

Plant capacity by power source



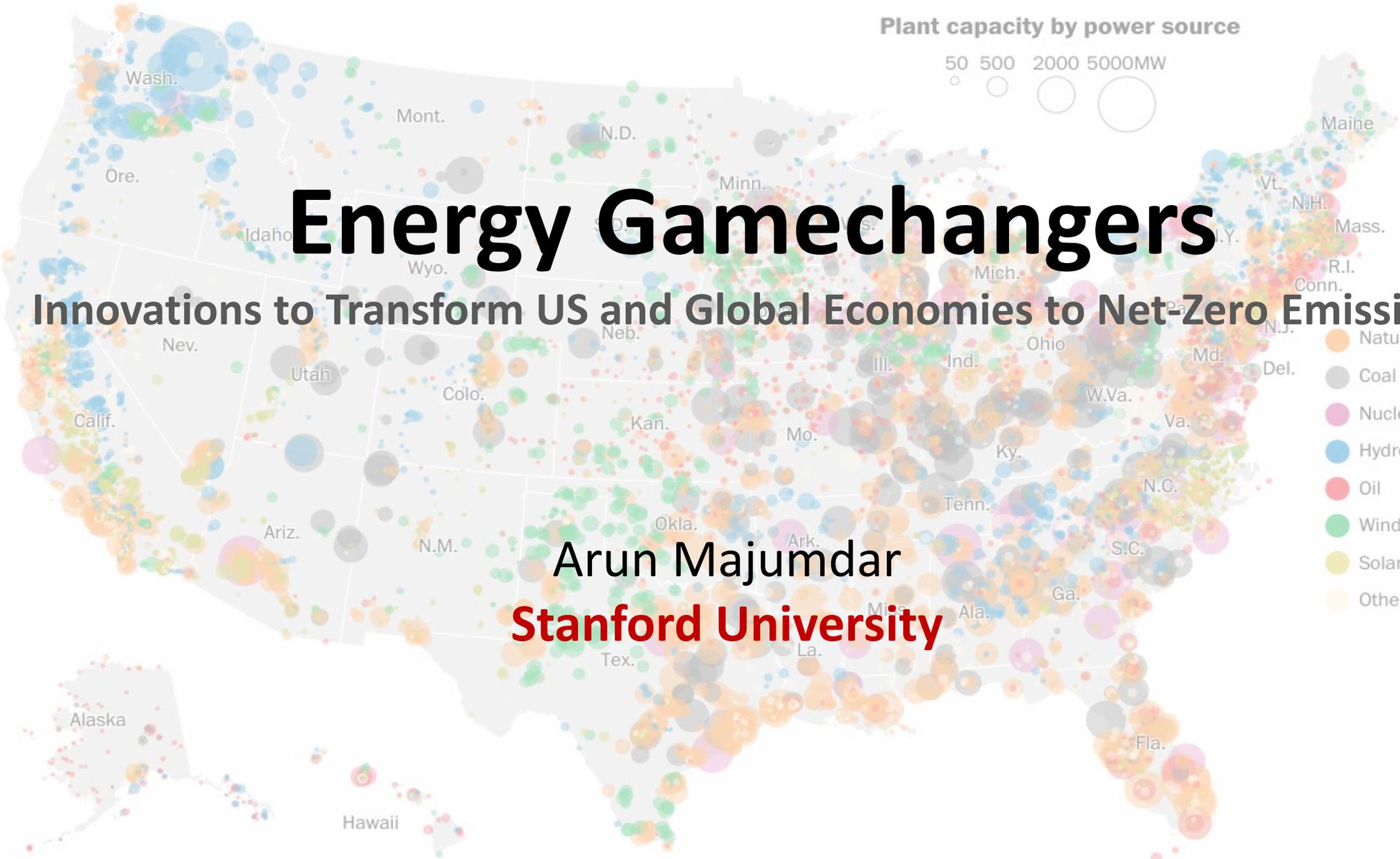
# Energy Gamechangers

Innovations to Transform US and Global Economies to Net-Zero Emissions

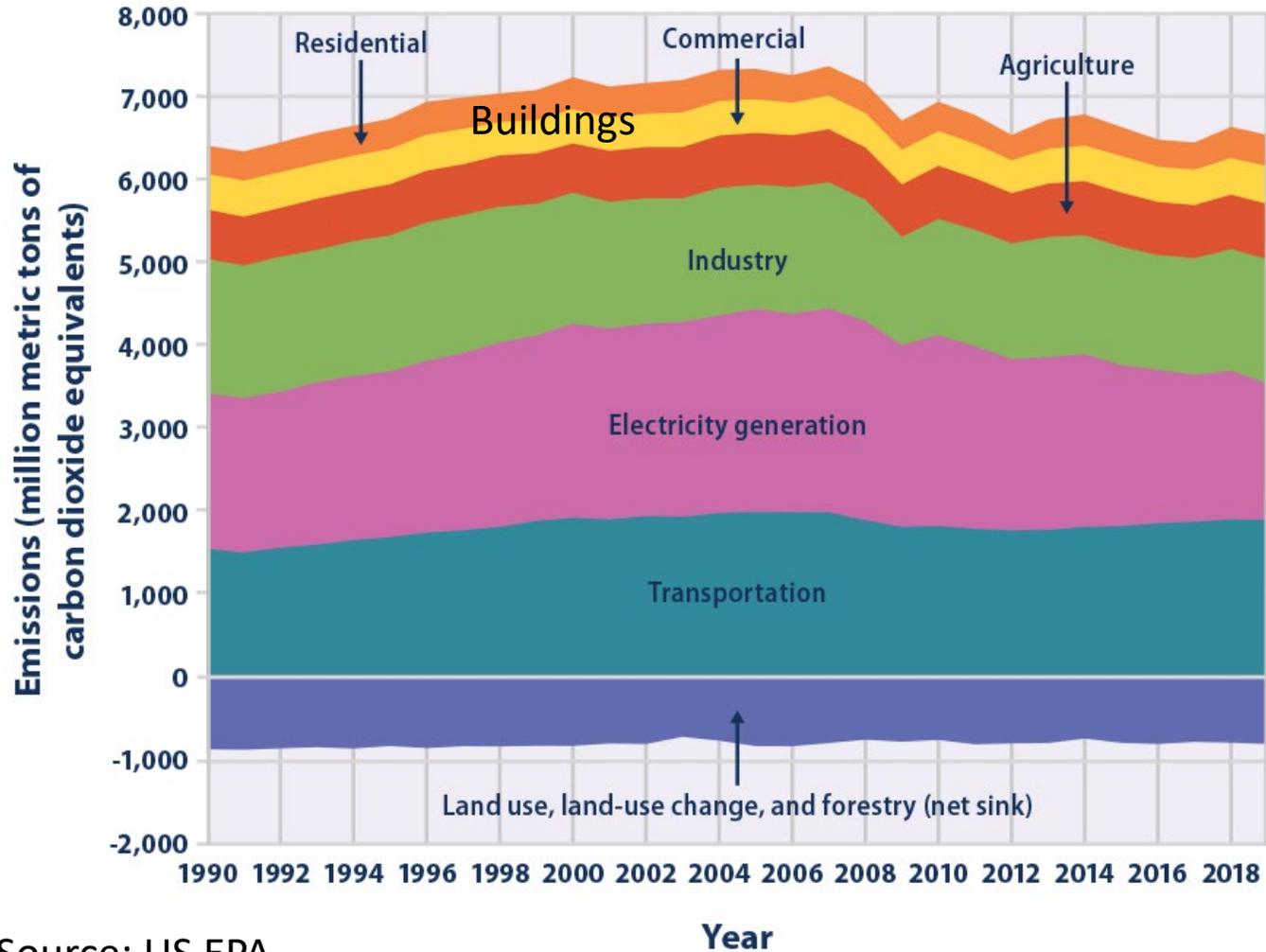
Arun Majumdar

Stanford University

- Natural Gas
- Coal
- Nuclear
- Hydroelectric
- Oil
- Wind
- Solar
- Other



# US Goals



**Equity & Environmental Justice**  
**Clean Energy Jobs**

100% Carbon-Free Electricity

