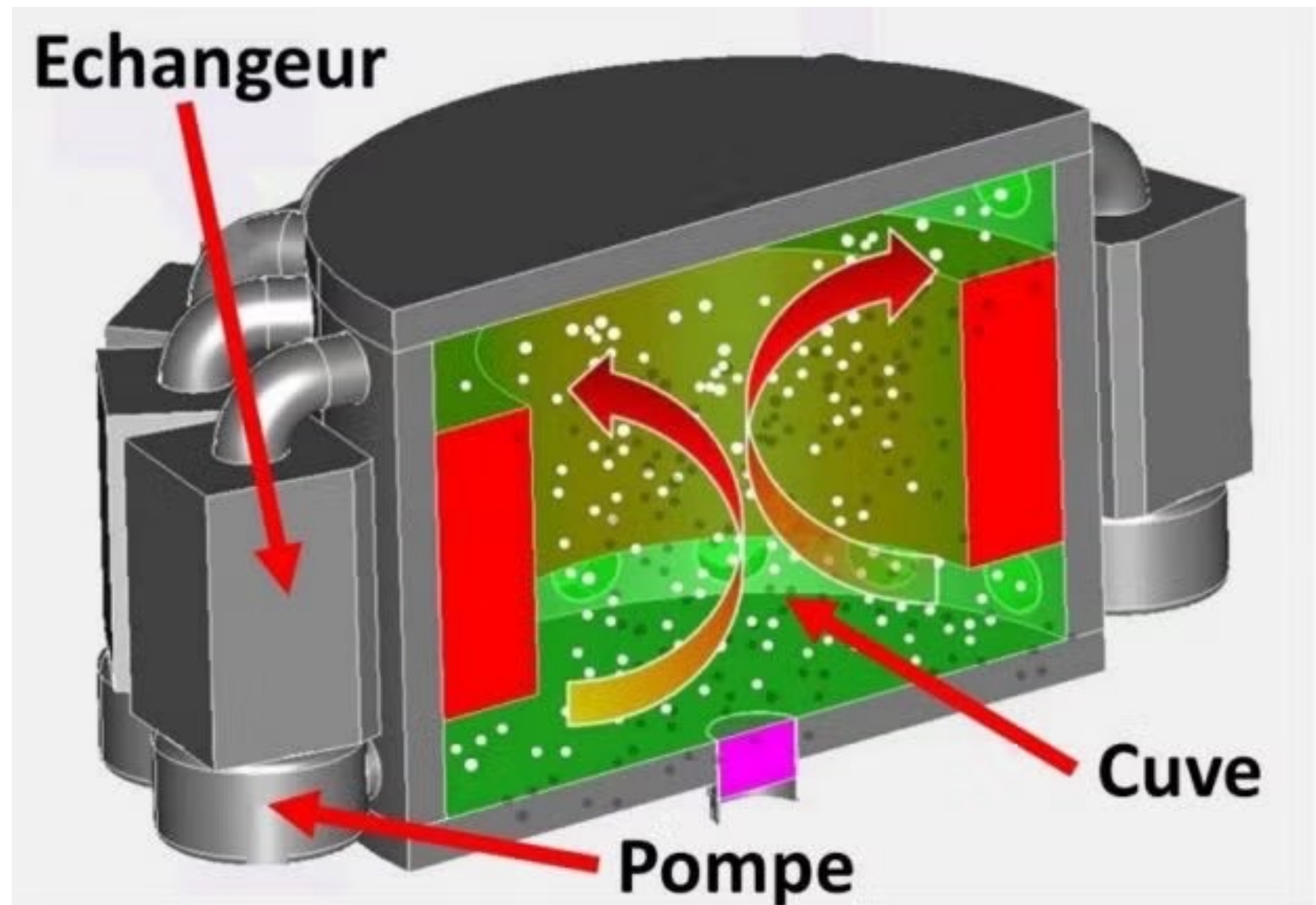
# Innovations in Generation



# 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

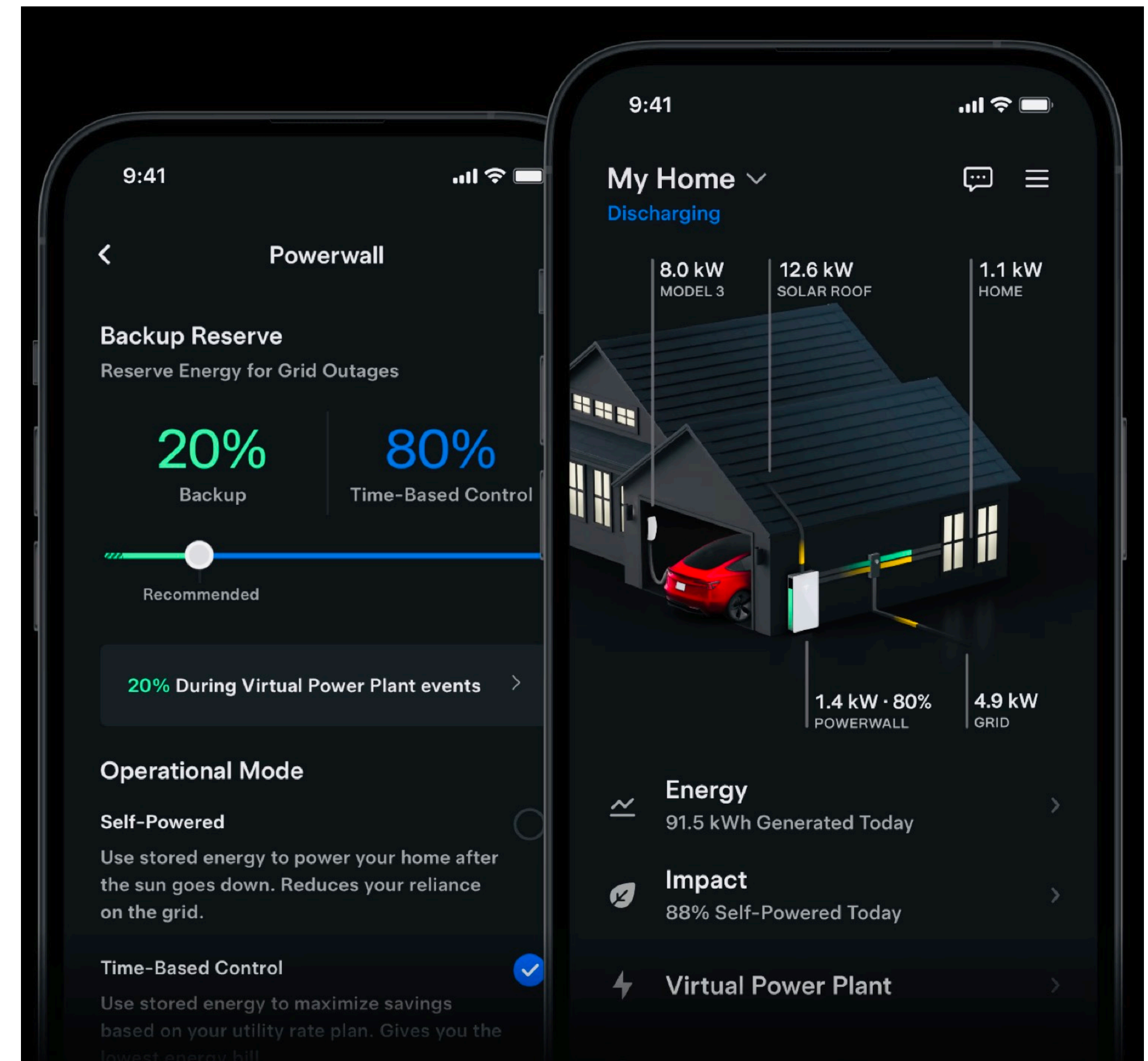




# Innovations in Energy Storage

# 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

Group ►		1	2											13	14	15	16	17	18
Period ▼																			
Nonmetals	1	1																	2
		H																	He
Metals	2	3	4											5	6	7	8	9	10
		Li	Be											B	C	N	O	F	Ne
	3	11	12											13	14	15	16	17	18
		Na	Mg											Al	Si	P	S	Cl	Ar
	4	19	20											31	32	33	34	35	36
		K	Ca											Ga	Ge	As	Se	Br	Kr
	5	37	38											49	50	51	52	53	54
	Rb	Sr											In	Sn	Sb	Te	I	Xe	
6	55	56	La to Yb	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
	Cs	Ba		Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	87	88	Ac to No	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
	Fr	Ra		Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
		s-block (plus He)		f-block	d-block										p-block (excluding He)				
				Lanthanides	57	58	59	60	61	62	63	64	65	66	67	68	69	70	
					La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	
				Actinides	89	90	91	92	93	94	95	96	97	98	99	100	101	102	
					Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	



