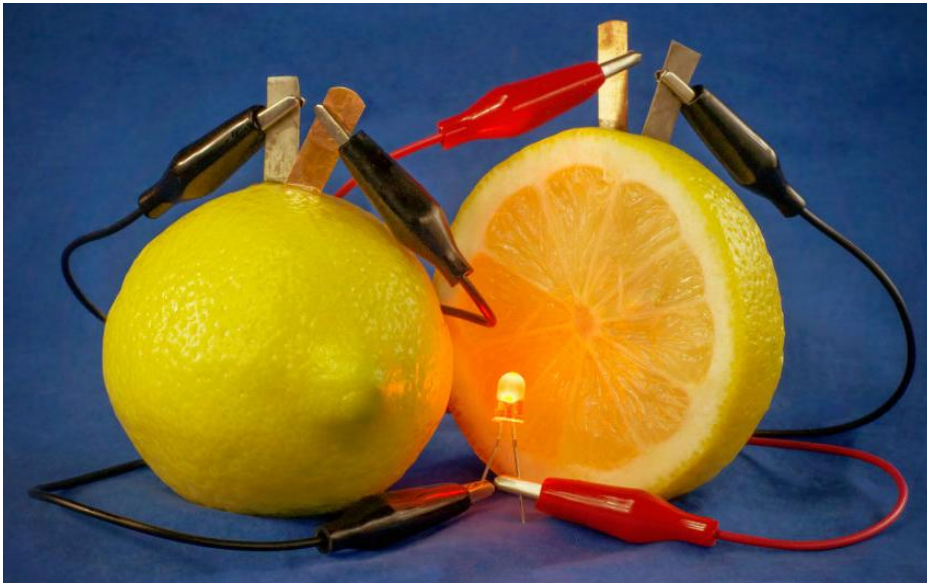


CH EN 5308/6308

Fall 2025

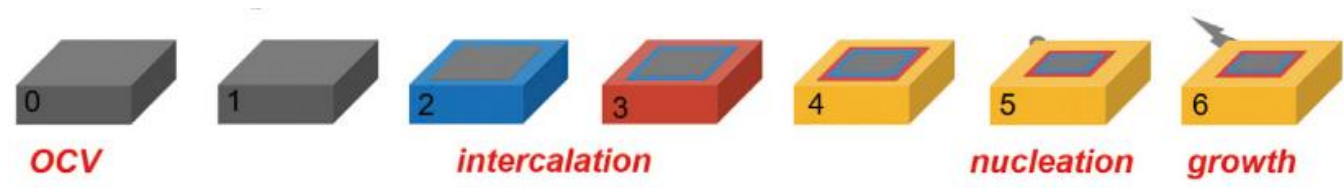
# Battery Technology and Electrochemical Engineering

# Course content: three modules



Source: MCL chemistry

- I. Electrochemical System
  - L1: What is it?
  - L2-5: How does it work?
  - L6: How to characterize it?
- II. Battery Technology
  - L7: Li-ion batteries
  - L8: Li-metal batteries
  - L9: Na-ion batteries
  - L10: aqueous and flow batteries
  - L11: Manufacturing and supply chain
- III. Current topics in electrochemical engineering
  - Sustainable metal production
  - Electrochemical separation
  - CO<sub>2</sub> capture and conversion
  - Electro-chemical synthesis

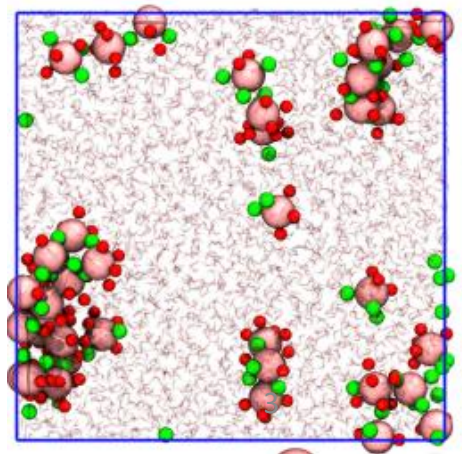
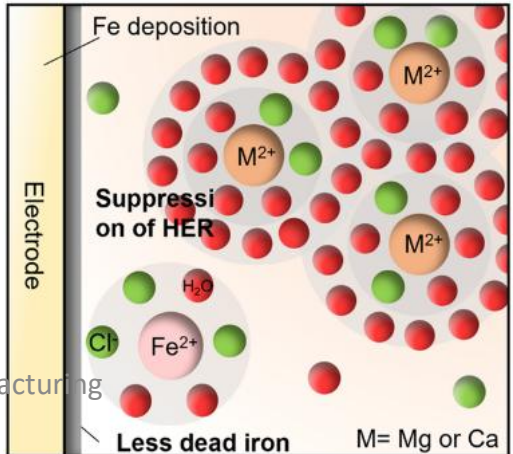


# Multiscale Electrochemical Engineering Lab

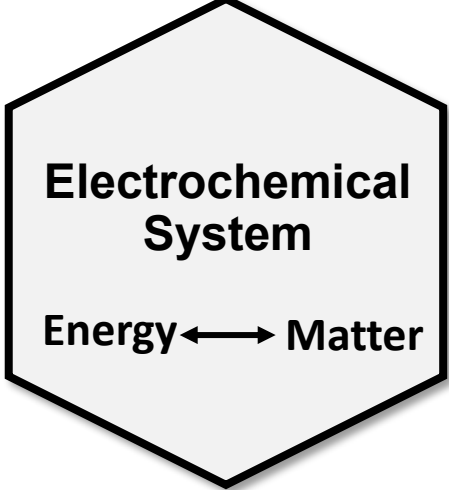
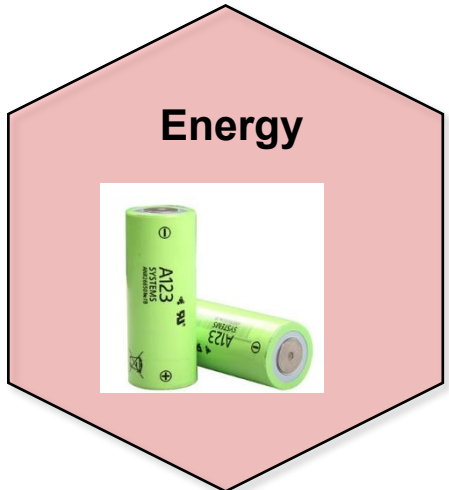
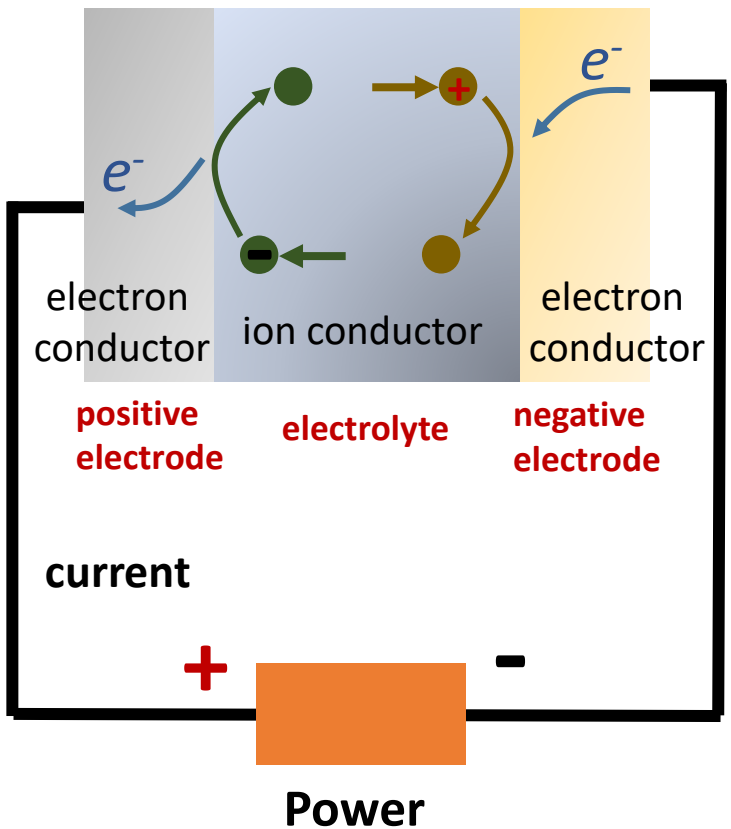
## ME<sup>2</sup> Lab

Tao Gao, PhD

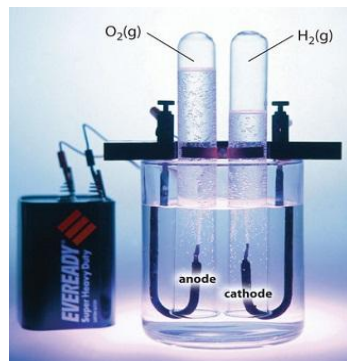
Assistant Professor  
 Department of Chemical Engineering  
 The University of Utah



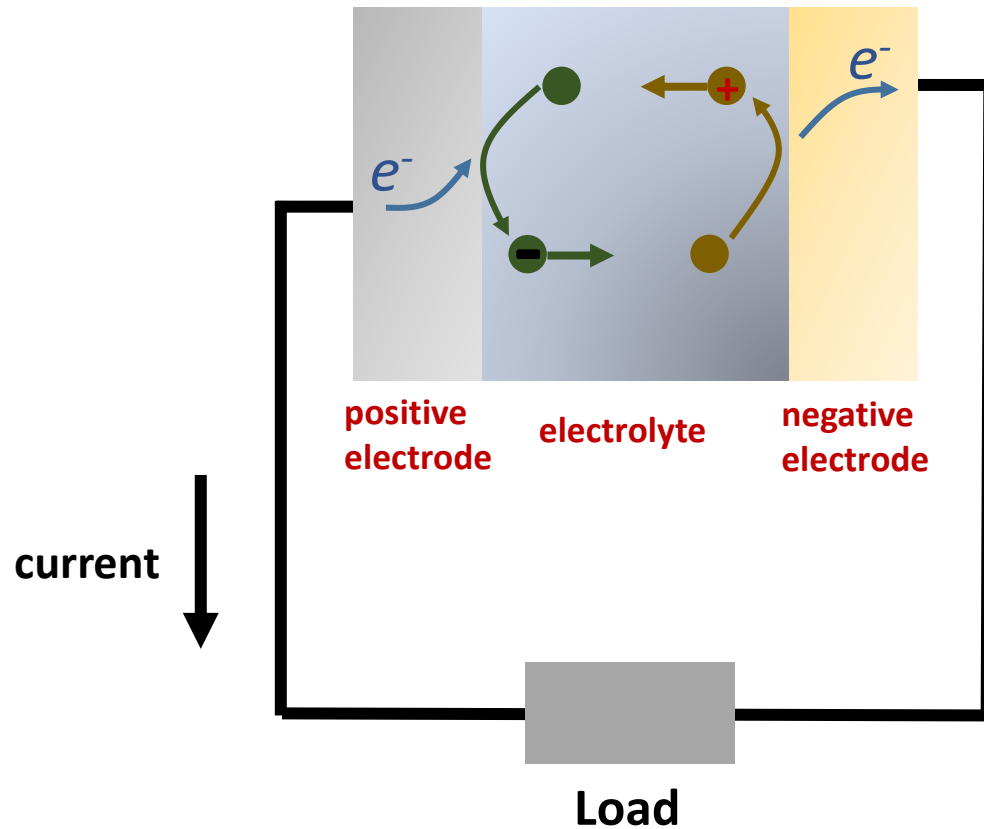
## Electrochemical System



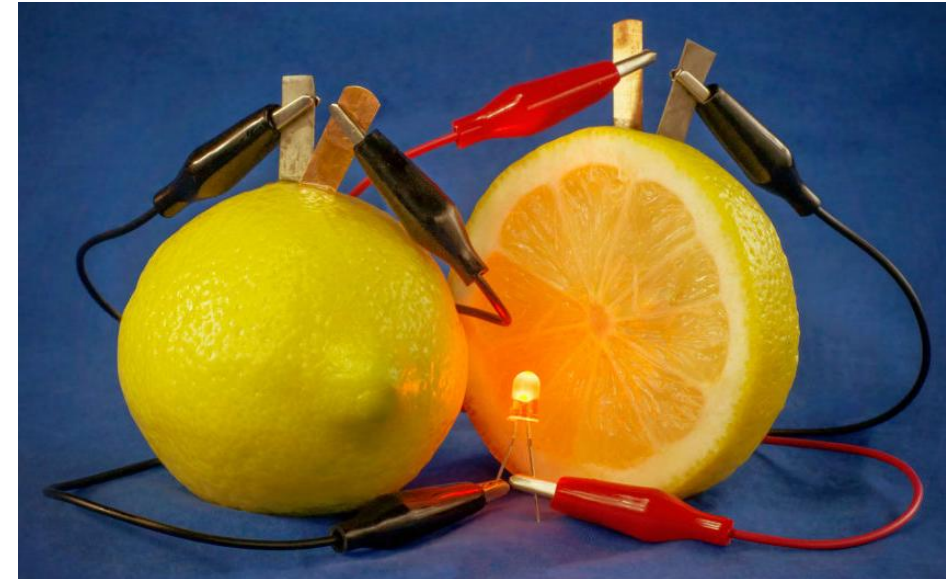
## Energy and Sustainability



# A battery is an electrochemical system



## Batteries



Source: MCL chemistry

- Energy released or stored
- Chemical reactions
- Mass transport
- Interface between two phases