80% Clean Electricity

2030

2035

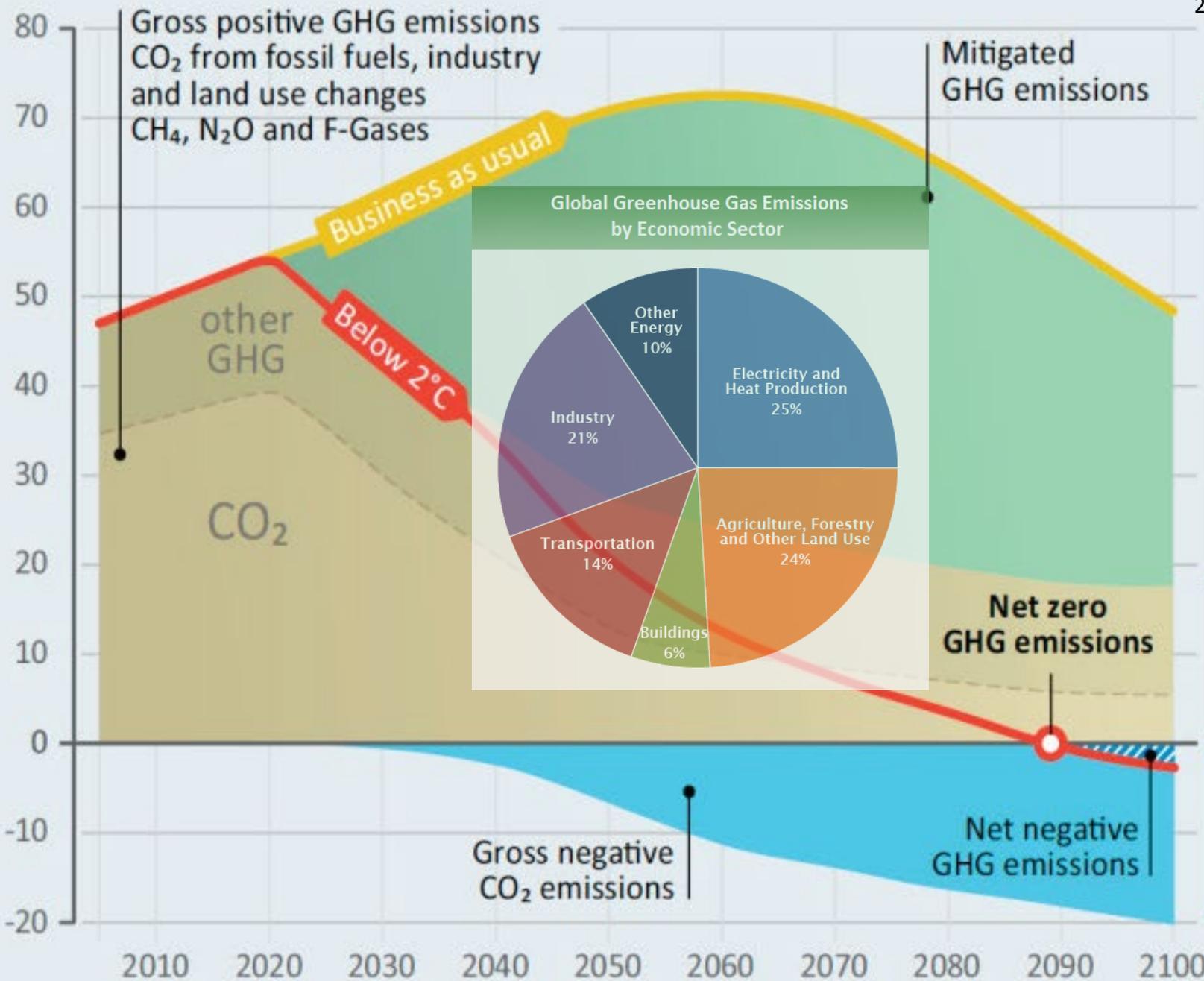
2050

Source: US EPA

# GHG emissions (GtCO<sub>2</sub>e/year)

## GLOBAL

Gasser, T., Guivarch, C., Tachiiri, K., Jones, C.D. and Ciais, P., 2015. Negative emissions physically needed to keep global warming below 2 C. *Nature communications*, 6(1), pp.1-7.