# 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**

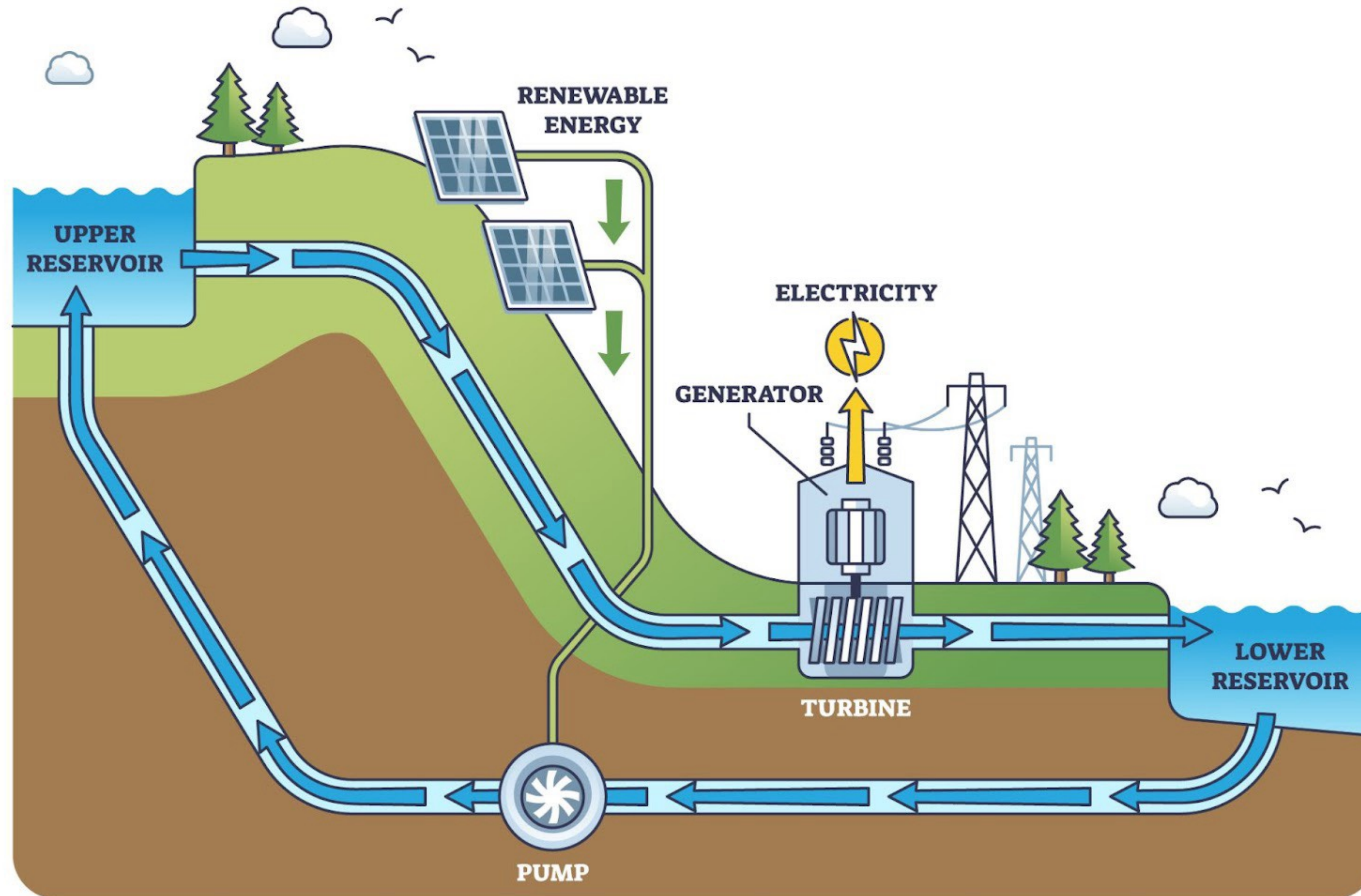
- [Aluminium-ion battery](#)
- [Calcium battery](#)<sup>[1]</sup>
- [Flow battery](#)
  - [Iron redox flow battery](#)
  - [Vanadium redox battery](#)
  - [Zinc–bromine battery](#)
  - [Zinc–cerium battery](#)
  - [Hydrogen–bromine battery](#)
- [Lead–acid battery](#)
  - [Deep-cycle battery](#)
  - [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](#)<sup>[2][3]</sup>
- [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](#)<sup>[4]</sup>
- [Super iron battery](#)
- [Wet cell](#)
- [Zinc ion battery](#)