## Energy

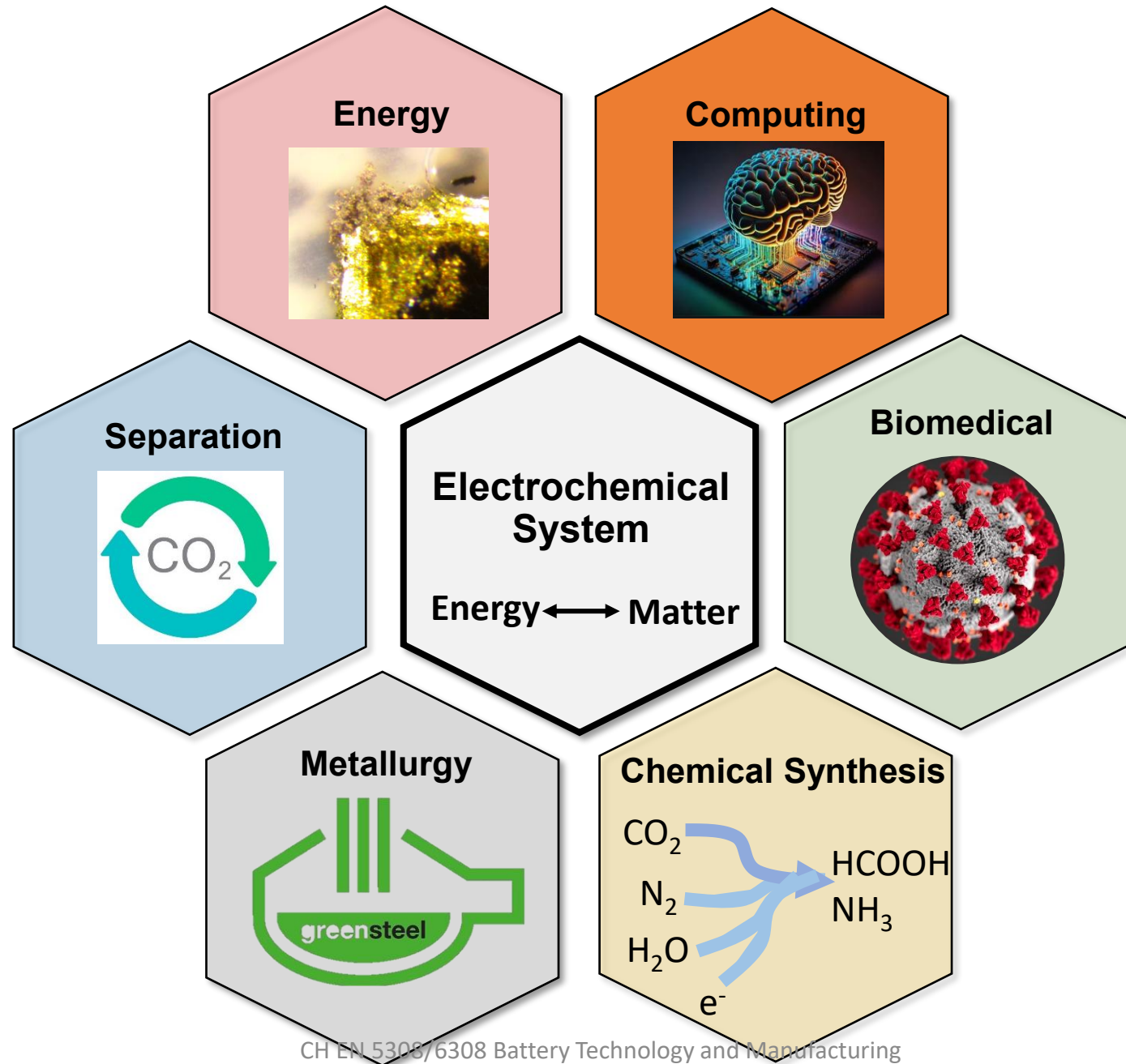
- Batteries
- Fuel cell
- Electrolyzer

## Separation

- Carbon capture
- Desalination
- Mineral extraction

## Metallurgy

- electrowinning
- electrorefining



## Computing

- memristor

## Biomedical

- Biosensor
- Biofuel cell

## Synthesis

- Synthetic fuel
- Nanomaterials
  - Ammonia
- Drug molecules

## Glucose Analyzer



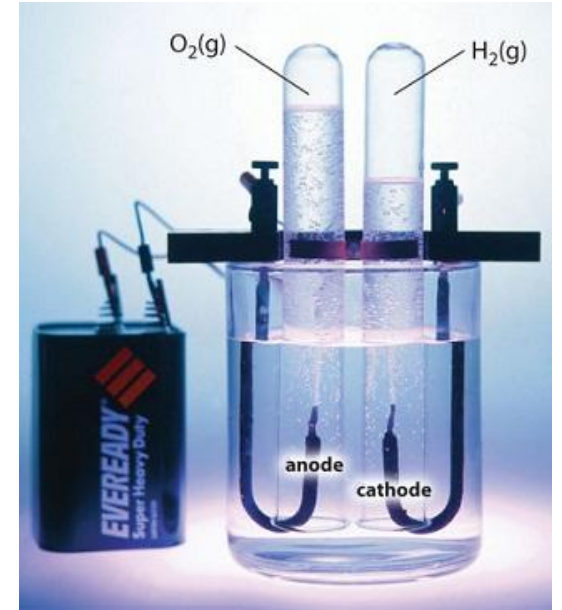
Source: Wikipedia

## Corrosion



Source: Raliant Institute of Tech

## Electrolyzer



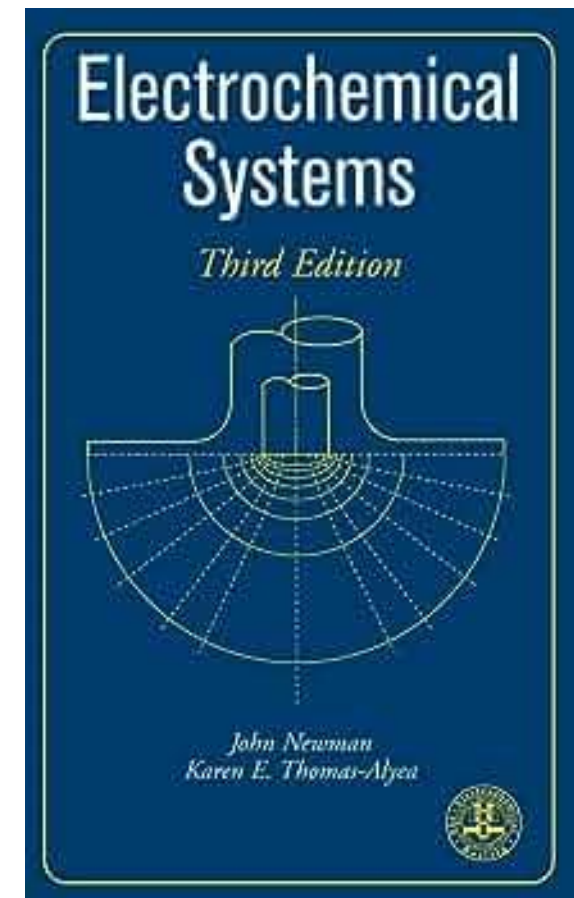
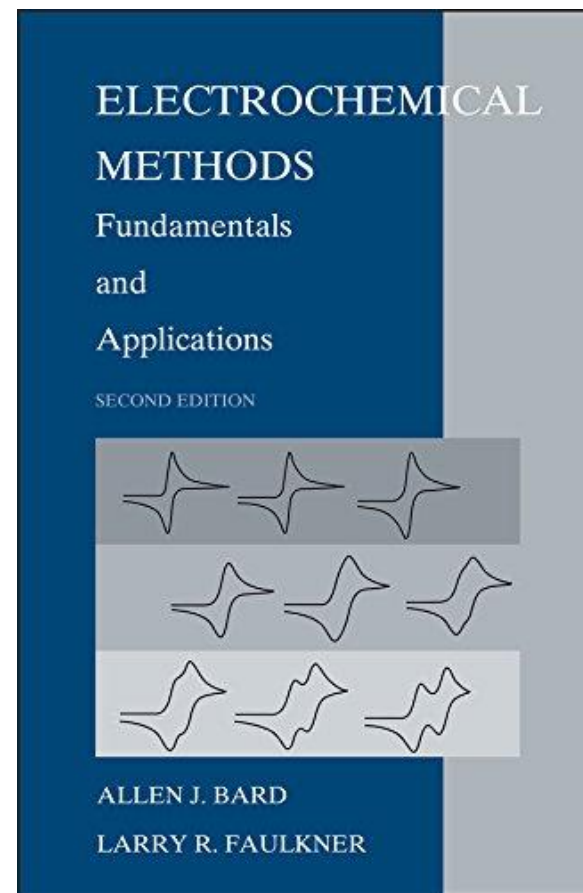
Source: chemistry Libre text

# Learning Objectives

- Apply basic concepts of electrochemical systems to analyze and solve problems in electrochemical engineering.
- Develop preliminary designs of battery technologies including specification of materials for different energy storage needs.
- Apply the knowledge to understand other emerging electrochemical technologies

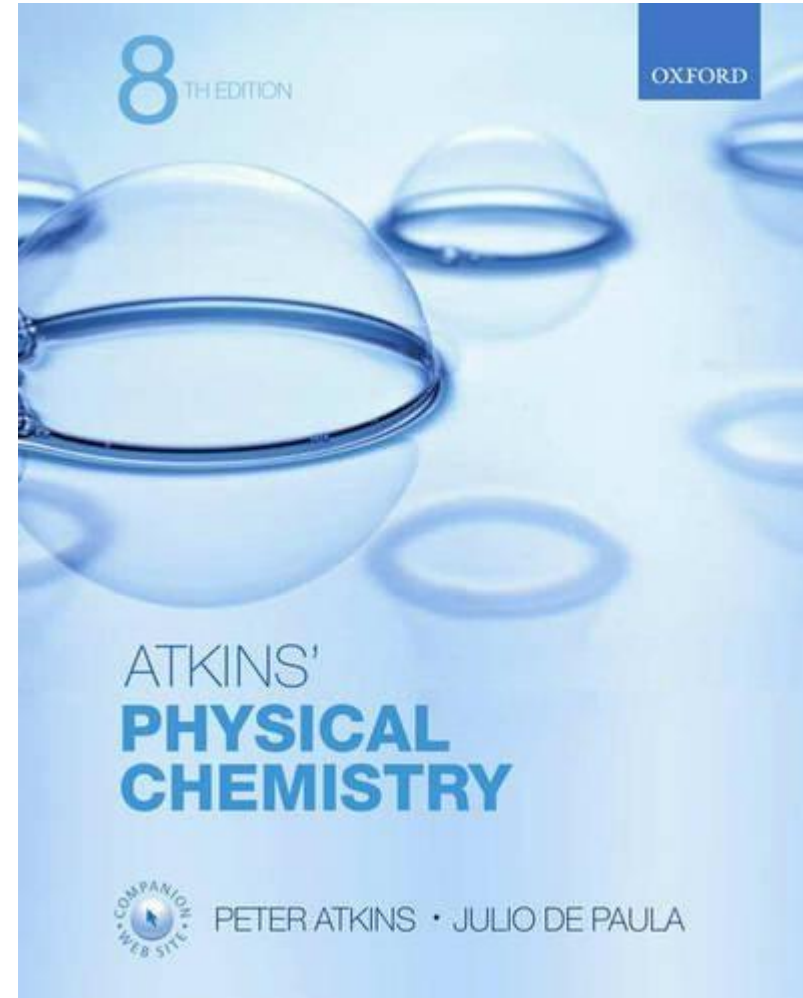
# Reference books

- Electrochemical methods: fundamentals and applications. Allen J. Bard, Larry R. Faulkner, 2<sup>nd</sup> edition, John Wiley & Sons, Inc. 2001
  - Hard copy available from Marriot Library
  - Electronic copay: contact TA
- Electrochemical Systems, John Newman, Karen E. Thomas-Alyea, 3rd edition, John Wiley & Sons, Inc. 2004
  - Electronic copy available from Marriot Library



# Reference books

- Atkins' Physical Chemistry, 8<sup>th</sup> edition
  - Electronic copay: contact TA
- Contact TA if need help to find the reference book.