### Examples of associated technologies

**Conventional abatement technologies**

**Emitting technologies**

**Carbon removal technologies**

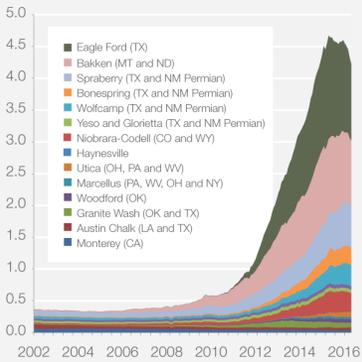
# Energy Breakthroughs

## Unconventional Gas



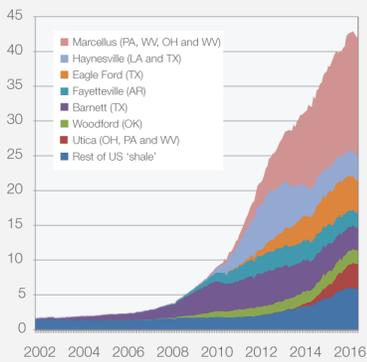
This change is driven by production from unconventional reserves using fracking and horizontal drilling.

Shale And Tight Oil Production  
million barrels per day

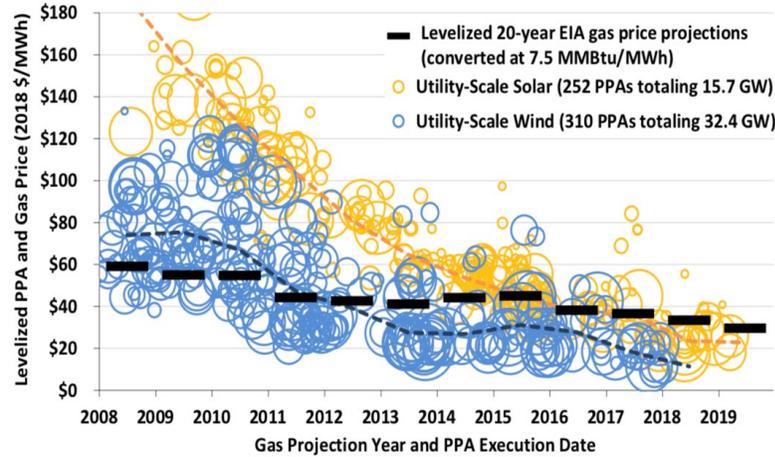


Source: EIA.