# PUMPED HYDROPOWER STORAGE



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

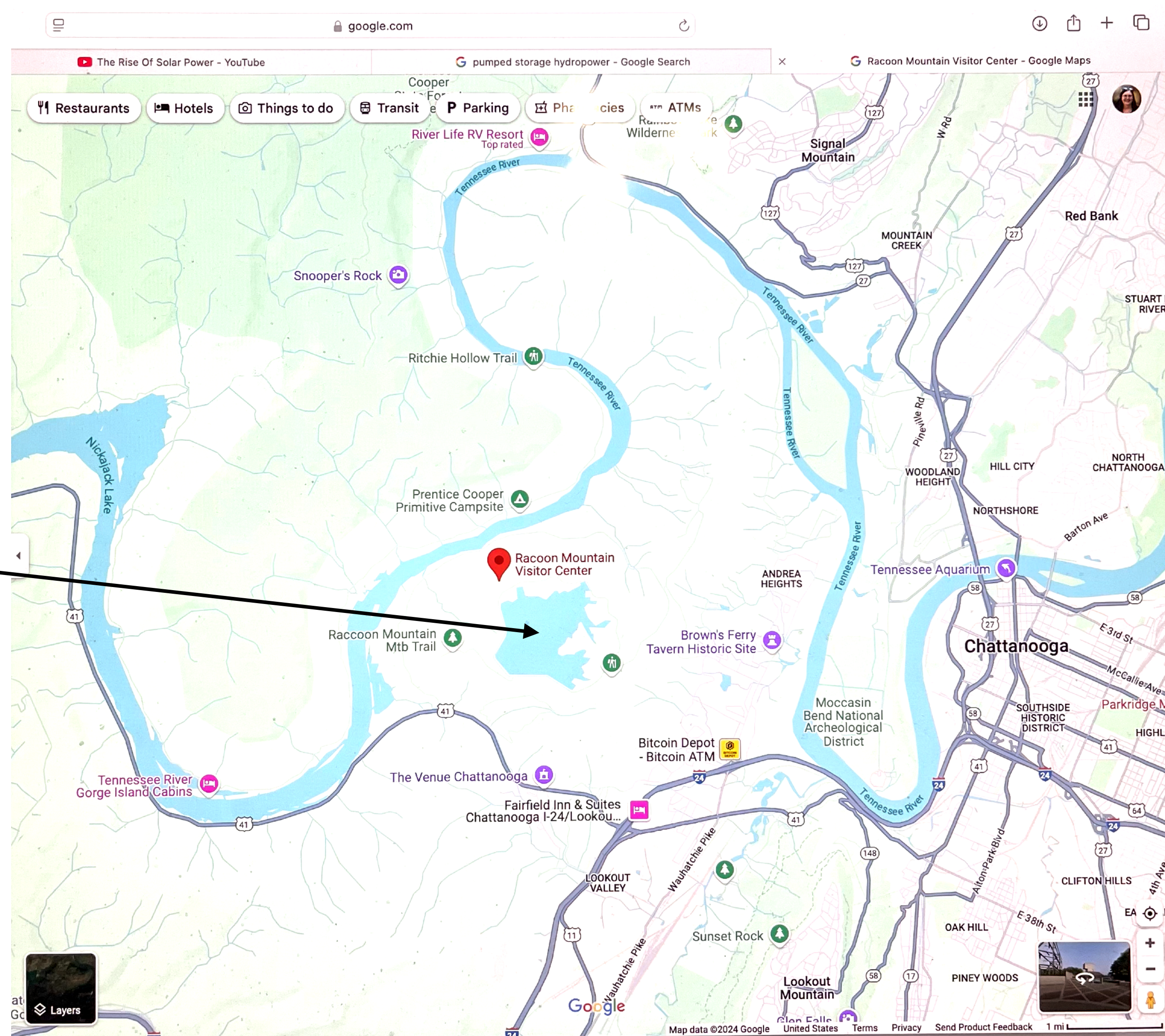
Pumped Storage Hydropower near Chattanooga, Tennessee





# Raccoon Mountain

Pumped hydro  
Reservoir





# Factory scale energy storage



# Other Gravity Energy Storage Systems

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INNOVATION


Two massive gravity batteries are nearing completion in the US and China

The system helps to plug the gap when it comes to renewable energy sources.

