

Plant capacity by power source

50 500 2000 5000MW

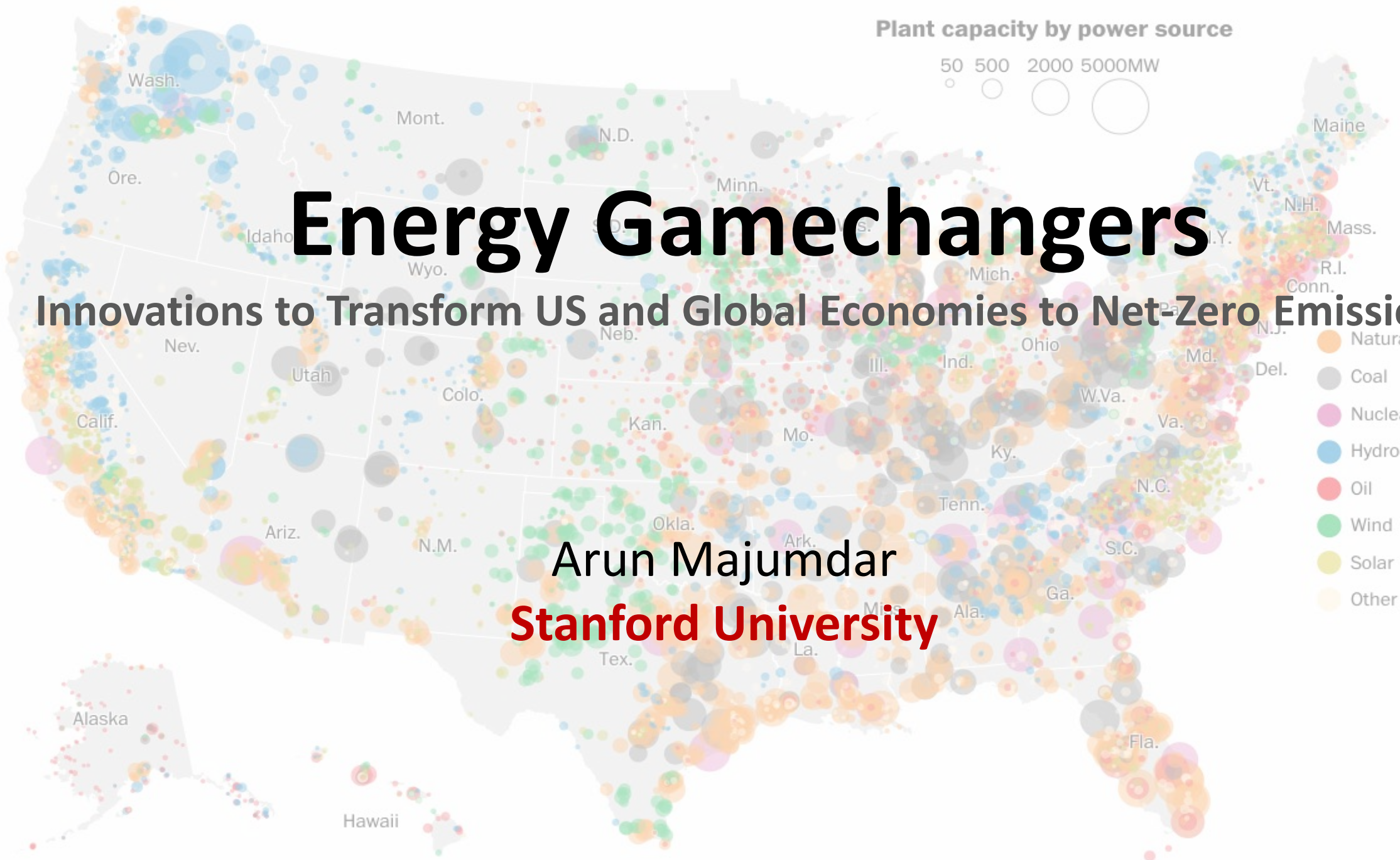
Energy Gamechangers

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

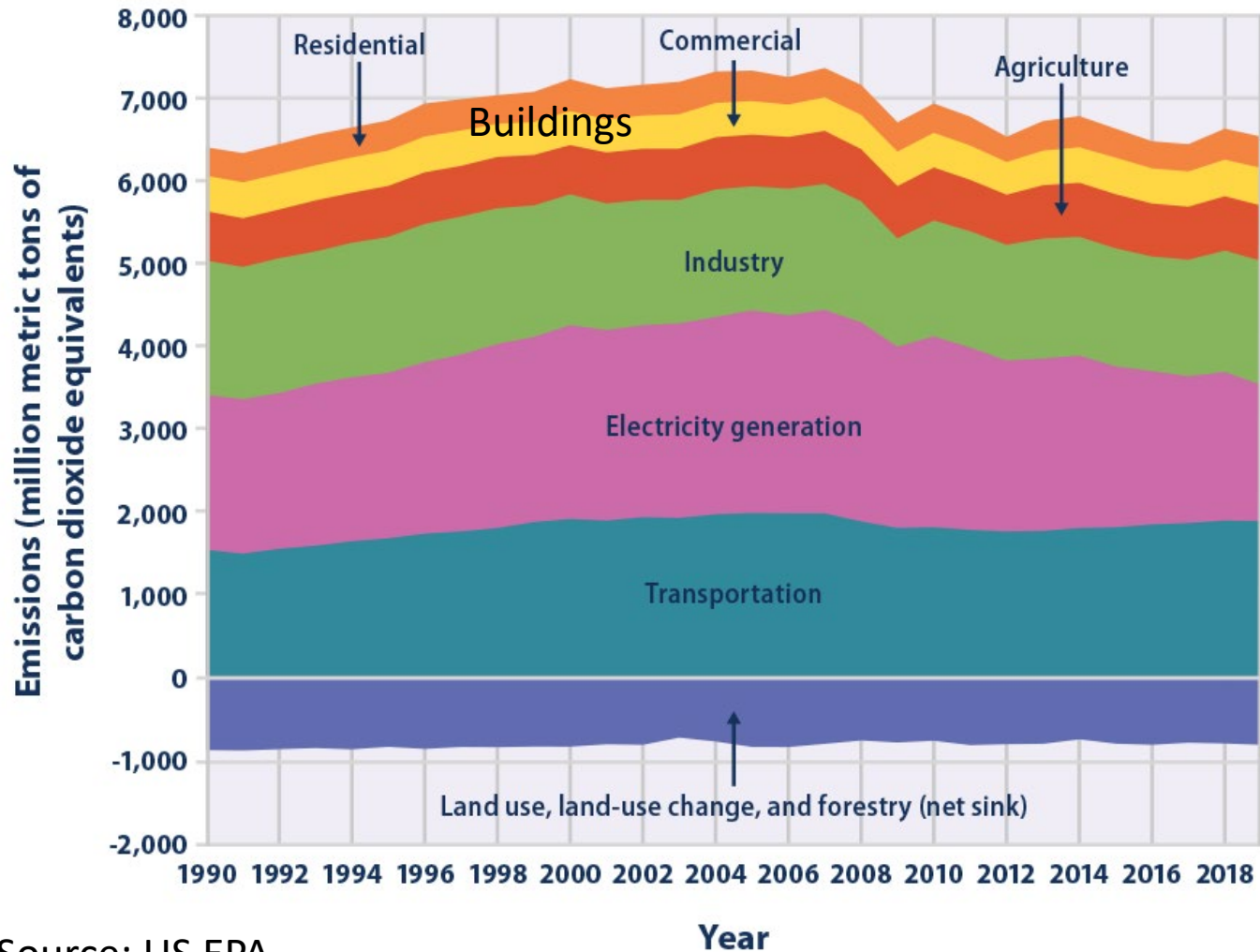
Arun Majumdar

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