Dry Shale Gas Production  
billion cubic feet per day



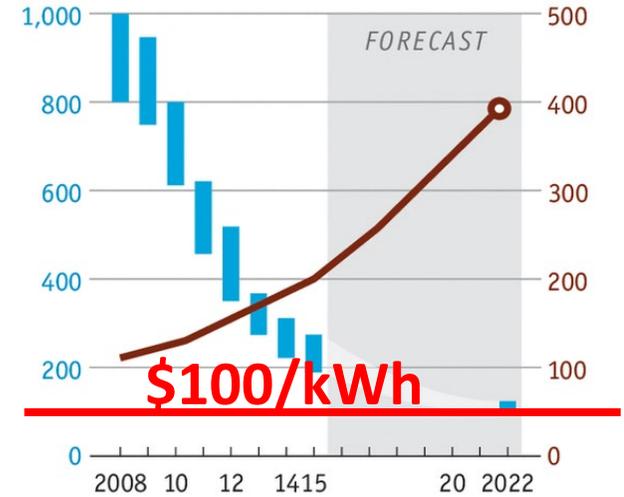
## Renewable Electricity



## Battery Electric Vehicles



Battery cost  
Worldwide, \$/kWh



# We need much more!!



Multi-day grid-scale storage at  
~ \$10/kWh



Small modular nuclear plants at  
~ \$3-4/W construction cost



Refrigerants with **ZERO** GWP



Zero net energy buildings at  
Zero net cost

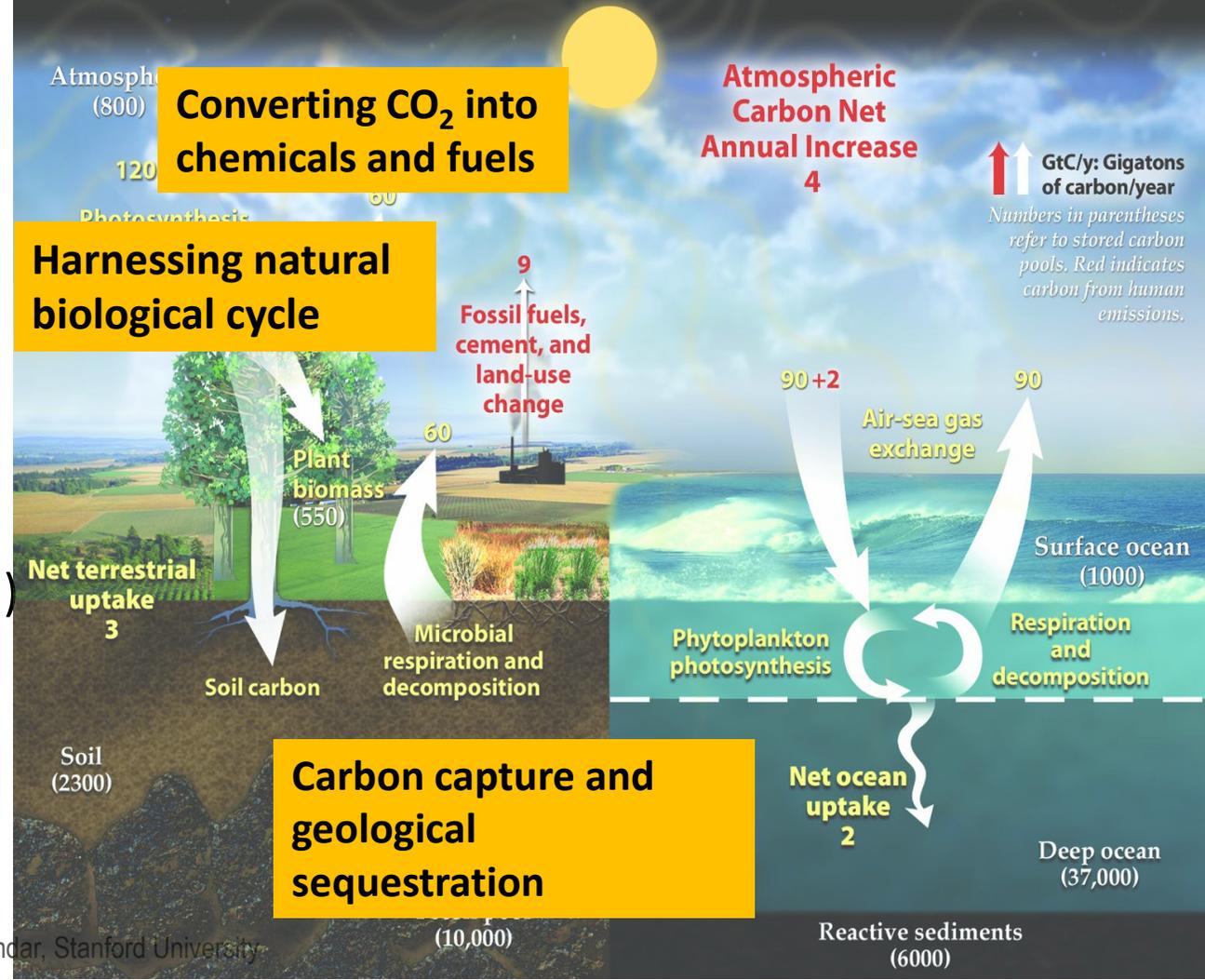


Decarbonizing industrial heat (Hydrogen)  
Reimagining steel, concrete and  
petrochemical processes