Updated: Apr 27, 2024 06:13 AM EST


Jijo Malayil

2 years ago



Energy Vault's original design for gravity storage is a solution to the unpredictable nature of solar and wind power, gravity batteries are being pitched as an ideal remedy To

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# Other Gravity Energy Storage Systems

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Gravitricity

Long-life, distributed, underground energy storage

Our impact

8

Patents Granted

15+

Skilled Employees

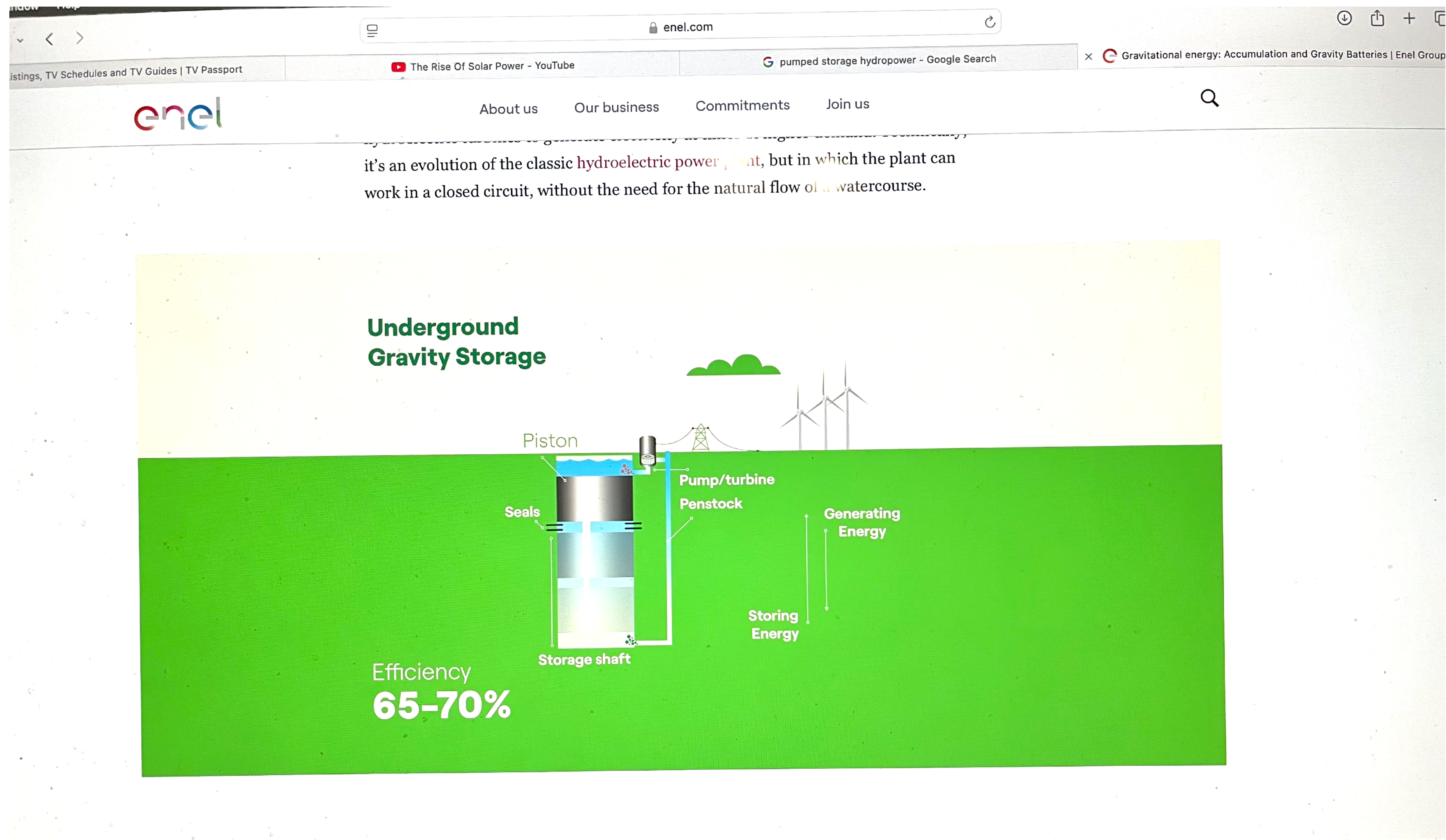
300+

Sites Identified Worldwide

As the world generates more electricity from intermittent renewable energy sources, there is