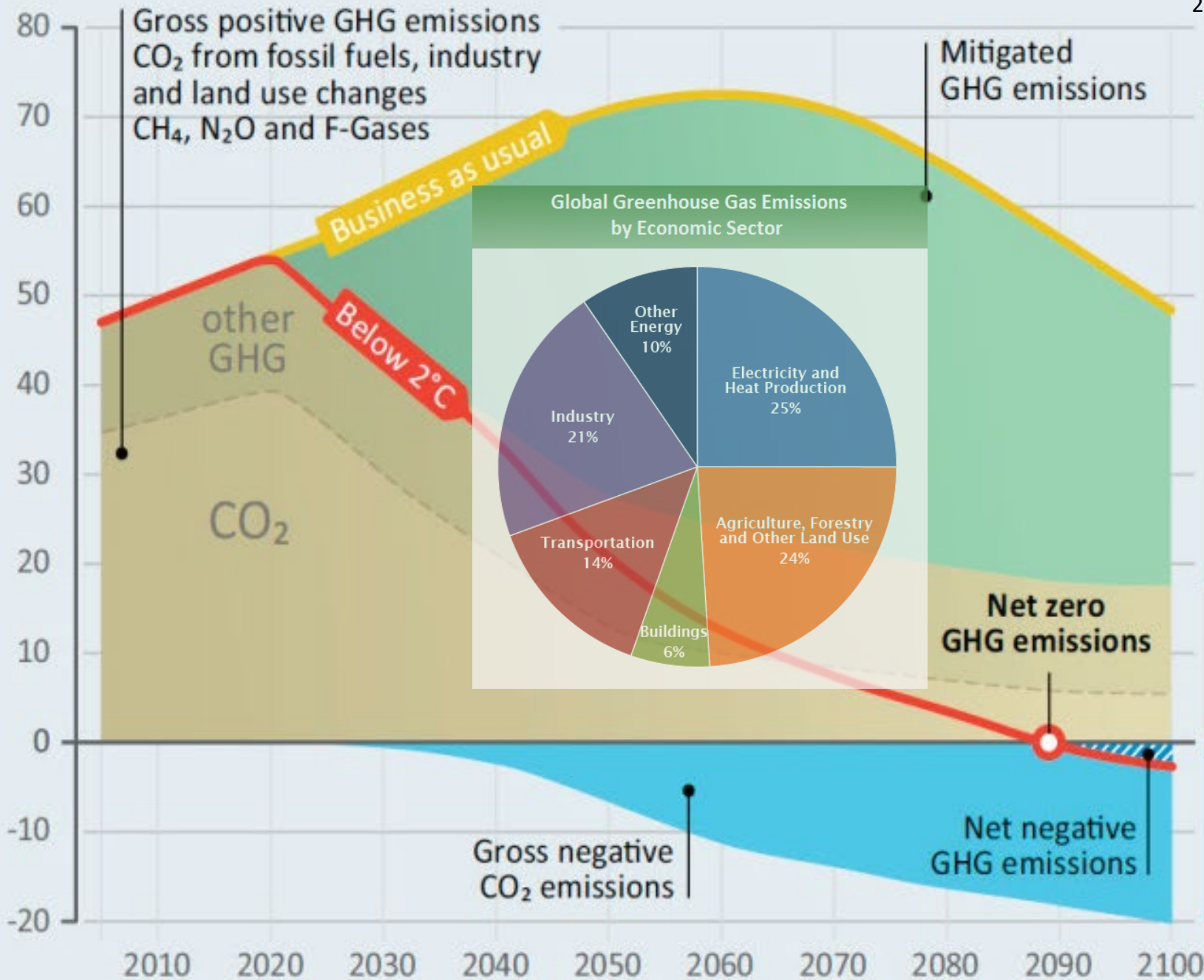
2050

Source: US EPA

GHG emissions (GtCO₂e/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



National Academies Report (2019)

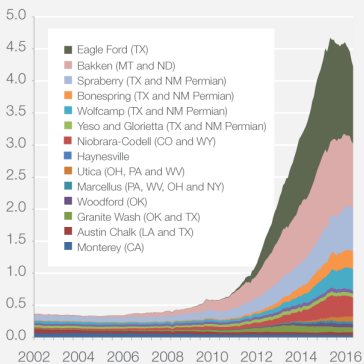
Energy Breakthroughs

Unconventional Gas