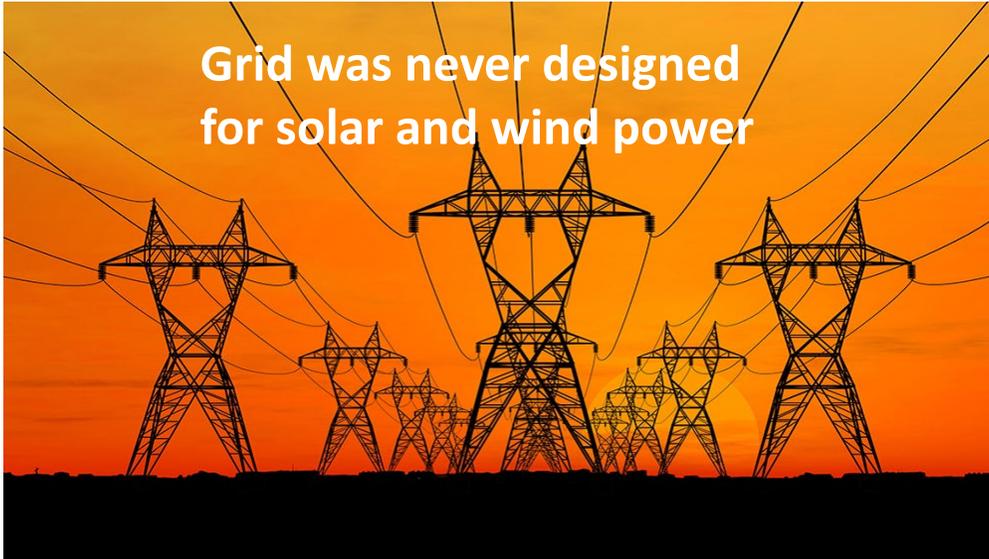


Decarbonizing food  
& agriculture

## Global Carbon Management at GigaTonne Scale

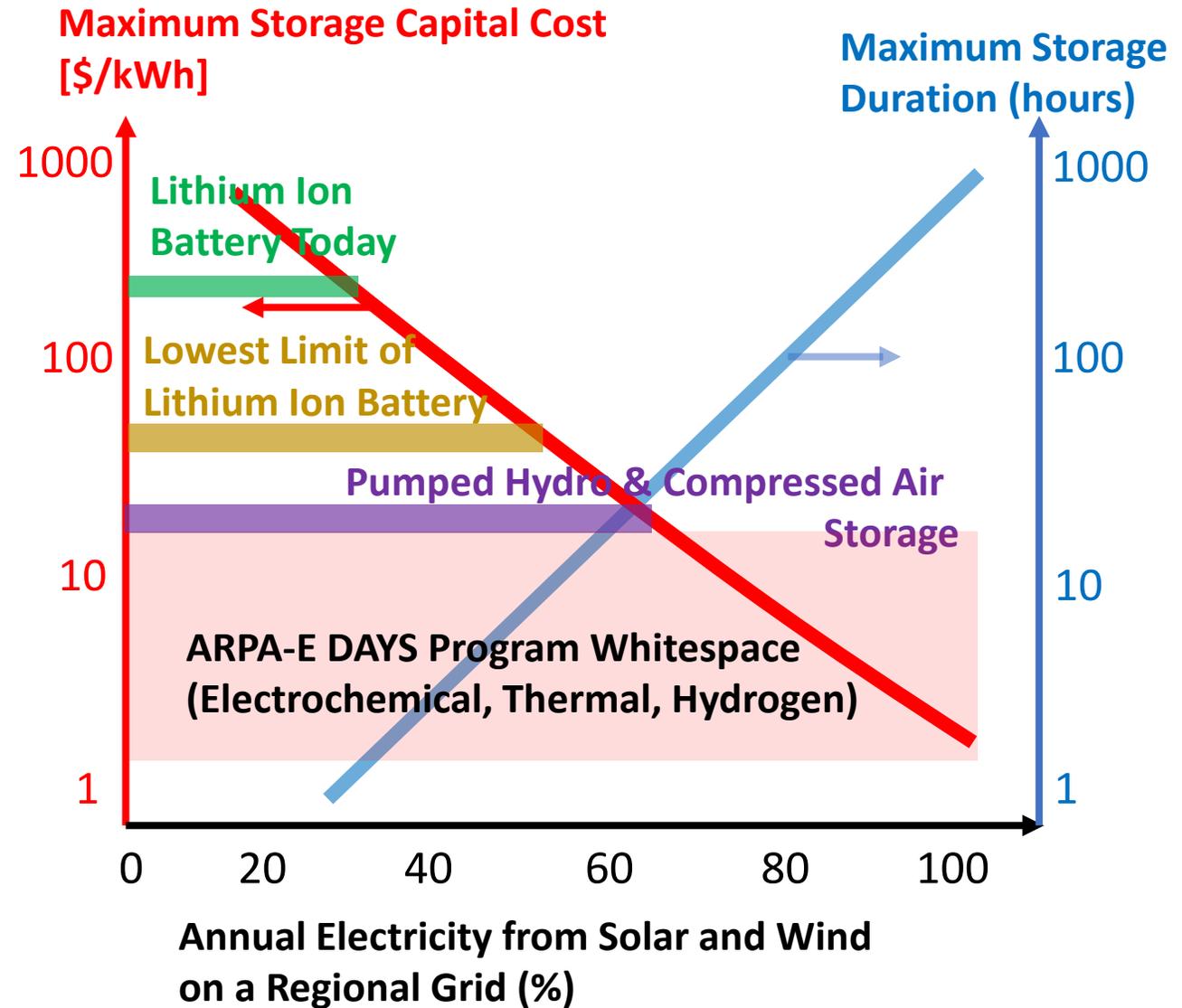


# Long-Duration Grid-Scale Storage



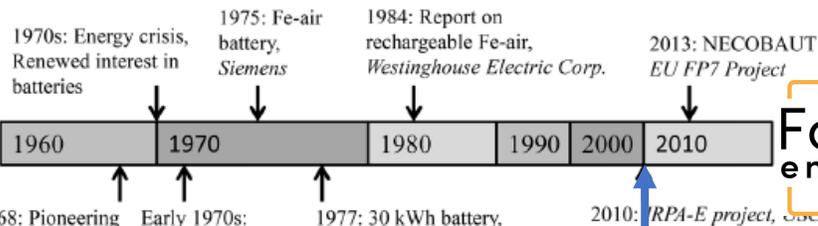
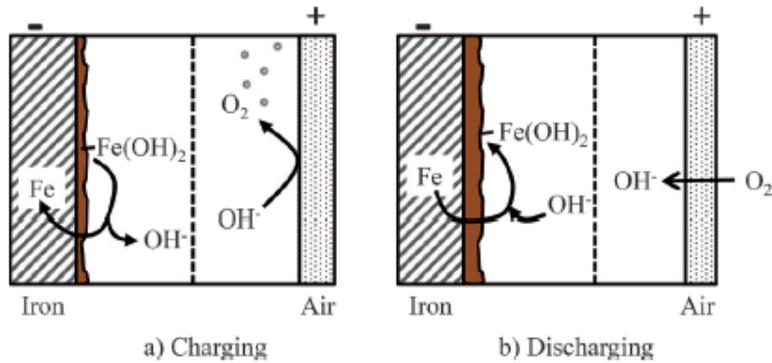
P. Albertus, J.S. Manser, S. Litzelman, "Long-duration electricity storage applications, economics, technology," *Joule* 4, 21-32 (2020)

- ARPA-E, EERE, OE, SC
- Senate Bill in process : BEST



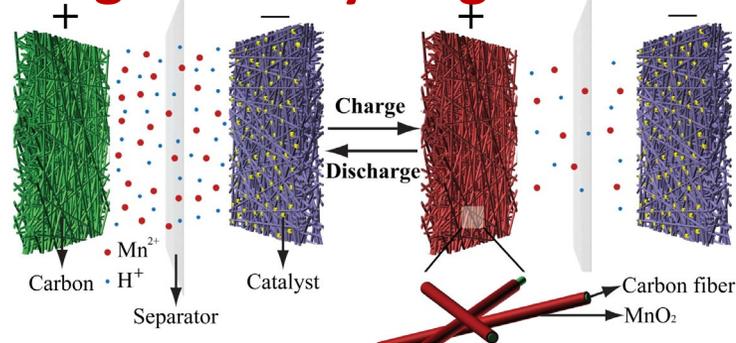
# Some Potential Candidates

## Iron-Oxygen Battery



ARPA-E Funding to USC Project

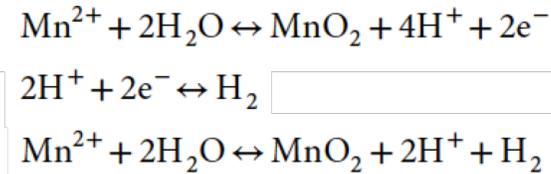
## Manganese-Hydrogen Battery



Cathode

Anode

Overall



ENERVENUE

## Solid-State Thermal Battery



Antora Energy

McKerracher et al., A review of the iron-air secondary battery for energy storage, *ChemPlusChem* (2014)