- We will use equations and examples from these books.
- Notation or symbol of use may be slightly different
- I will try to make it clear whenever necessary

# Notations: Bard vs Newman

- Equations come from both Bard's book and Newman's book
  - For mass transport, we mostly use Newman's book
  - For kinetics, we mostly use Bard's book
- There are some slight differences in notations, but most are the same
  - Concentration: Newman uses  $c$ , Bard uses  $C$
  - Mobility: Newman uses velocity per force, Bard uses velocity per field strength
  - Subscript for species: Newman uses  $i$ , Bard uses  $j$
  - Electrostatic field: Newman uses  $\Phi$ , Bard uses  $\phi$
  - Flux: Newman uses  $N$ , Bard uses  $J$

# Course Structure

- 3 modules: electrochemical system, battery, emerging topics
- 12 lectures
- 2 labs (1 week each for lab and report)
  - Lab 1. Make an electrochemical cell
  - Lab 2. Make a Li-ion battery
  - TA will guide the lab
- 4 homework assignments
  - example problems in class
- 2 exams (take home exam, no final)
  - review session
  - example problems in class

# Grading

- Homework: 20% (5% each)
- Lab: 20% (10% each)
- Exam: 60% (30% each)
  
- Final Score
  - $\geq 90$  A(A-, A)
  - $\geq 80$  B (B-, B, B+)
  - $\geq 70$  C(C-, C, C+)
  - $\geq 60$  D.
  
- Last year
  - Average: 90.8 (A-)

# More about the content and grade

- I believe you are taking this course because you want to learn about electrochemical systems
  - The lecture notes are broad and, in some cases, deep
  - This may make it overwhelming, or even intimidating, especially if you are an undergrad
- However, since this is an elective course
  - The bar for homework and exams will be much lower than some of the course content
  - The average is A-, so you will be fine
- Try to enjoy the course and learn as much as you can, but don't be stressed about grade
  - I do not expect you can master everything in one elective course
  - But the materials can guide your through self-learnings if you want to learn more

# Office hour

- TBD
  - TA will send a poll later
- TA: Thomas Webb
  - Email: please see syllabus

# Introduction 1: why study battery technology?

# Content

- Why energy storage is important?
- The metrics to evaluate an energy storage technology
- Different types of energy storage technology

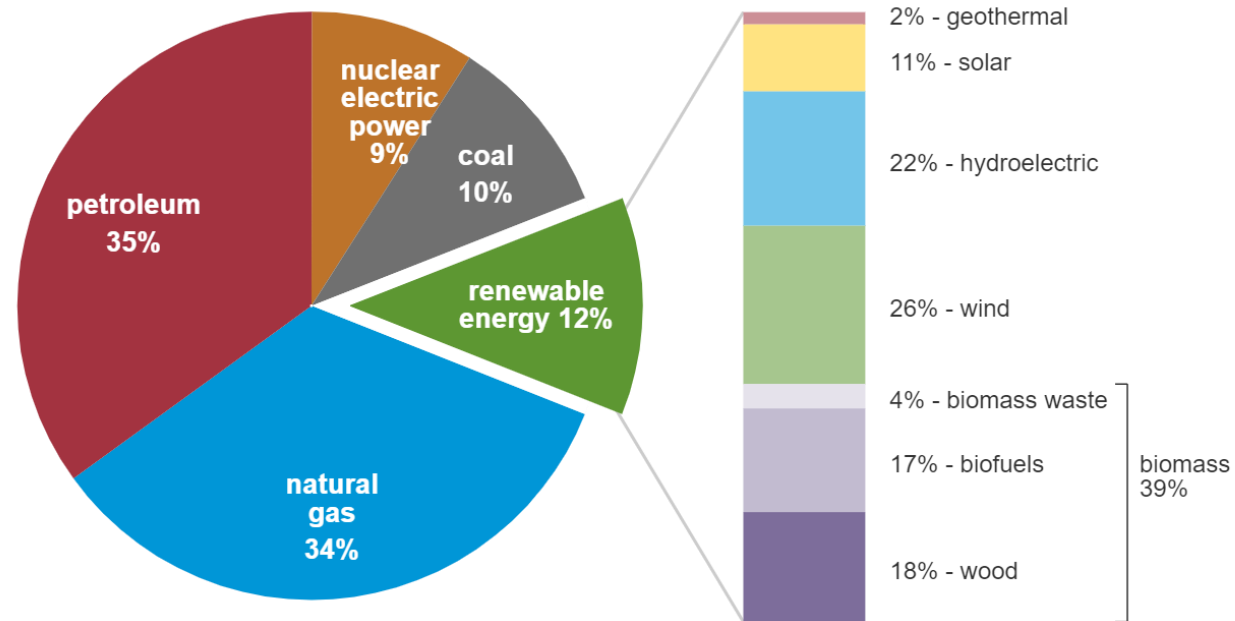
# We heavily rely on fossil fuel

In US, ~80% energy consumption comes from fossil

## U.S. primary energy consumption by energy source, 2020

total = 92.94 quadrillion  
British thermal units (Btu)

total = 11.59 quadrillion Btu

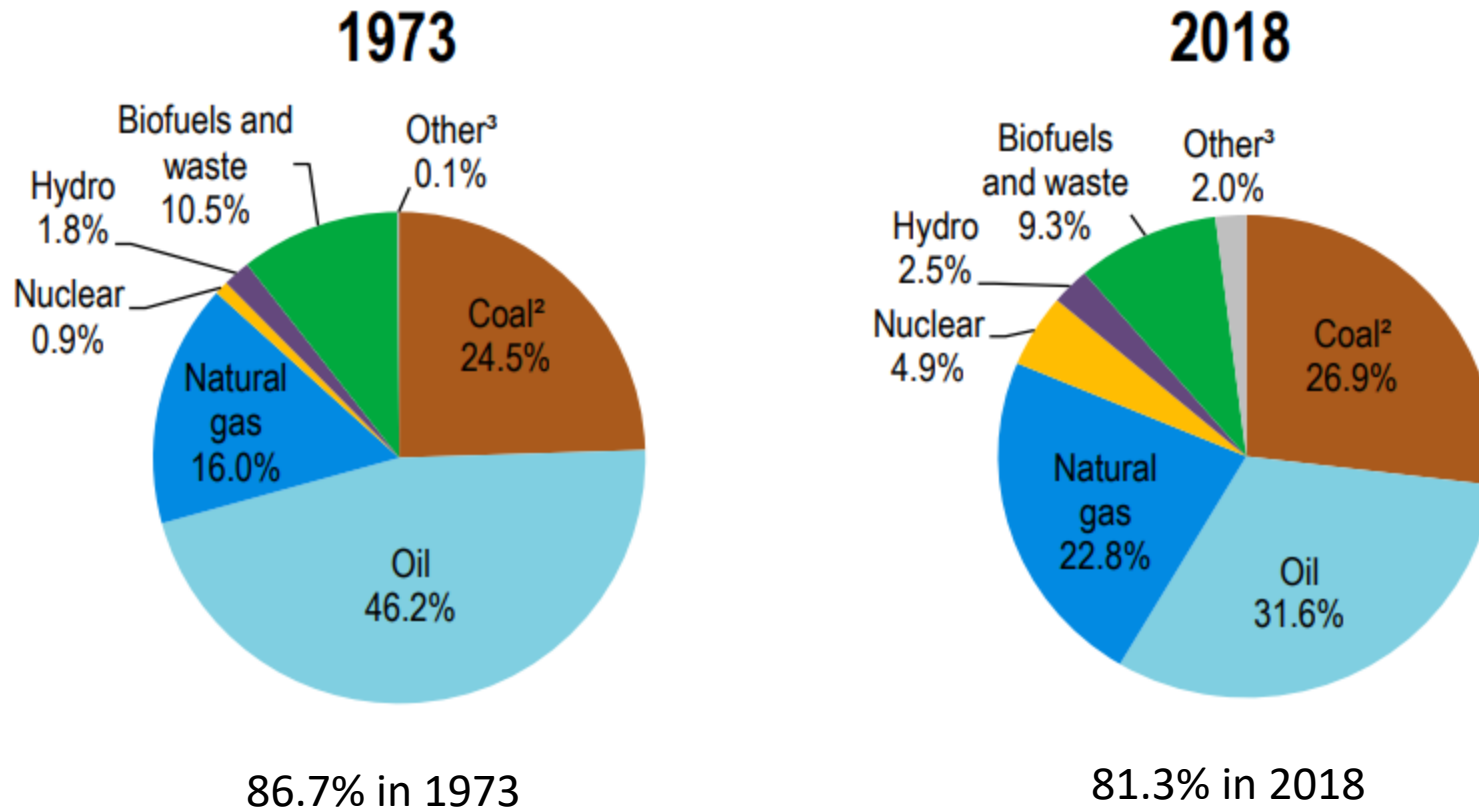


Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2021, preliminary data  
Note: Sum of components may not equal 100% because of independent rounding.



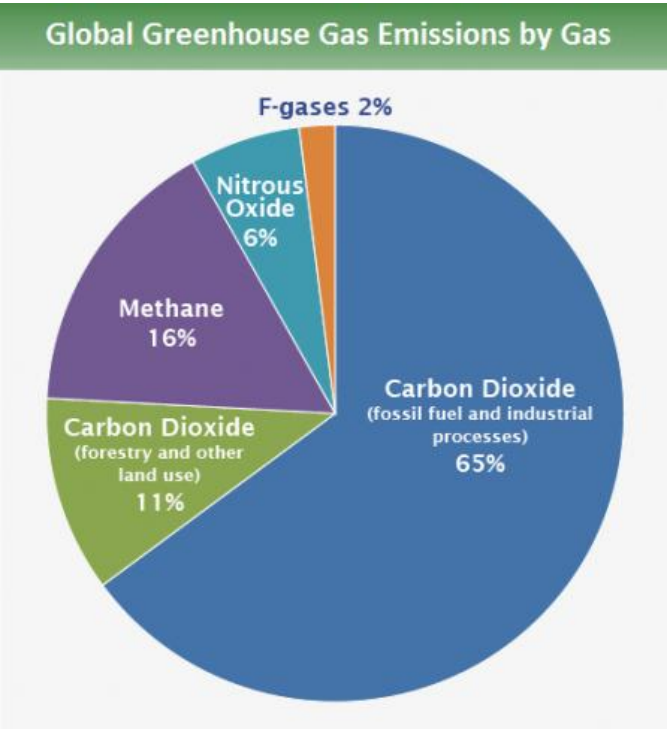
World-wide, ~82% energy consumption comes from fossil