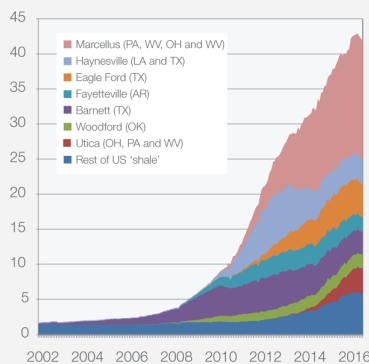
This change is driven by production from unconventional reserves using fracking and horizontal drilling.

Shale And Tight Oil Production
million barrels per day

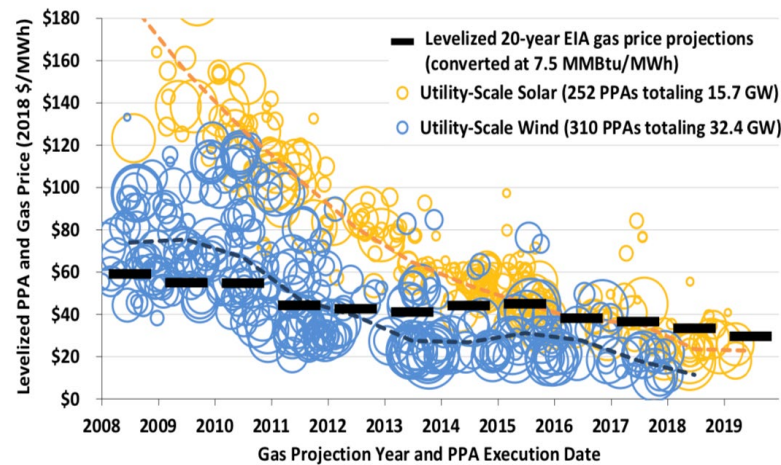


Source: EIA.