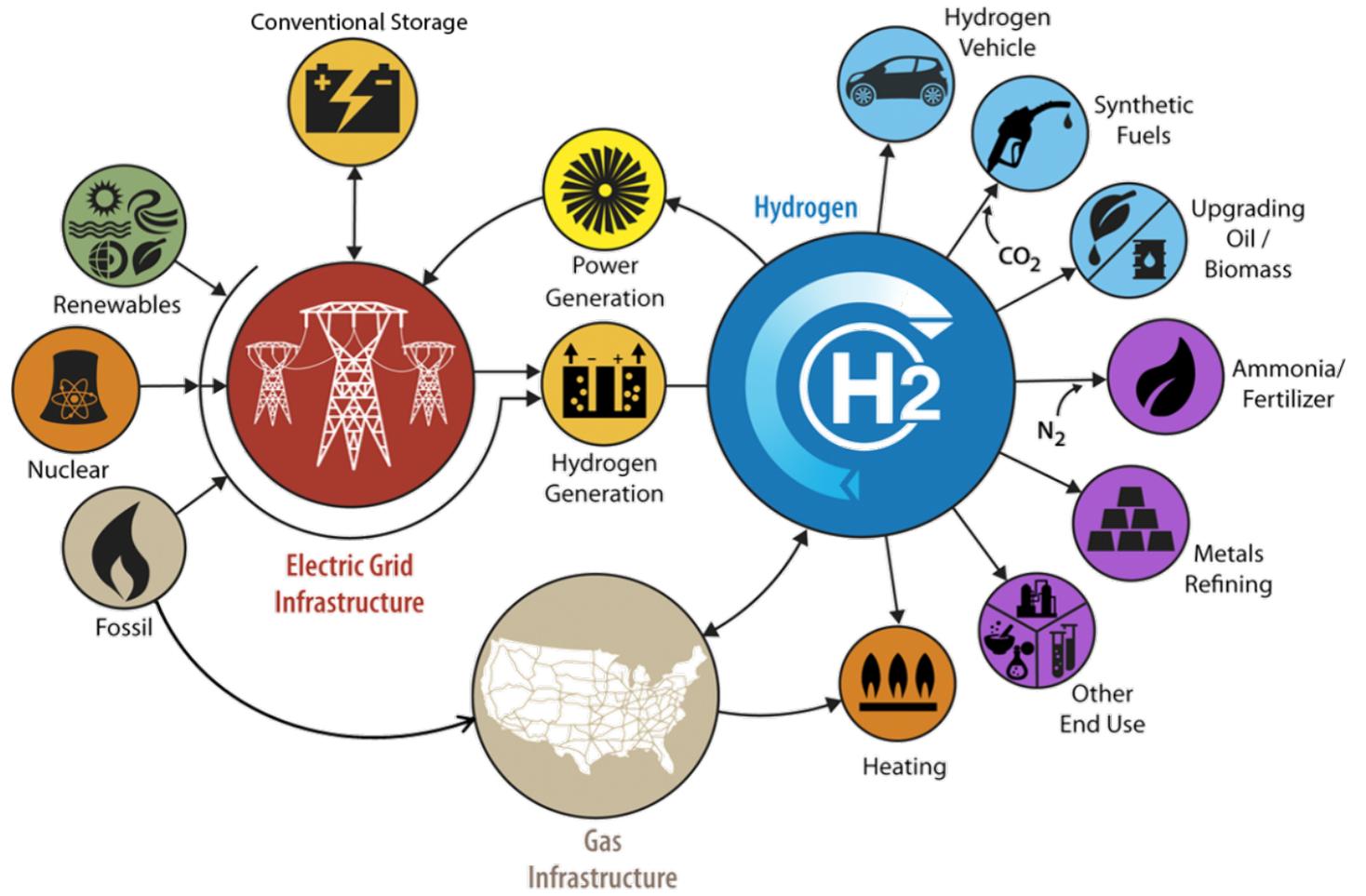
Wei Chen<sup>#</sup>, Guodong Li<sup>#</sup>, Yi Cui<sup>\*</sup>, et al. *Nature Energy*, 2018, 3, 428-435.



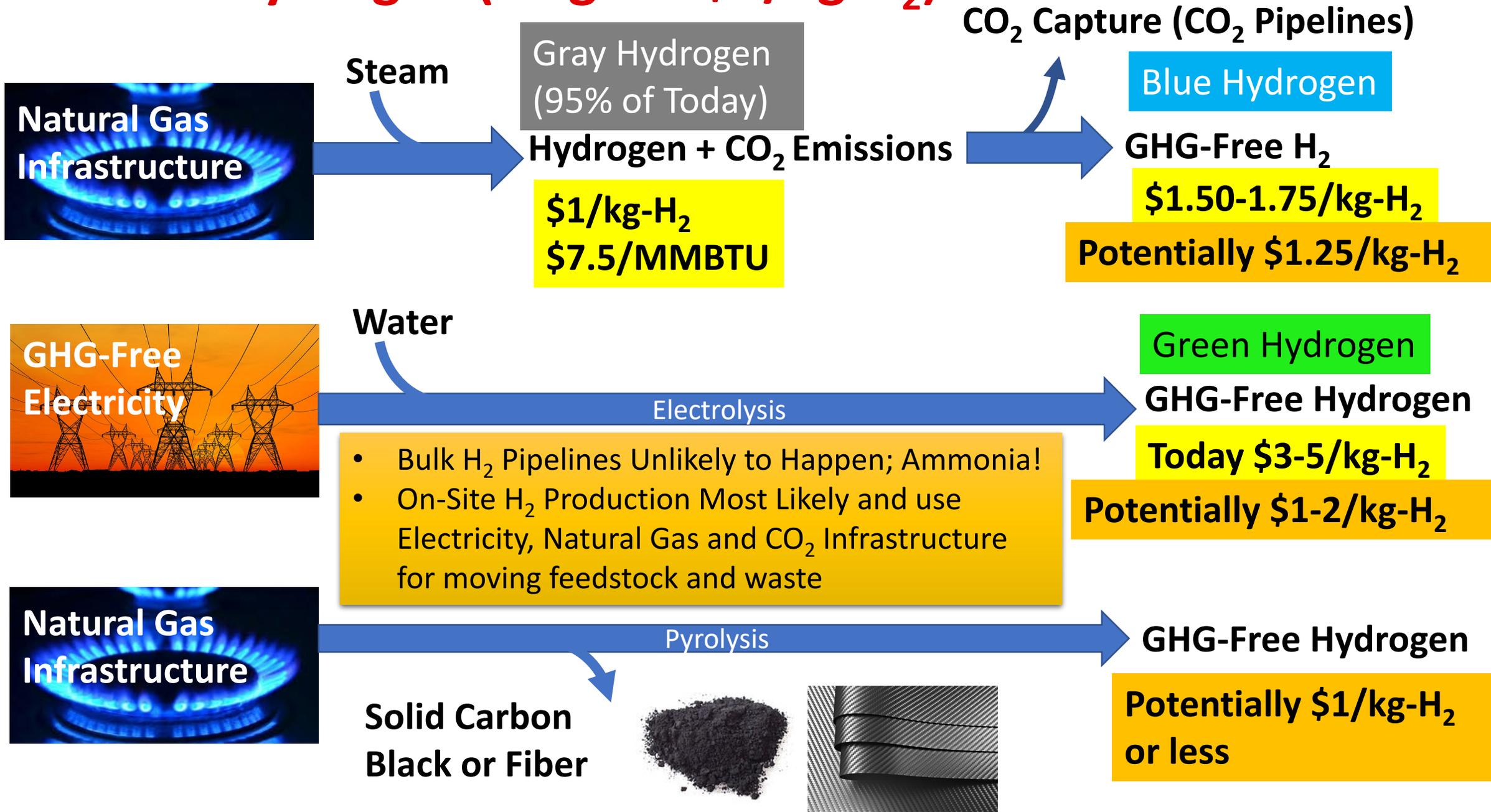
# Secretary Granholm Launches Energy Earthshots Initiative to Accelerate Breakthroughs Toward a Net-Zero Economy