# Other Gravity Energy Storage Systems





# Compressed Air Energy Storage

Local TV Listings, TV Schedules and TV Guides | TV Passport

The Rise Of Solar Power - YouTube

pumped storage hydropower - Google Search

Compressed Air Energy Storage (CAES) | MAN Energy Solutions

Company Careers Digital Center Press & Media Discover Location Finder Contact EN

MAN

MAN Energy Solutions


Our focus Energy & Storage Marine Process Industry Oil & Gas Services

## Access huge amounts of energy when you need it

**Compressed air energy storage (CAES) is a proven large-scale solution for storing vast amounts of electricity in power grids.**

As fluctuating renewables become increasingly prevalent, power systems will face the situation where more electricity is produced than it is needed to cover the demand. The solution: Effective energy storage systems store this excess energy, allowing operators to draw on it as needed.

CAES solutions make it possible to store energy on a very large scale while ensuring that the grid is stable – for a secure power supply. The technology uses electricity to compress and store ambient air under pressure in subterranean reservoirs, such as caverns and salt mines. When power is required, compressed air is drawn through the expander to power a generator. It is also possible to incorporate thermal storage or peaker plants to improve round-trip efficiency.

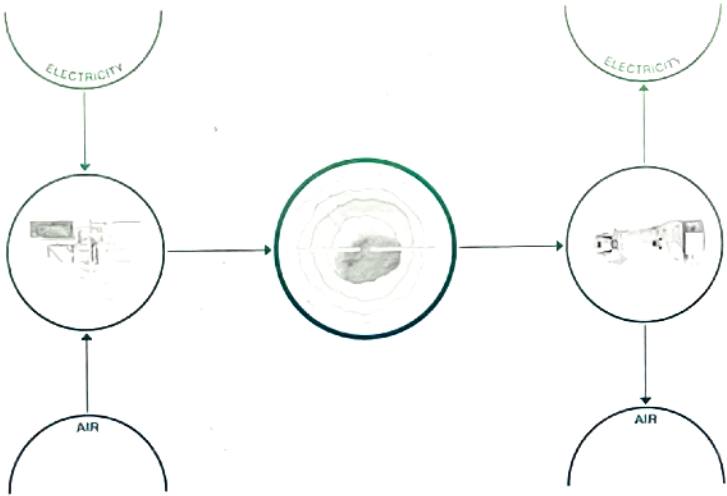


## Our state-of-the-art compressors and expanders for CAES help promote clean, green power

**MAN Energy Solutions develops industry-leading equipment and components for CAES solutions based on proven technology developed over decades.**