Dry Shale Gas Production
billion cubic feet per day



Renewable Electricity

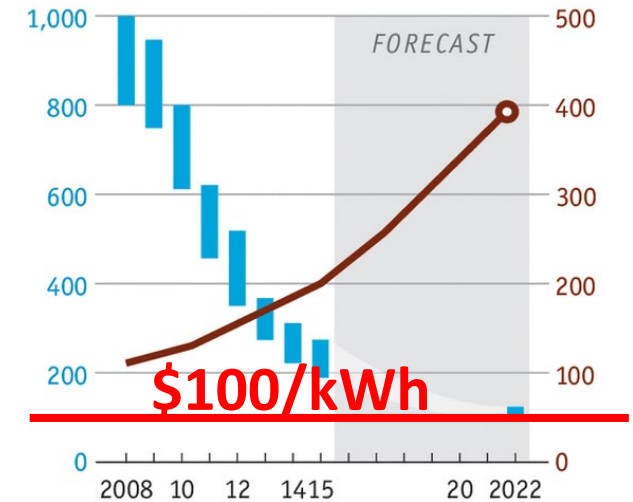


Battery Electric Vehicles



Battery cost
Worldwide, \$/kWh

Battery energy density
Watt-hours per litre



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

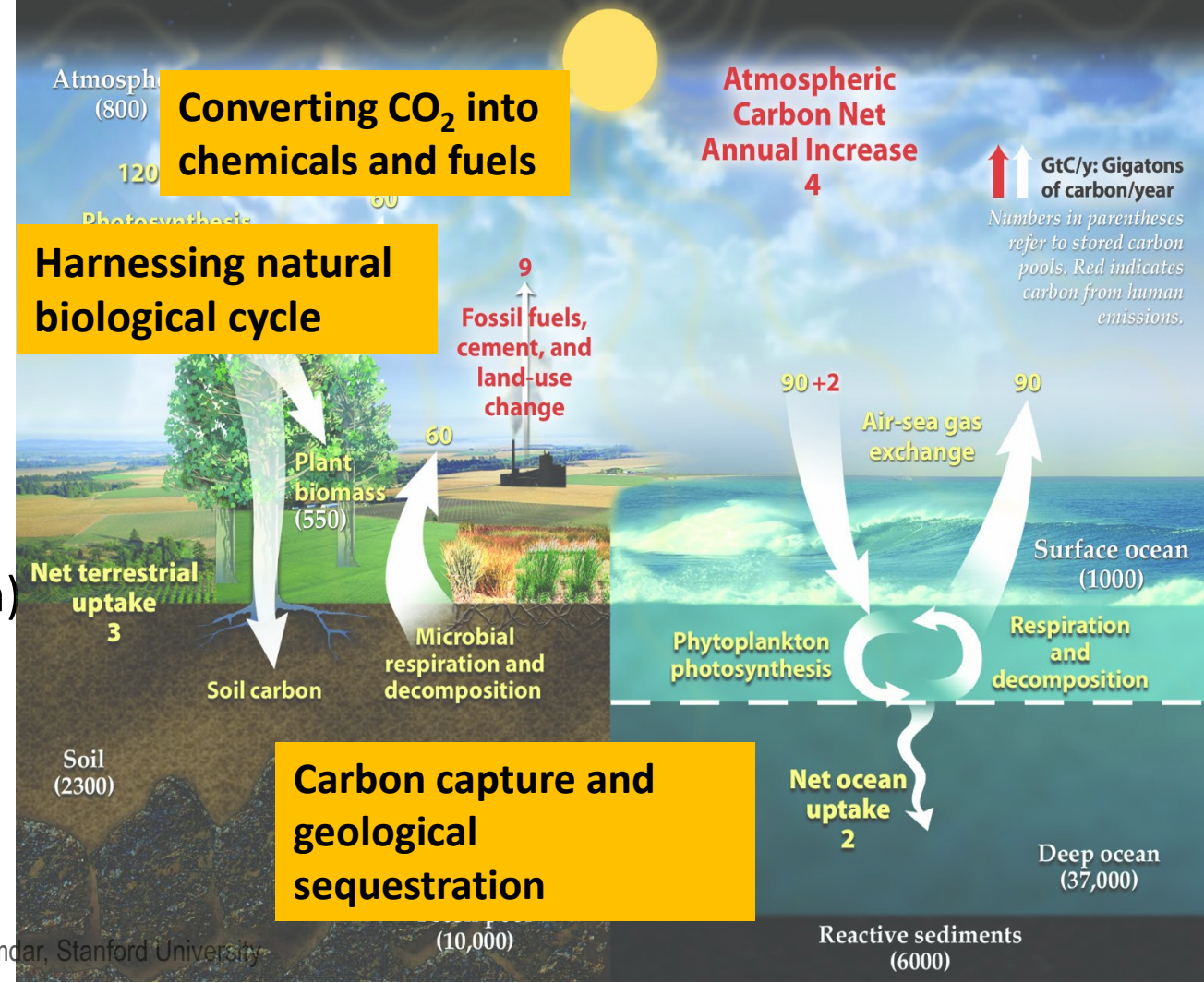


Decarbonizing industrial heat (Hydrogen)
Reimagining steel, concrete and
petrochemical processes