## World-wide primary energy consumption by sources



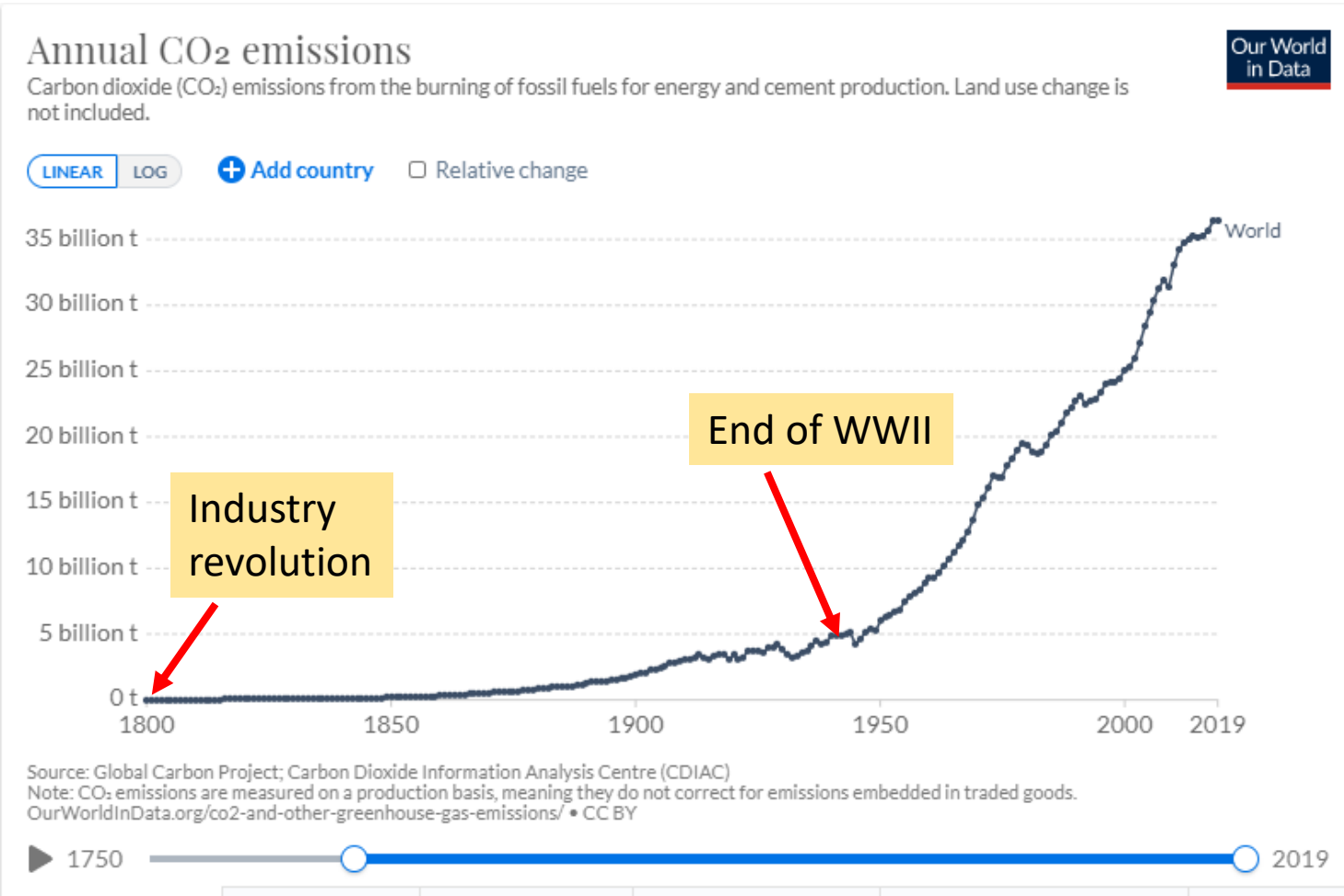
# ..., which generates huge amount of CO<sub>2</sub>

World-wide, CO<sub>2</sub> of fossil fuel accounts for 65% green house emission

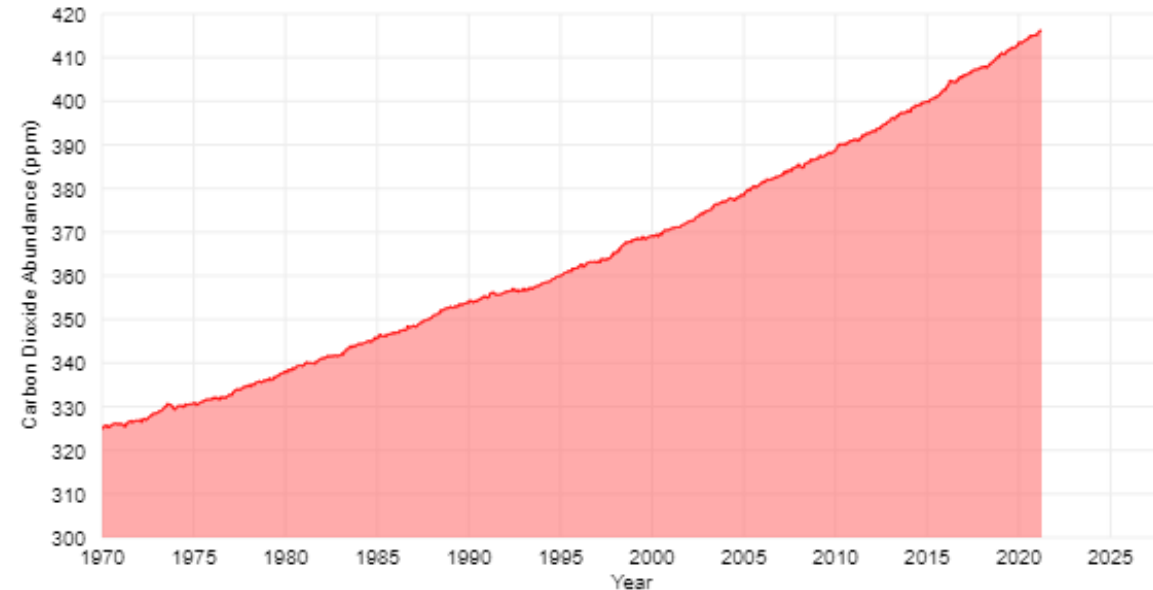
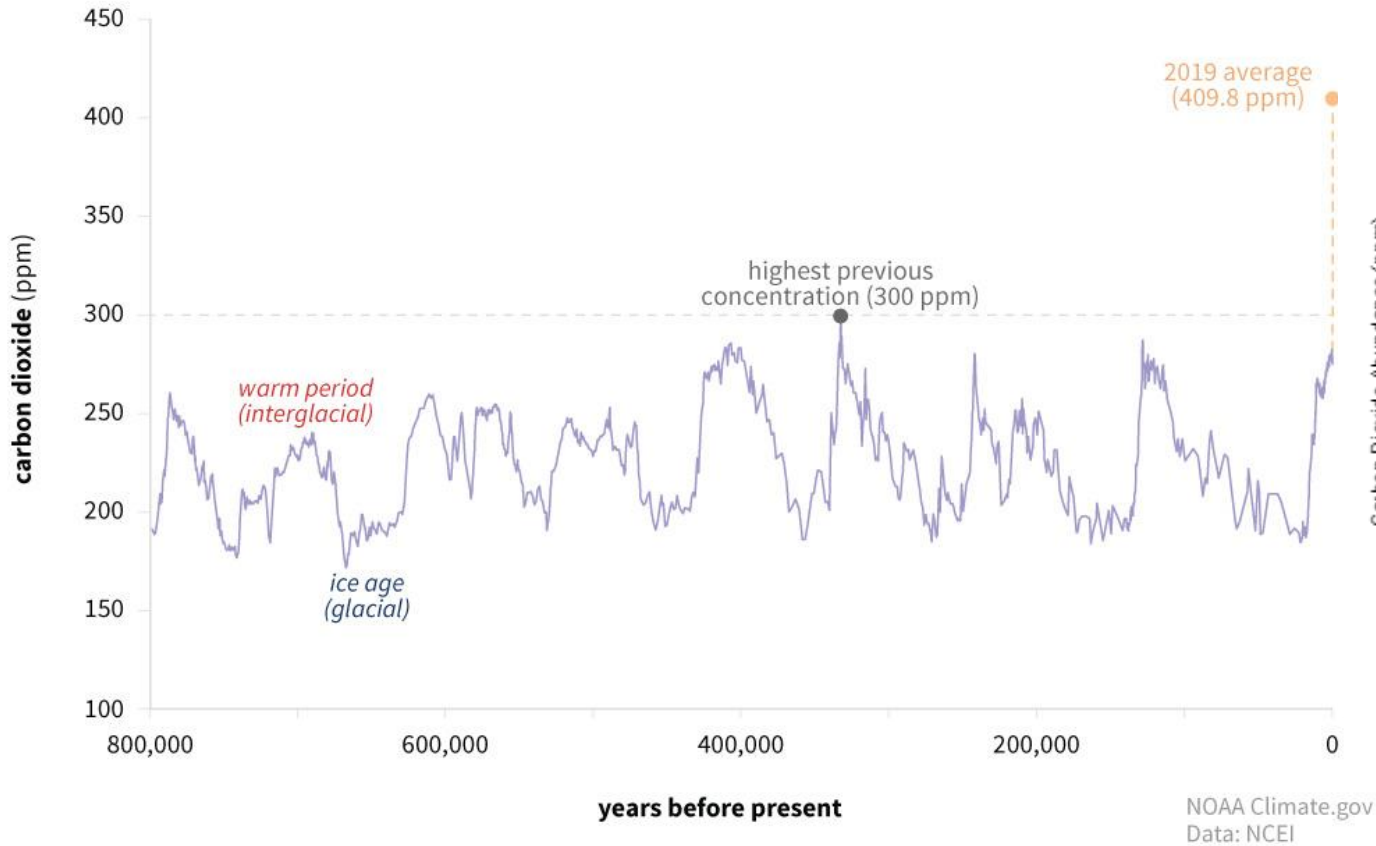


Source: [IPCC\(2014\)](#)