JUNE 7, 2021

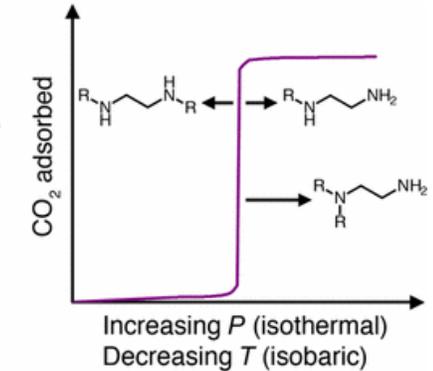
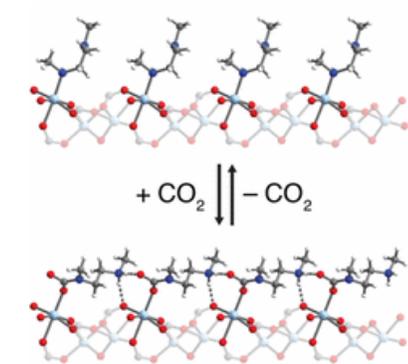
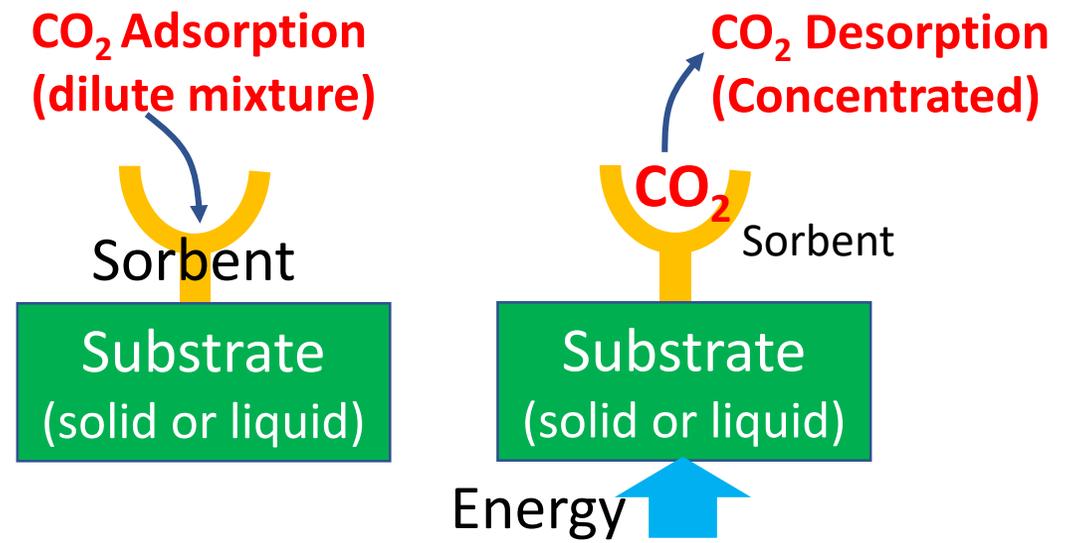
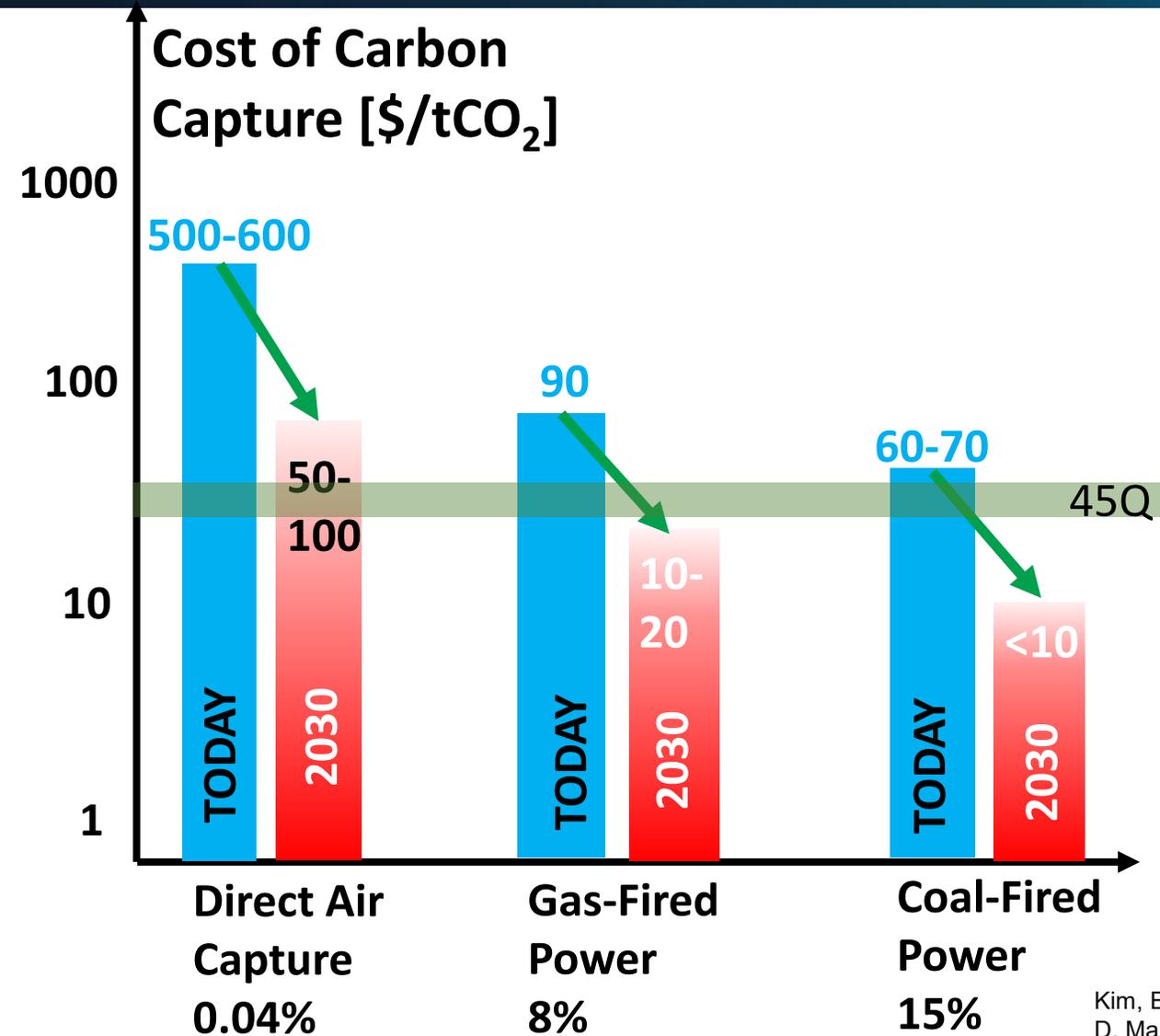
## First Earthshot