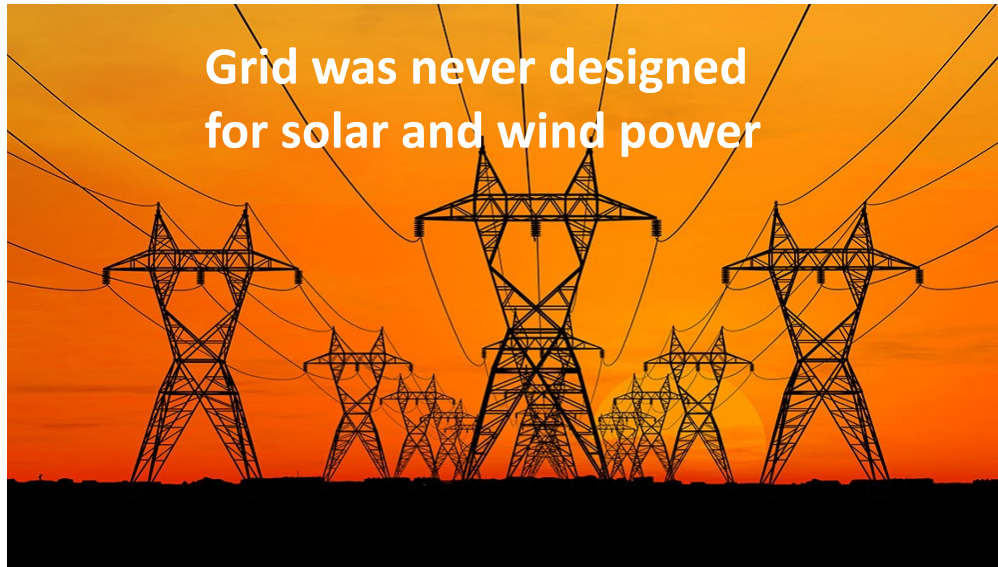


Decarbonizing food
& agriculture

Global Carbon Management at GigaTonne Scale

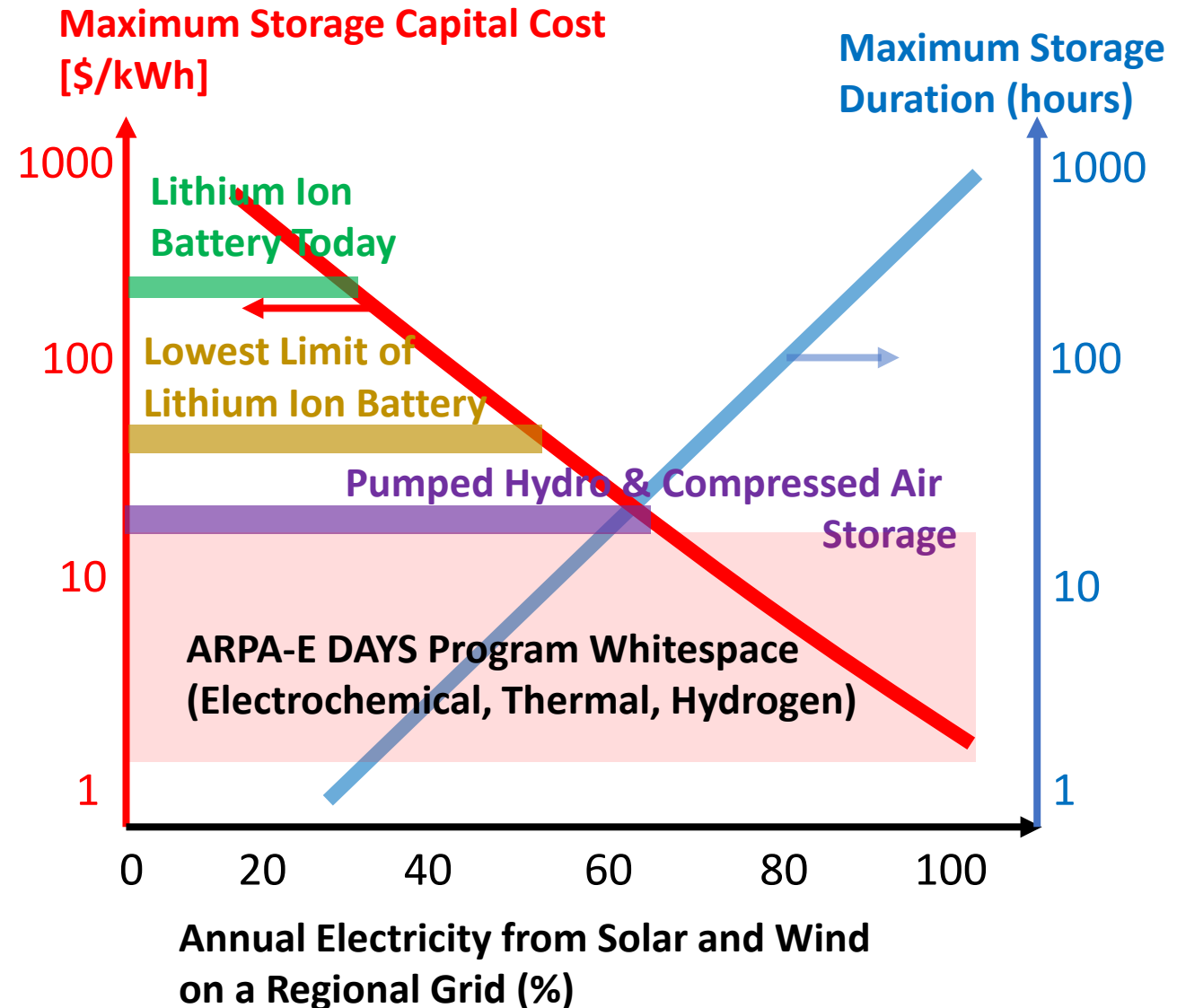


Long-Duration Grid-Scale Storage



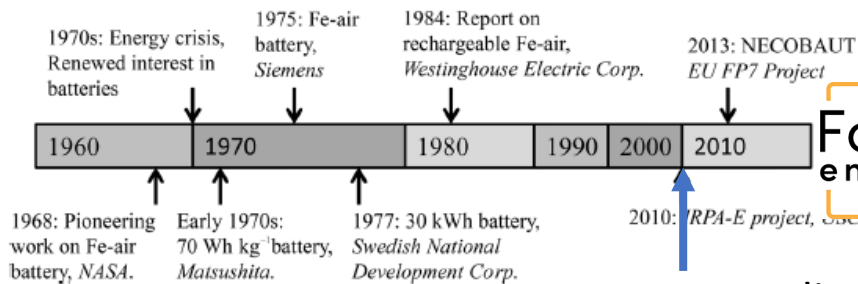
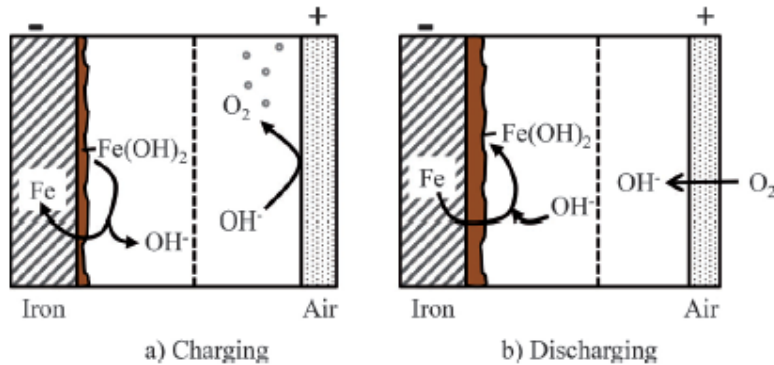
P. Albertus, J.S. Manser, S. Litzelman, "Long-duration electricity storage applications, economics, technology," *Joule* 4, 21-32 (2020)

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



Some Potential Candidates

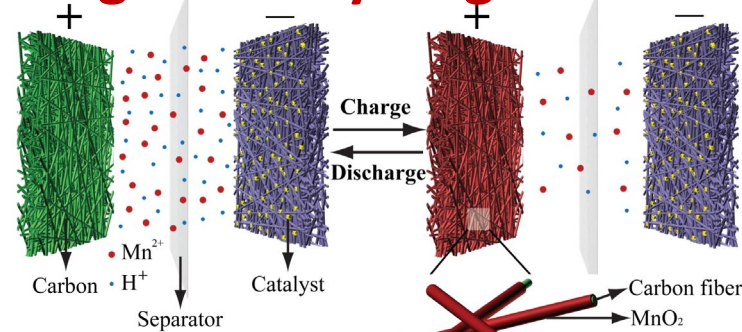
Iron-Oxygen Battery



ARPA-E Funding to USC Project

Form energy

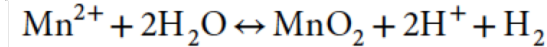
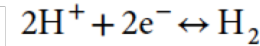
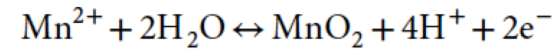
Manganese-Hydrogen Battery