CO<sub>2</sub> emission significantly increases since industry revolution



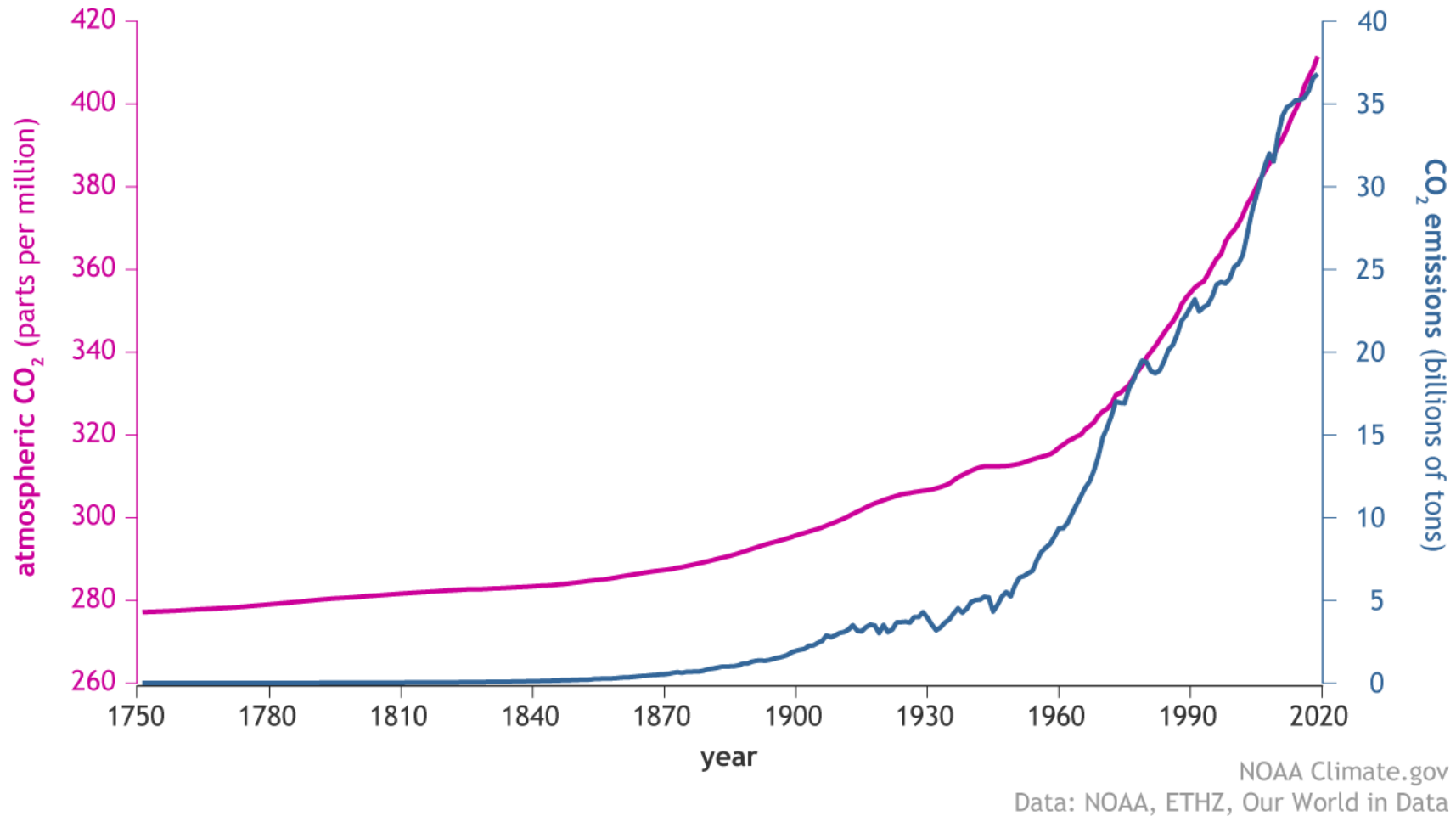
# CARBON DIOXIDE OVER 800,000 YEARS



CO2 level at historically high level, much higher than previous highest

## CO2 level in air correlated with CO2 emission

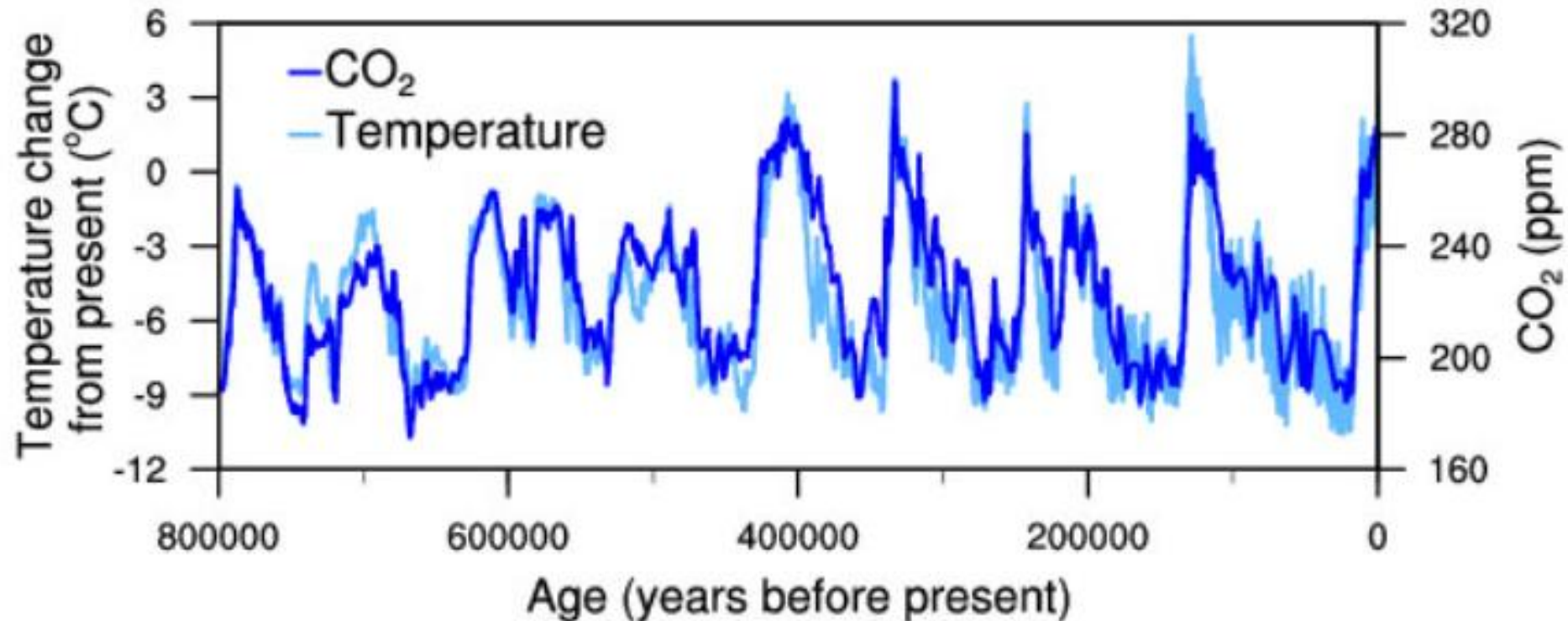
CO<sub>2</sub> in the atmosphere and annual emissions (1750-2019)



# ...,which leads to global warming

CO<sub>2</sub> absorbs infrared emit by earth surface

CO<sub>2</sub> level correlates with atmosphere temperature



- Earth's surface temperature has increased 1.18 Celsius since 1900s
- Ocean surface temperature has increased 0.33 Celsius since 1969

# ... and climate change

- The effect is astounding!


## Year of 2021

 The Guardian  
**'Potentially the worst drought in 1,200 years': scientists on the scorching US heatwave**  
The heatwave gripping the US west is simultaneously breaking hundreds of temperature records, exacerbating a historic drought and priming ...  
3 days ago




 Todayuknews  
**Europe Looks For Solutions As It Grapples With Catastrophic Wildfires - Todayuknews**  
As wildfires ravage the Mediterranean region, many have asked if such blazes are an inescapable part of global warming or whether steps can ...  
1 day ago




 Fox 13  
**Salt Lake City breaks historic temperature records; it'll only get hotter**  
The National Weather Service says that many years never see temperatures reaching 103 degrees. As of 4:44 PM Salt Lake City Airport has ...  
1 week ago




 Mississippi Today  
**Photos: Historic rainfall floods homes across north Mississippi**  
"One observer measured slightly over 20 inches of rain in the last three days," Andy Sniezak, National Weather Service meteorologist in Memphis ...  
1 week ago



 Time Magazine  
**The Biggest Wildfire in Californian History Is Still Growing**  
The Dixie Fire is the largest single fire in California history and the largest currently burning in the U.S. It is about half the size of ...  
1 week ago



 Yale Climate Connections  
**Extreme rainfall in China: over 25 inches falls in 24 hours, leaving 33 dead**  
Zhengzhou received more than a year's worth of rain on July 20.  
1 month ago



# Wildfire

## Year of 2021



The Dixie Fire burns on a mountain ridge sending embers into the air on August 5, 2021 in Greenville, California. Trevor Bexon/Getty Images



A huge forest fire in the Avila region last weekend means that this season bucked the recent trend in Spain where fires have declined © Cesar Manso/AFP/Getty

# Canada wildfires

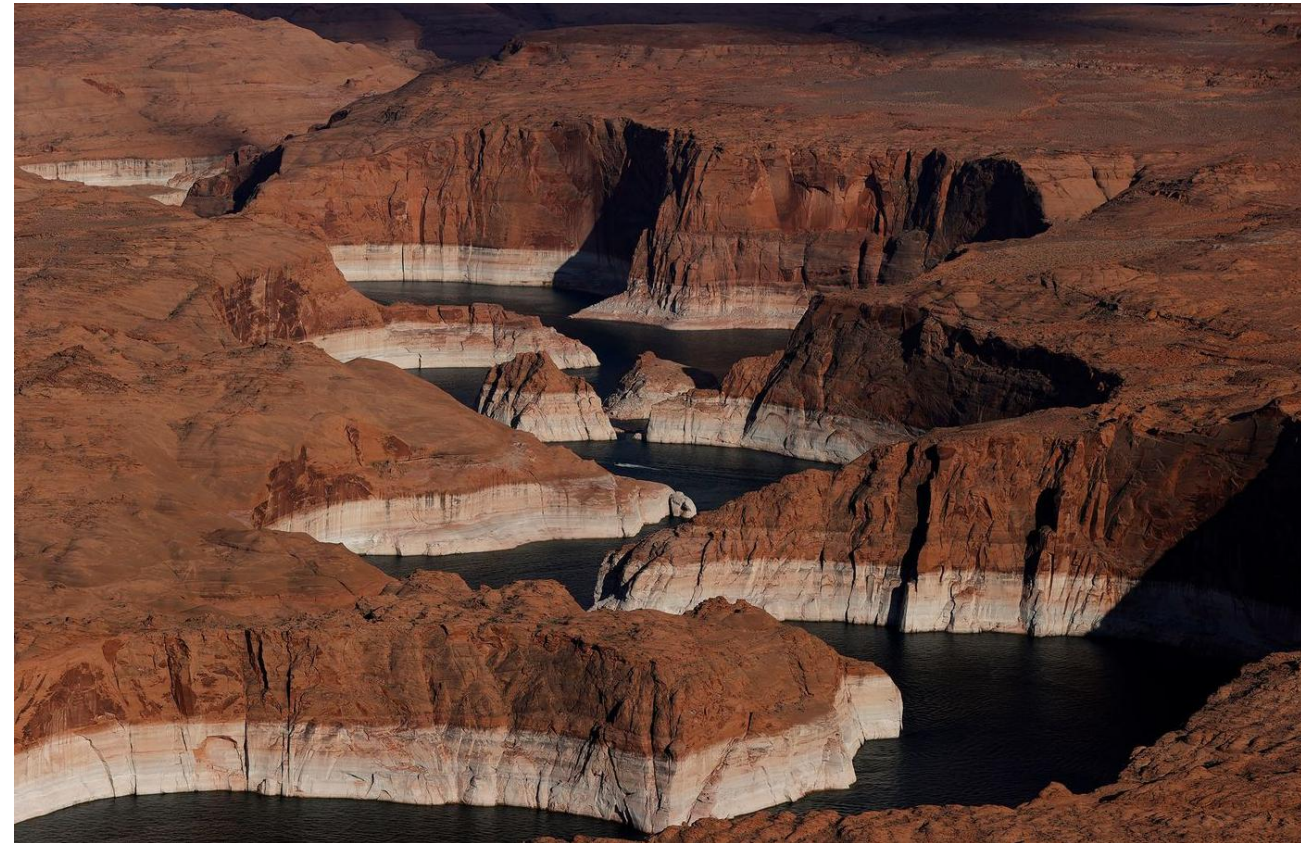
Year of 2023

-  Out of Control (671)
-  Being Held (160)
-  Under Control (219)



# Drought

Year of 2021



# Great Salt Lake water levels dropping dangerously low again

Jul 29, 2025, 11:45 AM | Updated: 4:25 pm

## *The Great Salt Lake Is Drying. Can Utah Save It?*

The loss of the Great Salt Lake would be an environmental disaster with health and economic effects far beyond Utah's borders. The state is taking action, but critics say it's not doing

enough.

# Flood


Year of 2021



Severe flooding in Tennessee has left at least 10 people dead in Humphreys County.



▲ Rescuers evacuate a child from a flooded area after heavy rains in Suizhou, in China's central Hubei province.  
Photograph: CNS/AFP/Getty Images



Year of 2023

In the wake of Typhoon Doksuri, extreme rain has battered the north, breaking a 140-year rainfall record in Beijing.

5/10/2026

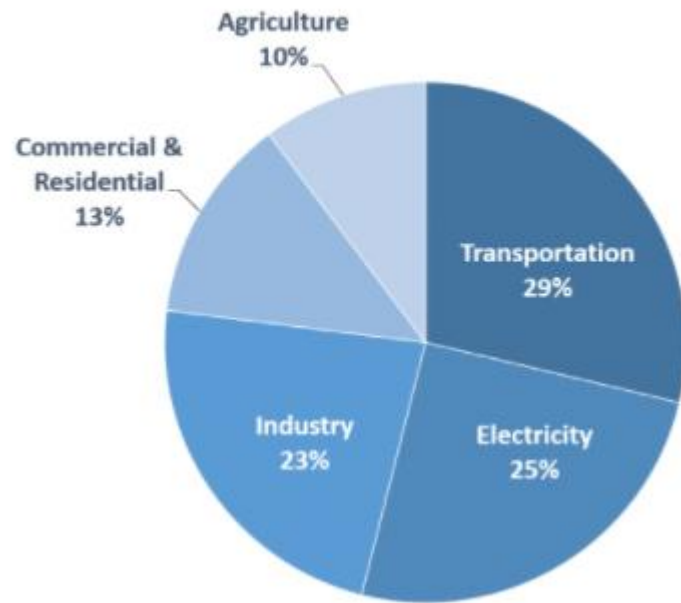
CH EN 5308/6308 Battery Technology and Manufacturing  
@Gao University of Utah

A flooded village after heavy rains in Zhuozhou, Baoding city in northern China's Hebei province [ Jade

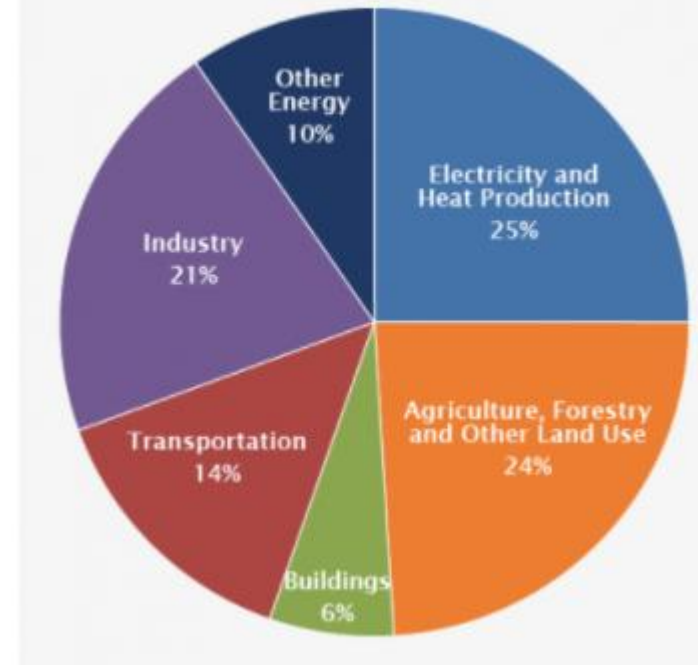
# Transportation, electricity generation and industry produce the most CO<sub>2</sub>

- In US, electricity and transportation accounts for 54% of greenhouse emission
- Globally, they account for 39%