# GHG-Free Hydrogen (Target = \$1/kg-H<sub>2</sub>)



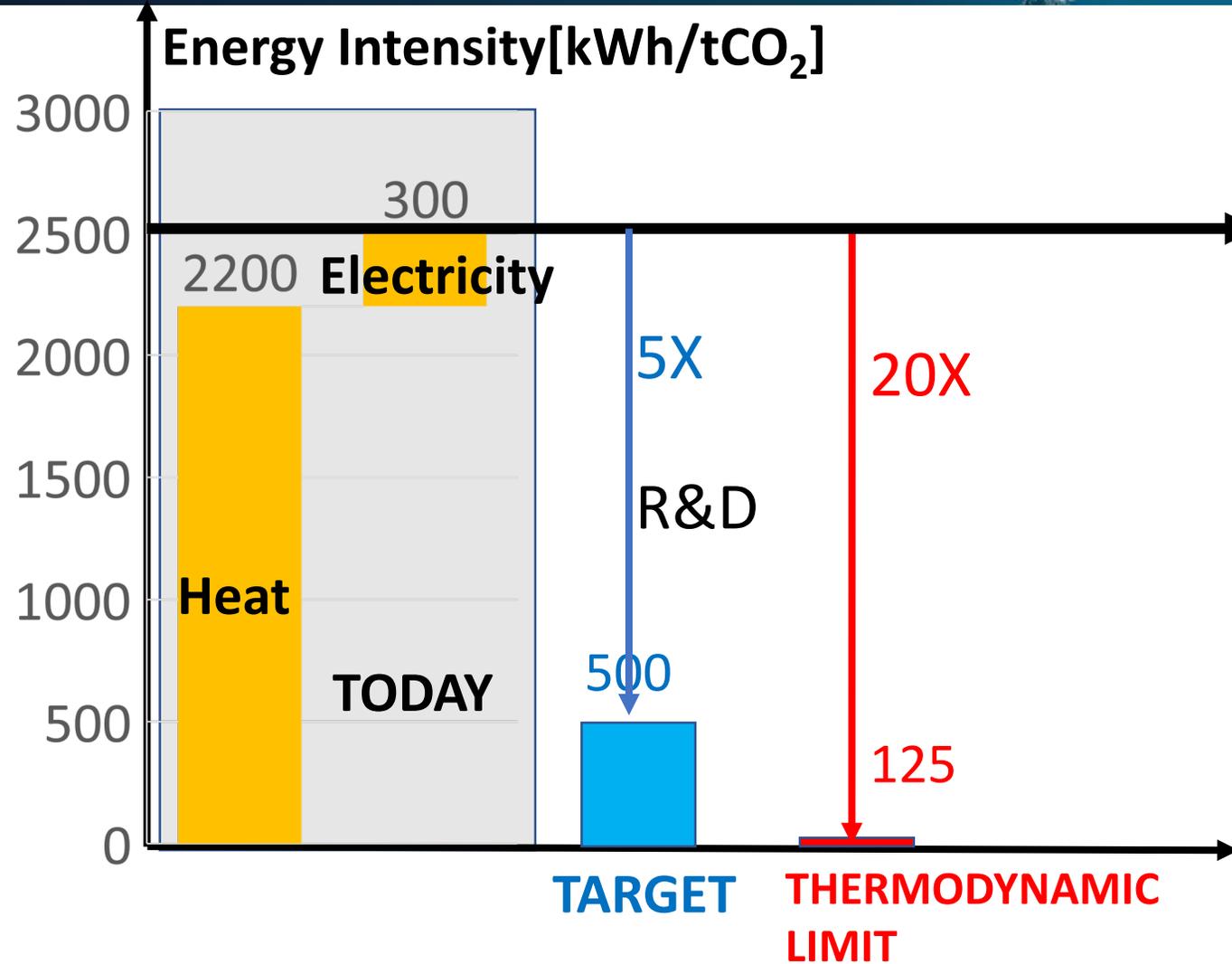
# Carbon Capture



Metal-organic frameworks (MOFs) for cooperative binding

Kim, Eugene J., Rebecca L. Siegelman, Henry Z. H. Jiang, Alexander C. Forse, Jung-Hoon Lee, Jeffrey D. Martell, Phillip J. Milner, et al. 2020. "Cooperative Carbon Capture and Steam Regeneration with Tetraamine-Appended Metal-organic Frameworks." *Science*,

# Atmospheric Carbon Dioxide Removal



**1 GigaTon of CO<sub>2</sub> removal will need 2500 TWh of Carbon-Free Energy**

2020 US Production of Carbon-Free Energy (Nuclear, Wind, Solar, Hydro) = **1510 TWh**

# Key Recommendations

- Deploy current technologies BUT ensure we don't lock-in to current technologies that could become obsolete.
- Innovations and breakthroughs in energy technologies are essential to reach net-zero emissions for US and global economies
- Use-inspired sustained R&D effort (science to systems w/ feedback loop) is critical
- To achieve economy wide scale with urgency, **acceleration of innovations** require policies to reduce barriers and risks along innovation value chain.

## Risks, Barriers & Constraints