Cathode

Anode

Overall



ENERVENUE

Solid-State Thermal Battery



Antora Energy

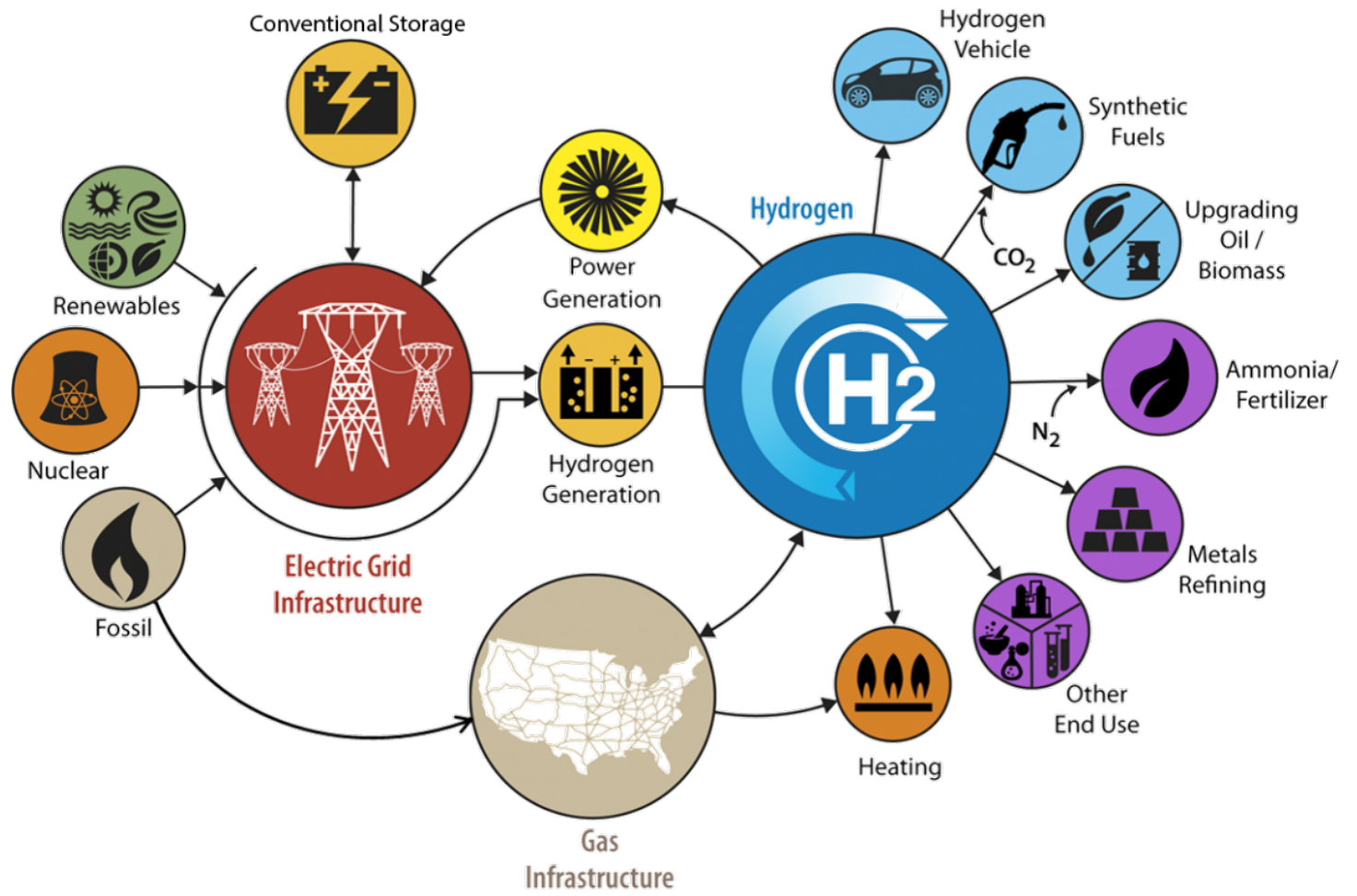
McKerracher et al., A review of the iron-air secondary battery for energy storage, *ChemPlusChem* (2014)

Wei Chen[#], Guodong Li[#], Yi Cui^{*}, et al. *Nature Energy*, 2018, 3, 428-435.