Total U.S. Greenhouse Gas Emissions  
by Economic Sector in 2019



Global Greenhouse Gas Emissions  
by Economic Sector

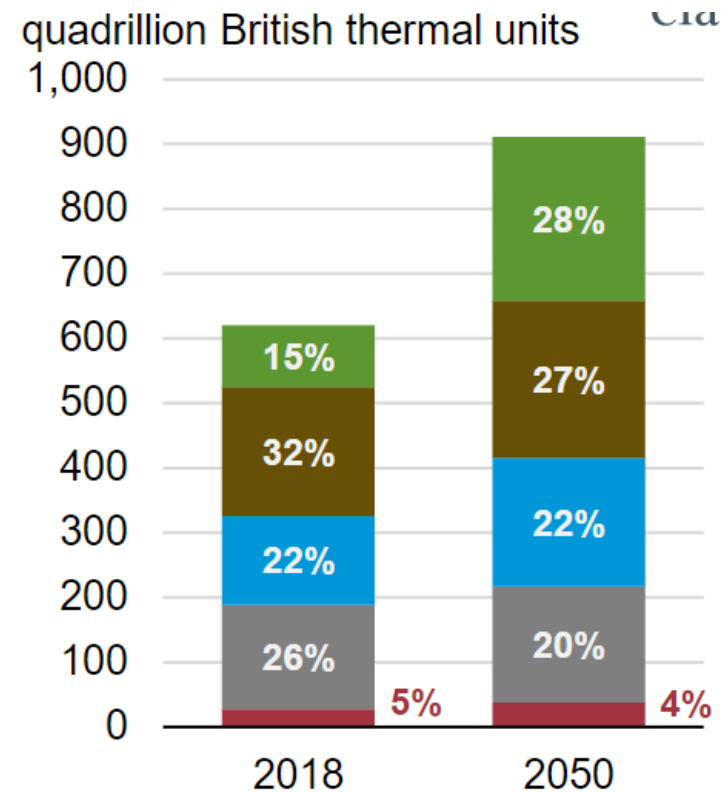
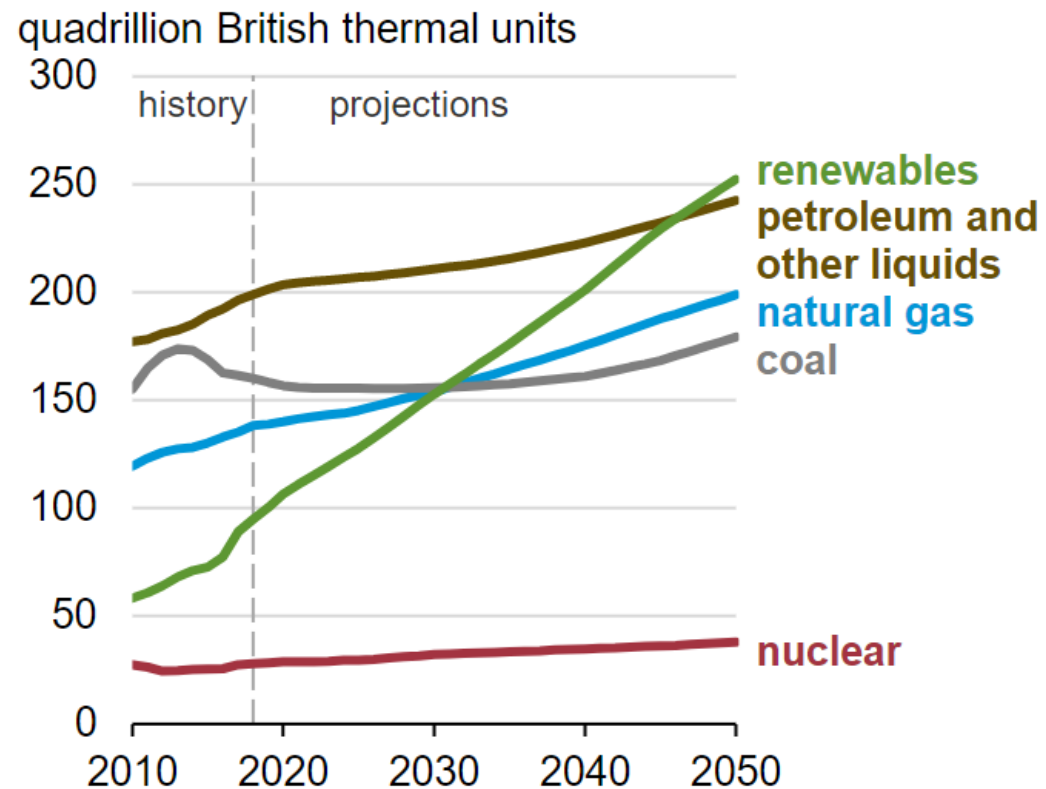


Source: [IPCC \(2014\)](#);

# Renewable energy will double by 2050

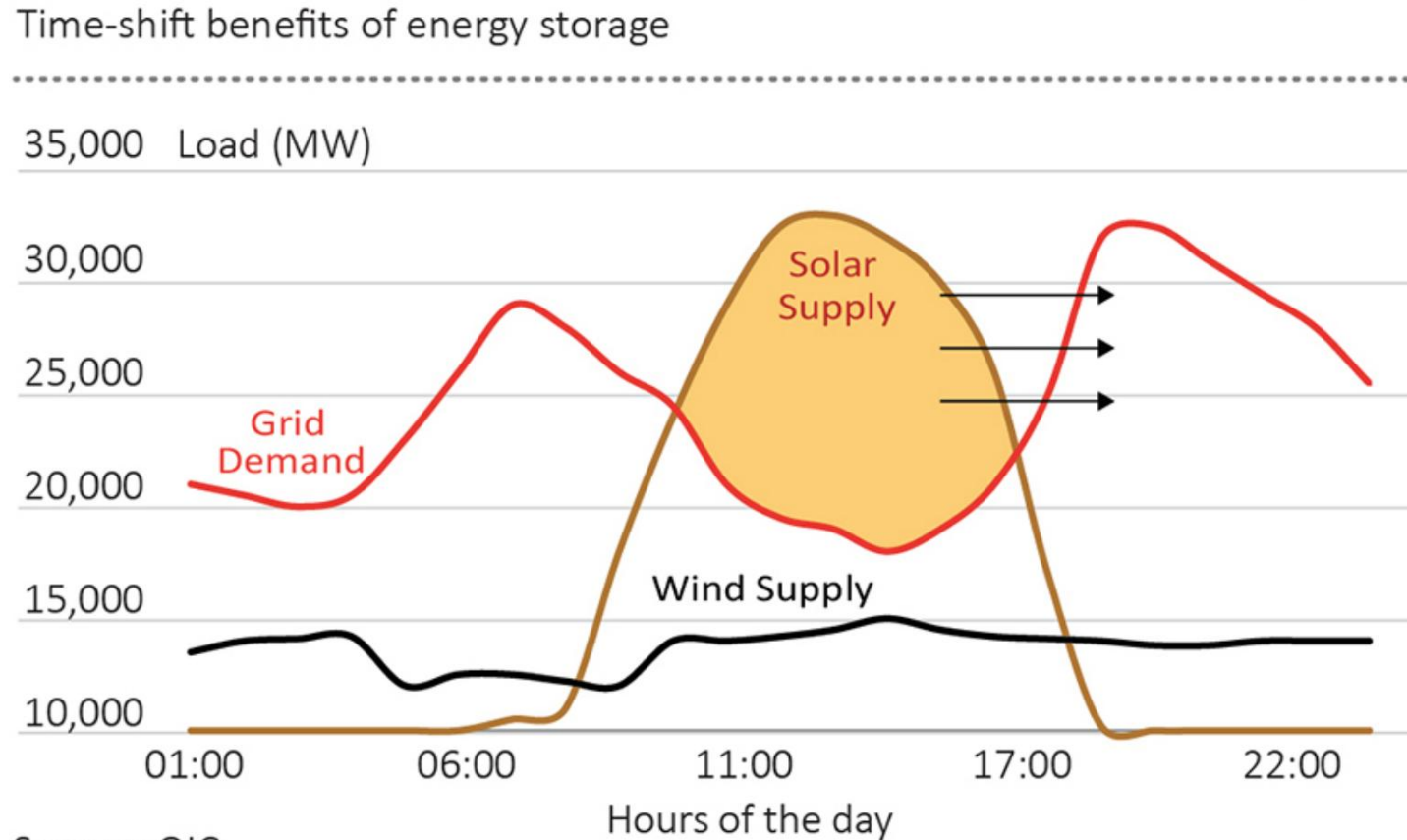
- Fast growing renewable energy

## World electricity generation



# The challenge of renewable energy: intermittency

- Energy storage is required to buff the intermittency of solar and wind



# The rise of EVs to de-carbonize our transportation



Climate Change Dec 11, 2019

## A fully electric aircraft has just made its first commercial flight



Sarasota Herald-Tribune

## 'Tesla of the sea': Swedish electric boat company sets logistics base in Sarasota with plans for growth

Swedish boat maker X Shore has shipped two Eelex 8000 electric boats to Sarasota as it. The company is still fairly small, with less than 60 full- ...  
1 day ago



Reuters

## U.S. automakers to say they aspire to up to 50% of EV sales by 2030 -sources

Detroit's Big Three automakers plan to announce on Thursday that they aspire to have 40% to 50% of new vehicle sales by 2030 be electric ...  
2 weeks ago