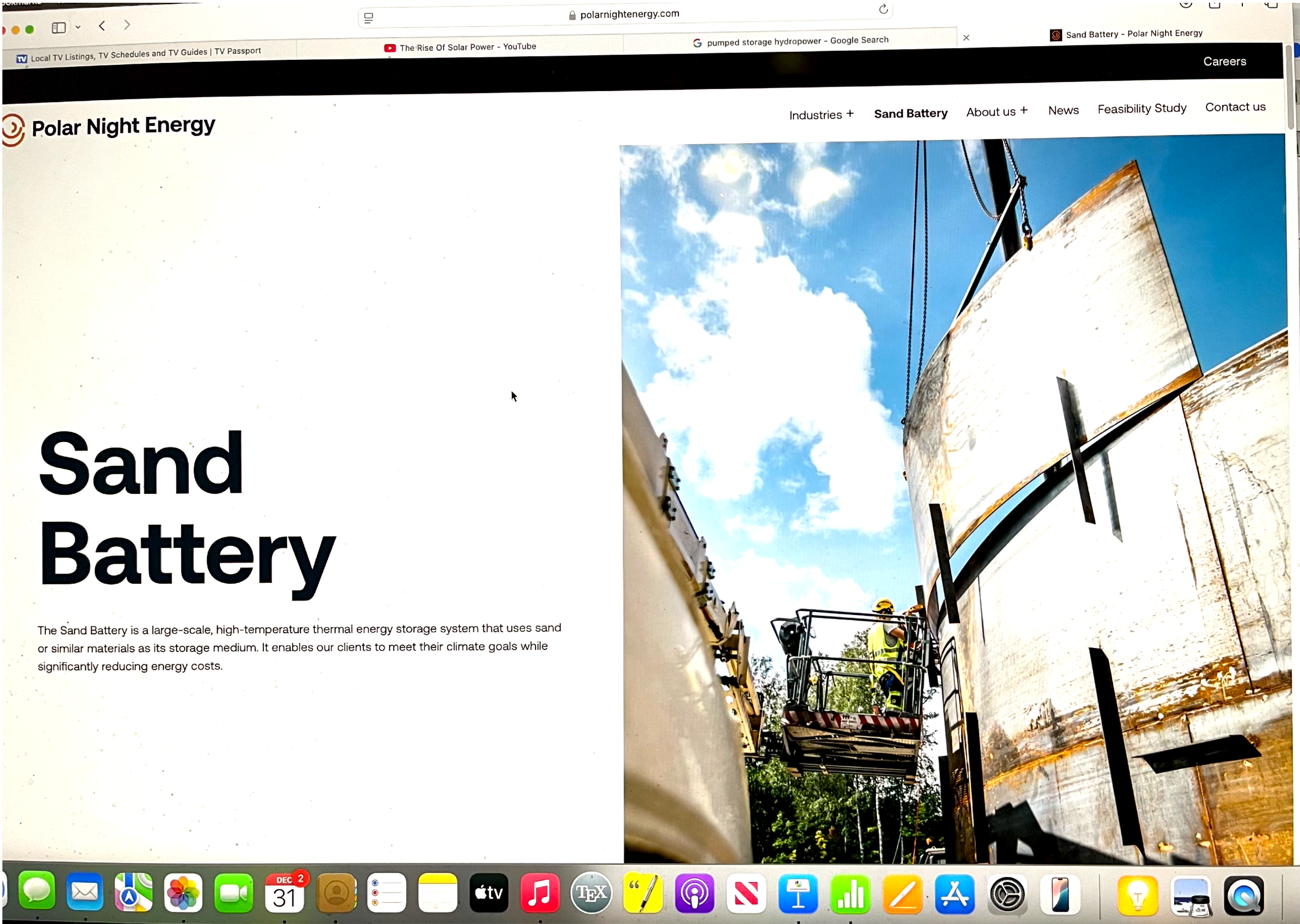
We are a leading provider of CAES turbomachinery, with decades of experience in developing compressors and expanders. Our expertise speaks for itself: We provided the compressors for the world's first large-scale CAES facility in Huntorf, Germany in 1978 – and it is still going strong today. CAES solutions allow for very high power outputs and capacities, as well as multiple energy services, including spinning reserve and black start.

MAN Energy Solutions offers a wide range of efficient air compressors, including combined axial and radial compressors for large units that are ideal for large-scale applications. Our air expander power recovery units are based on over 100 years of





# Heat Storage: Sand Battery





# Heat Storage: Salt Battery

The screenshot displays the website for innov.energy, specifically the 'Salt Technology' page. The browser's address bar shows 'innov.energy'. The website's header is orange with the 'innov.energy' logo on the left and navigation links (APPLICATIONS, INNOENERGY, INFOS, CONTACT) in the center. On the right, there are links for 'Login', 'DE | EN | FR', and a search icon. The main visual is a large image of a salt battery storage system, featuring a large, conical pile of white salt in the foreground, with a complex, geometric, orange-colored structure (the battery's internal structure) in the background. Below this image, the text reads: 'Storage with common salt. For the sake of our environment!'. A breadcrumb trail indicates the path: Home / APPLICATIONS / Technologies / Salt Technology. The section title is 'Where does it make sense to use a salt battery?'. Below this, a list of bullet points describes the ideal conditions for using a salt battery. At the bottom right, there is a circular logo for 'SUSTAINABLE SALT BATTERY STORAGE SYSTEM THE ECO bat' and a green button that says 'Become Partner with ECO-storages for your portfolio'. The macOS dock is visible at the very bottom of the screen.

Storage with common salt.  
*For the sake of our environment!*

Home / APPLICATIONS / Technologies / Salt Technology

## Where does it make sense to use a salt battery?

- Everywhere where a lot of energy is produced and medium power is required.
- Everywhere where a long service life is required.
- Everywhere where maintenance-free use is necessary.
- Everywhere where minimising the fire load is essential in critical infrastructure systems.
- Everywhere where extreme climatic conditions prevail.

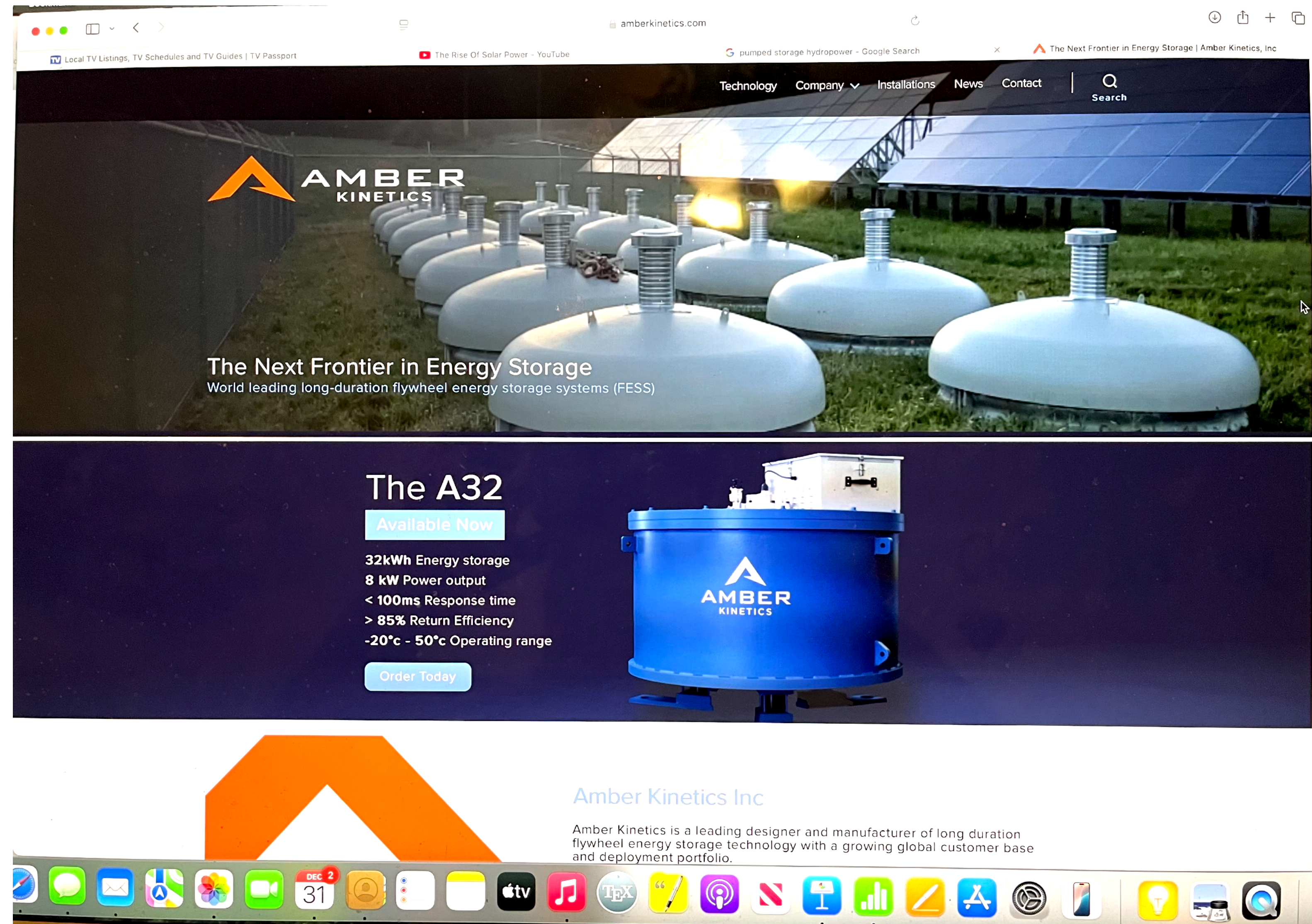
In concrete terms, this means households and commercial enterprises that require a stationary battery storage system for normal medium power demands.

**SUSTAINABLE SALT BATTERY STORAGE SYSTEM**  
**THE ECO bat**

**Become Partner**  
with ECO-storages  
for your portfolio



# 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.