# The rise of EVs to de-carbonize our transportation

Year of 2021



**Britain to ban sale of all diesel and petrol cars and vans from 2040**



**France set to ban sale of petrol and diesel vehicles by 2040**

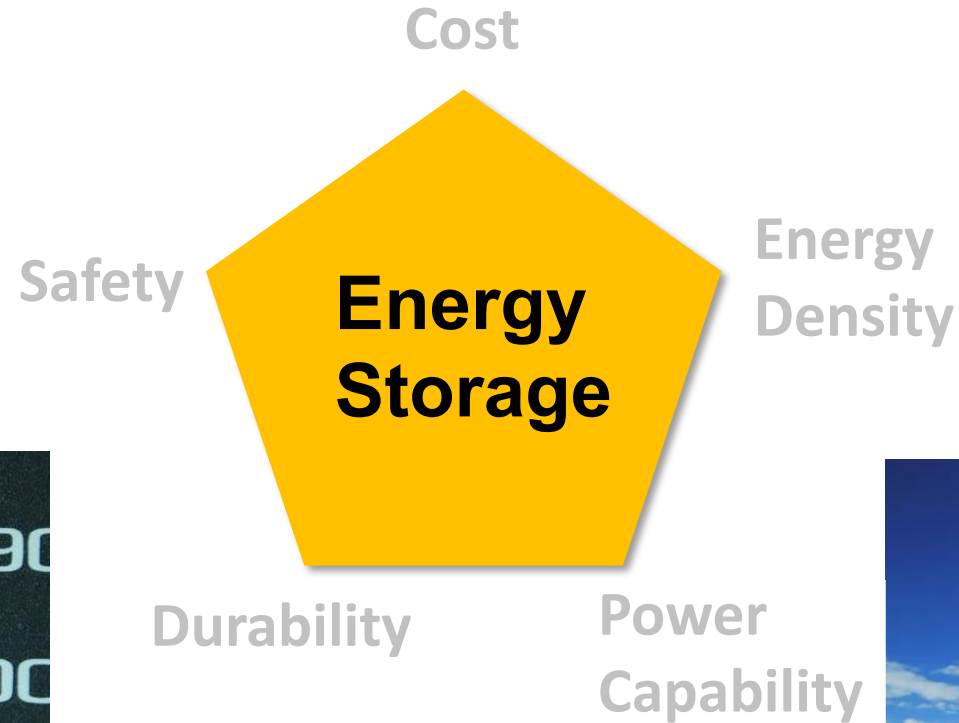


**China to ban petrol and diesel cars, state media reports**

# Summary

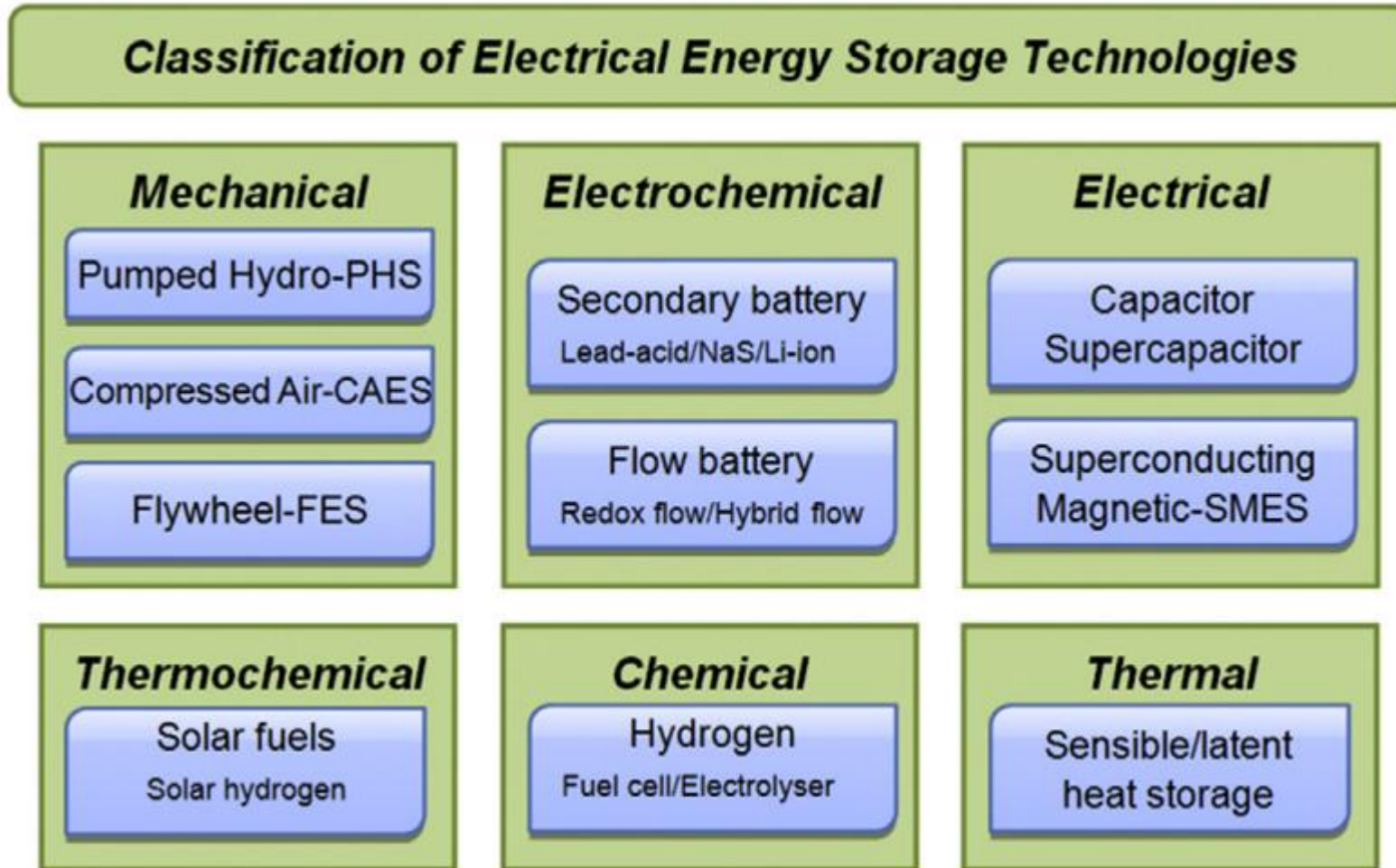
- Currently, we are heavily relying on fossil fuel to power human society
  - Transportation: ground, sea, air
  - Electricity generation
  - Industry: fuel, chemicals, fertilizers etc.
- However, CO<sub>2</sub> emission and climate change pose serious threat to human civilization
- Renewable energy, electric transportation and industry electrification are important measures to address these challenges
  - Renewable energy: solar, wind, etc.
  - Electric transportation: electric vehicles, airplanes etc.
  - Electrifying our industry: cement, iron and steel, chemical, etc.
- High-performance and low-cost energy storage technologies are critical to enable renewable energy and electric transportation

# Key performance metrics of energy storage technologies



source: top gear

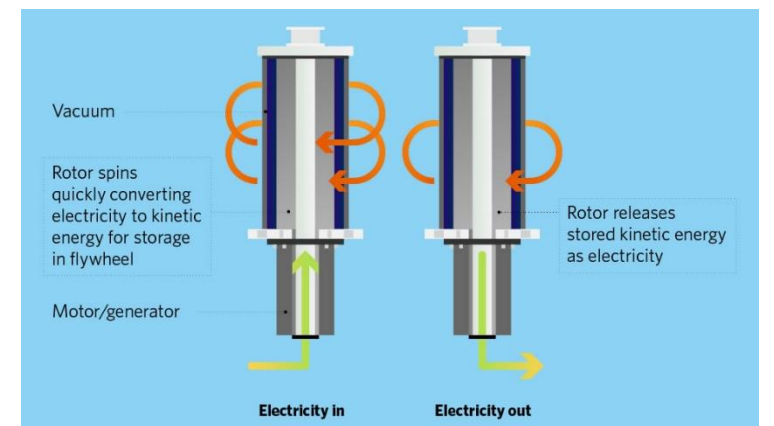
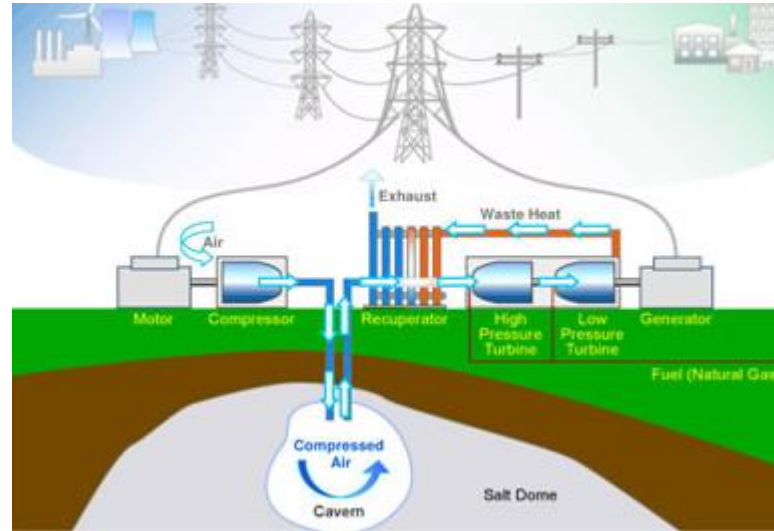
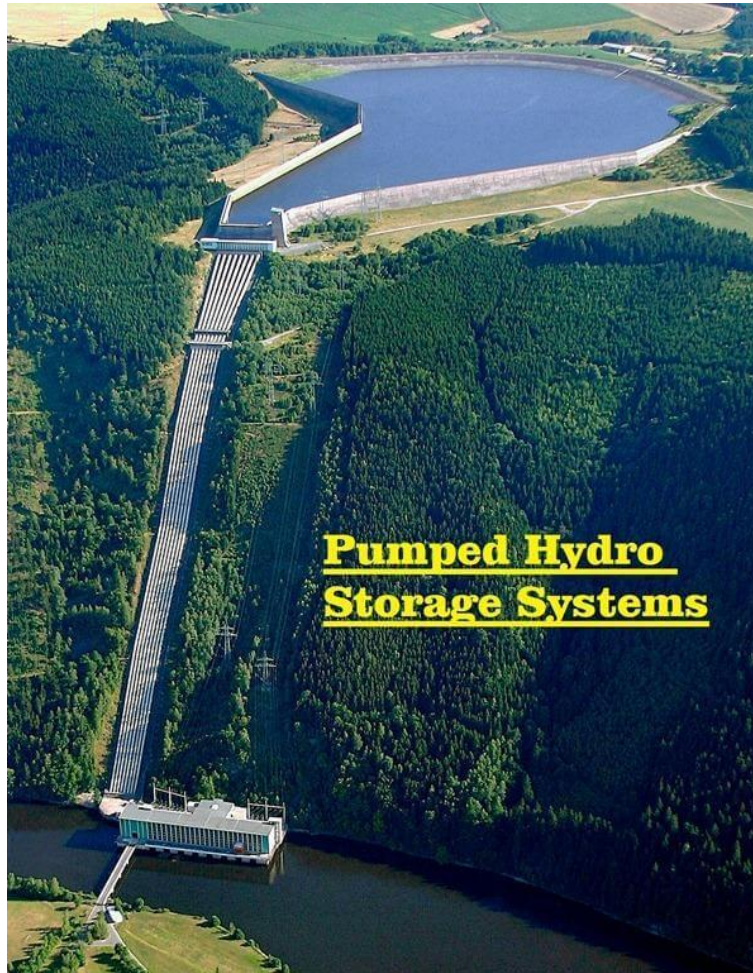
# Different types of energy storage technologies



X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, 2015, doi: 10.1016/j.apenergy.2014.09.081.

5/10/2026

# Mechanical



# Electrochemical



X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, 2015, doi: 10.1016/j.apenergy.2014.09.081

# Chemical

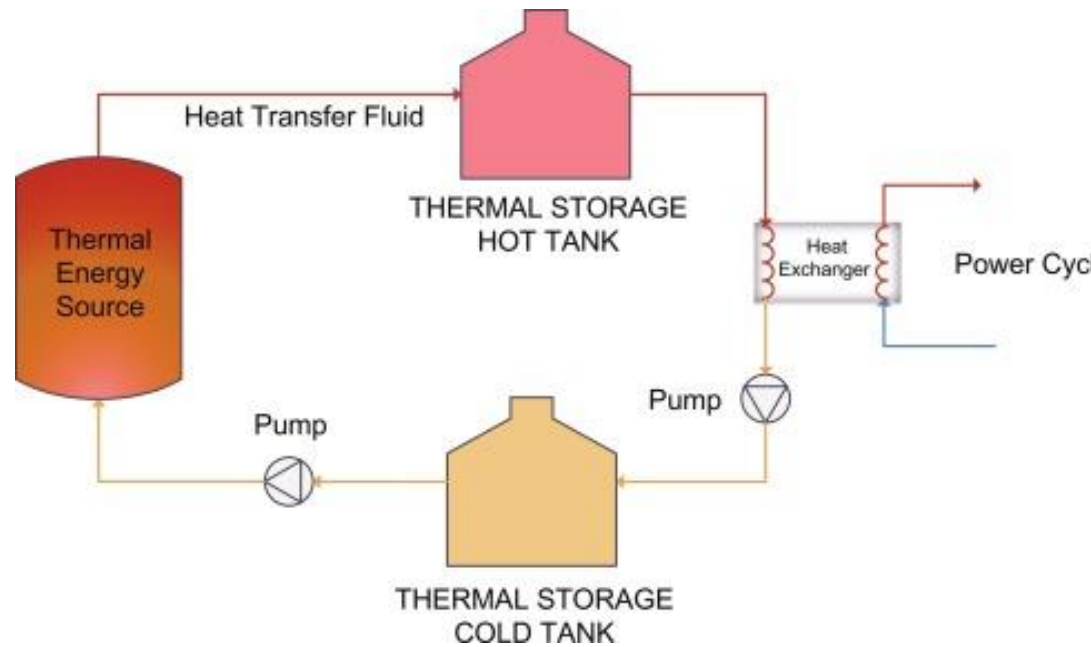
## Electrolyzer



- Energy stored in the chemical bonds of fuels, hydrogen, etc.
- Requires energy conversion technology to convert primary or secondary energy into these chemicals
  - Hydrogen: can come from primary (methane) or secondary energy (electricity)

X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, 2015, doi: 10.1016/j.apenergy.2014.09.081.

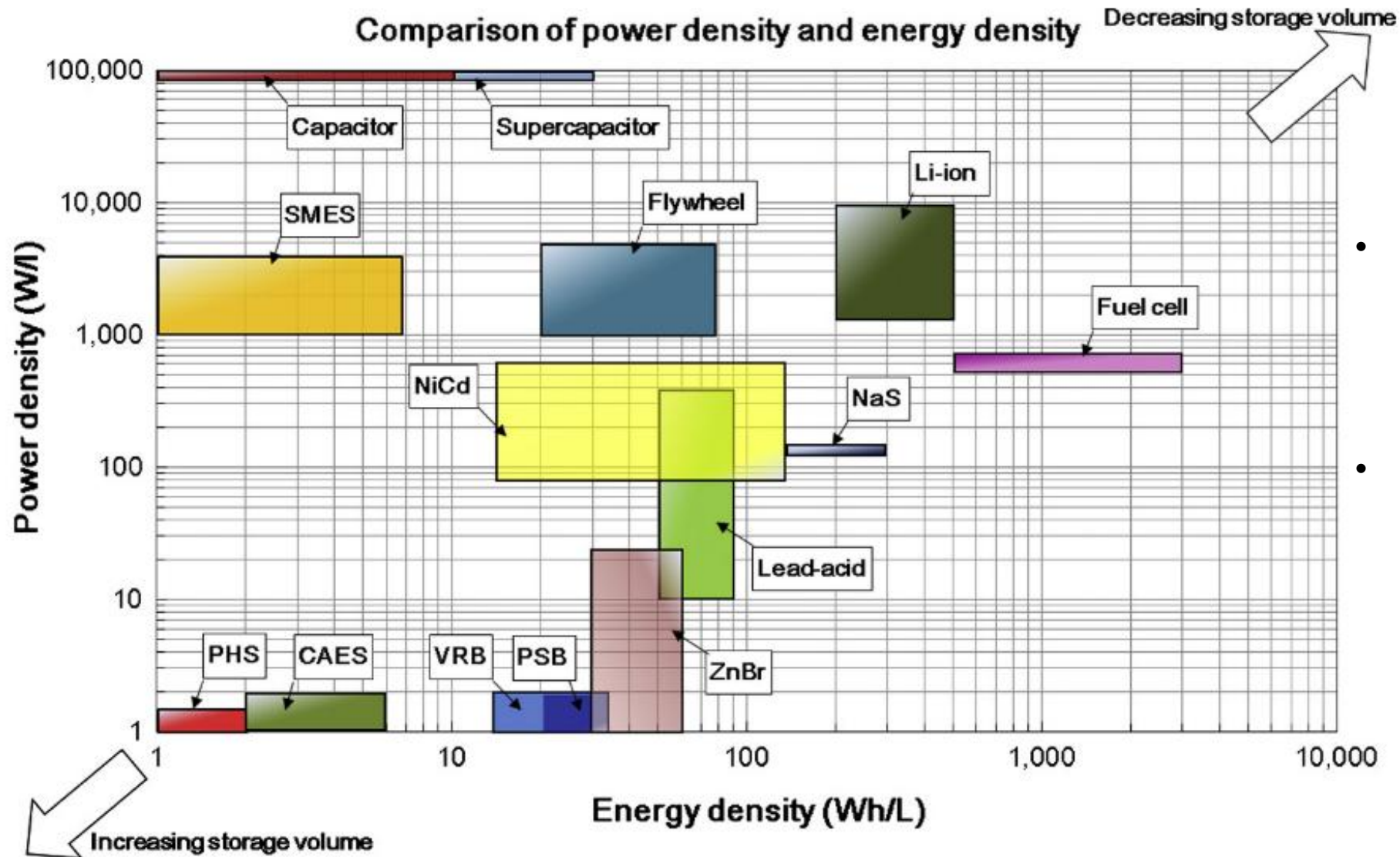
# Thermal



X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, 2015, doi: 10.1016/j.apenergy.2014.09.081.



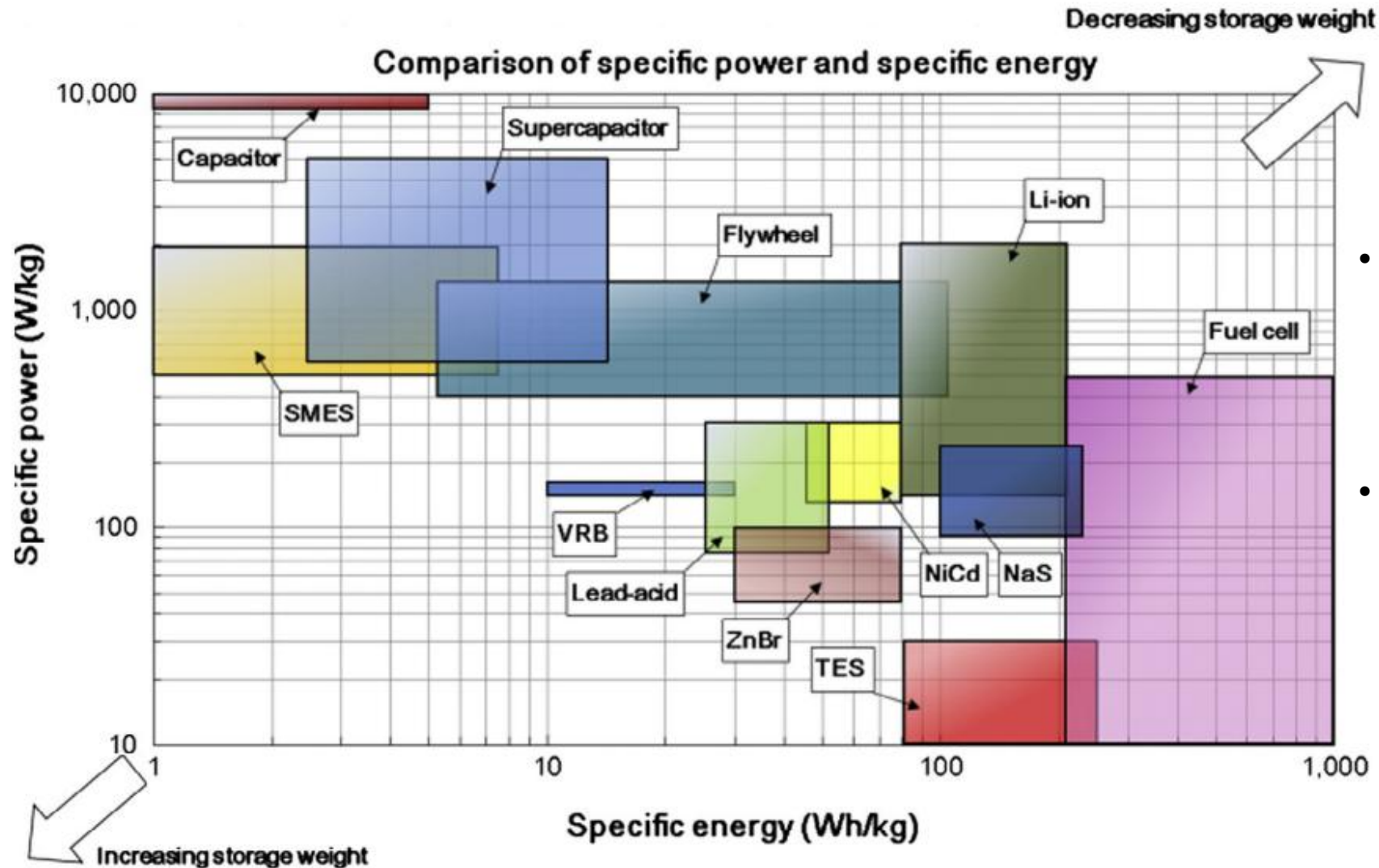
# Comparison of energy/power density



- Right-top corner: suitable for volume-limited applications
  - Including Li-ion, fuel cell
  - Vehicle, plane, consumer electronics
- Left-bottom corner: suitable for stationary application
  - PHS, CAES, VRB, PSB, ZnBr

**Fig. 14.** Comparison of energy density and power density.

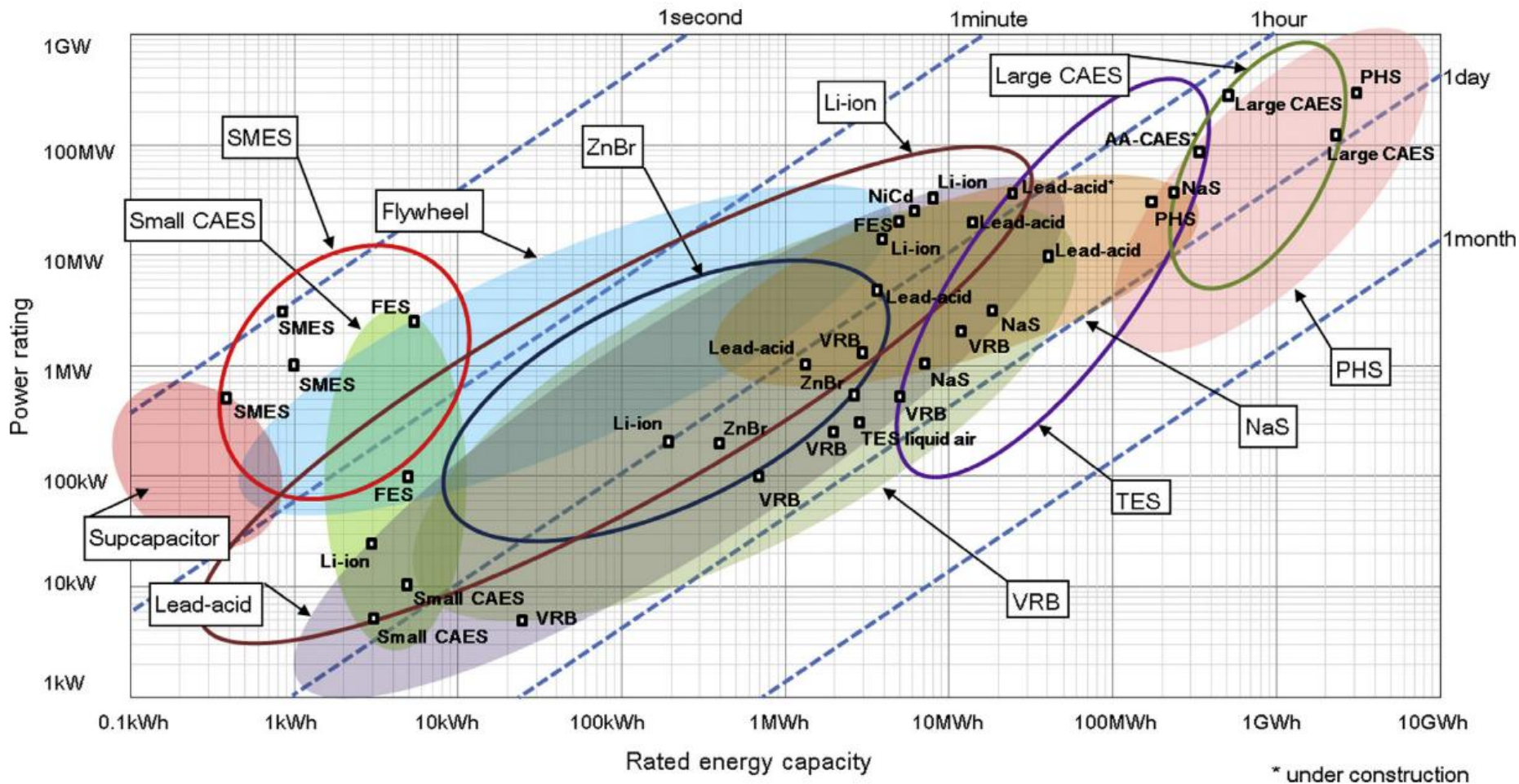
# Comparison of specific energy/power



- right-top corner: suitable for light-weight applications
  - Including Li-ion, fuel cell
  - Vehicle, plane, consumer electronics
- Left-bottom corner: suitable for stationary application
  - VRB, PSB, ZnBr, lead-acid

Fig. 15. Comparison of specific energy and specific power  
© EN 5368/308 Battery Technology and Manufacturing  
@Gao University of Utah

# Comparison of power/energy rating



Discharge: 1 hour – 1day

- Li-ion
- ZnBr, NaS, Lead-acid, VRB
- PHS, TES

Discharge > 1 day

- VRB
- TES, PHS, large CAES
- Solar fuel

Time=energy/power

# Summary

- There are many different energy storage technologies, suitable for different applications
  - Medical device: compact, non-toxic
  - Consumer electronics and robots: compact
  - Transportation: compact, light-weight
  - Stationary: low-cost
- Electrochemical energy storage are versatile in terms of power and energy
  - Non-flow batteries: Pb-acid, Ni-Cd, Li-ion, Na-S
  - Flow batteries: VRB, Zn-Br, etc.
- For transportation application (vehicle, planes)
  - Li-ion batteries are dominating
  - Pb-acid, Na-ion batteries for light-duty vehicles
- For stationary applications
  - Pumped hydro and compressed air are cheap but has geographic restrictions and environmental footprints.
  - Li-ion, Na-ion and etc. are promising for small-scale application (household)
  - Flow batteries are promising for large-scale application

# Quiz 1

Which of the following applications does not belong to electrochemical system?

- A. Pt-acid battery
- B. Glucose sensor
- C. Hot rubber water bag
- D. Electrolysis of water to produce hydrogen

# Quiz 2

Why can energy storage technology help combat climate change challenge?

- A. Decarbonizing transportation sector needs battery to power EVs
- B. Energy storage technology reduces our energy demand
- C. Renewable energy source like solar energy is intermittent

# Quiz 3

Which energy storage technology are suitable for volume-limited and light-weight applications?

- **A.** Li-ion batteries
- **B.** Fuel cells
- **C.** VRB (vanadium flow batteries)
- **D.** ZnBr

# Quiz 4

Which energy storage technologies below are best for discharge duration of > 1 day?

- **A.** Li-ion batteries
- **B.** VRB (vanadium flow batteries)
- **C.** fly wheel
- **D.** none of the above

# Supplementary material

# Climate 101

[https://youtu.be/G4H1N\\_yXBiA](https://youtu.be/G4H1N_yXBiA)



Electric vehicle vs gas vehicle  
Tesla Model 3 vs BMW 3