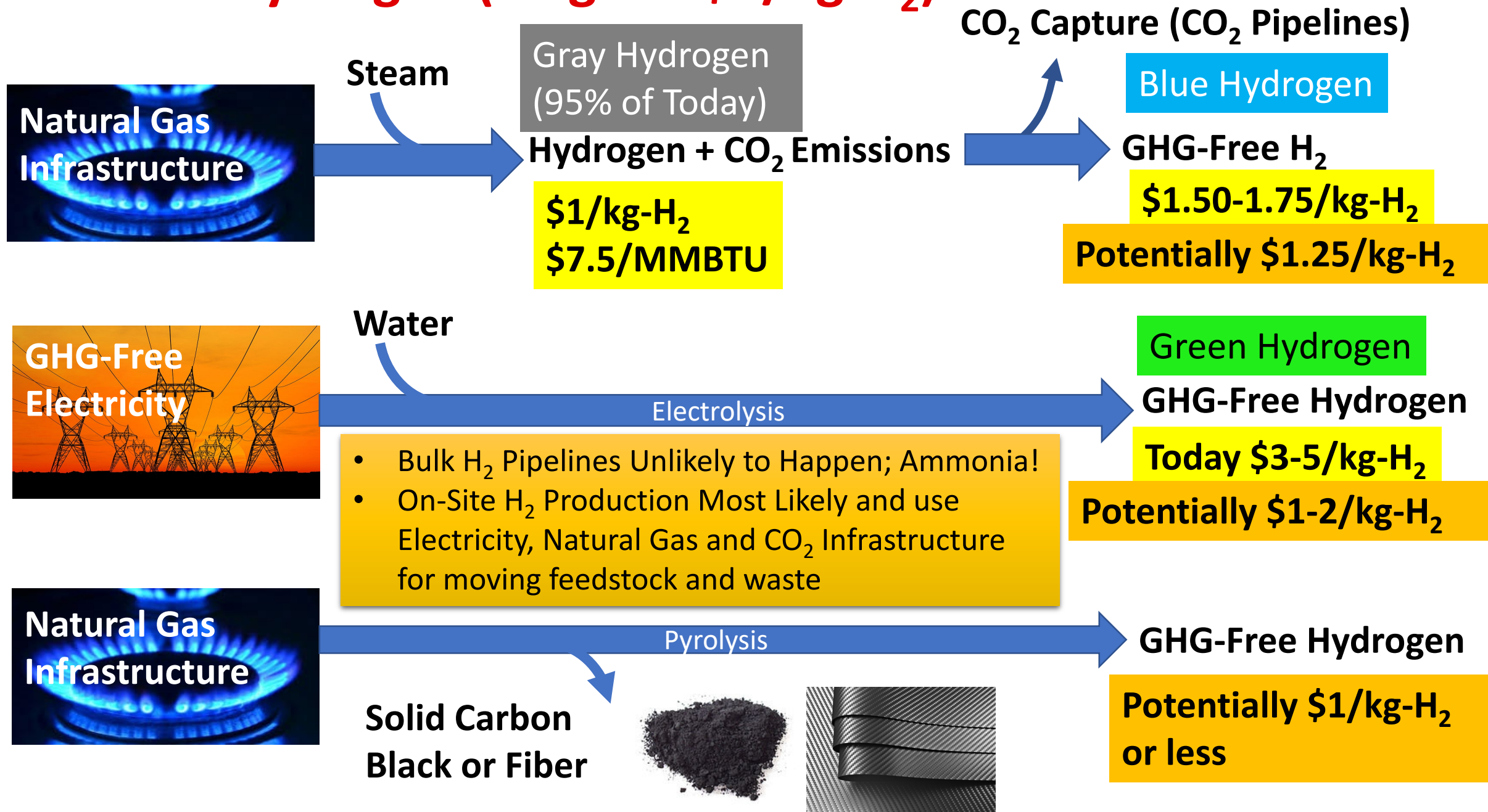
Secretary Granholm Launches Energy Earthshots Initiative to Accelerate Breakthroughs Toward a Net-Zero Economy

JUNE 7, 2021

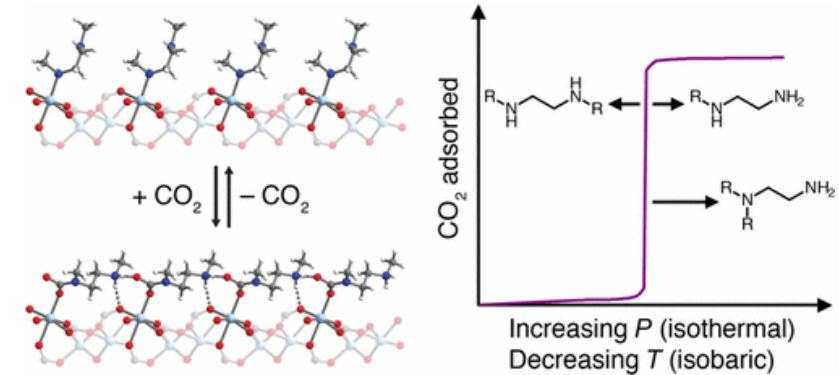
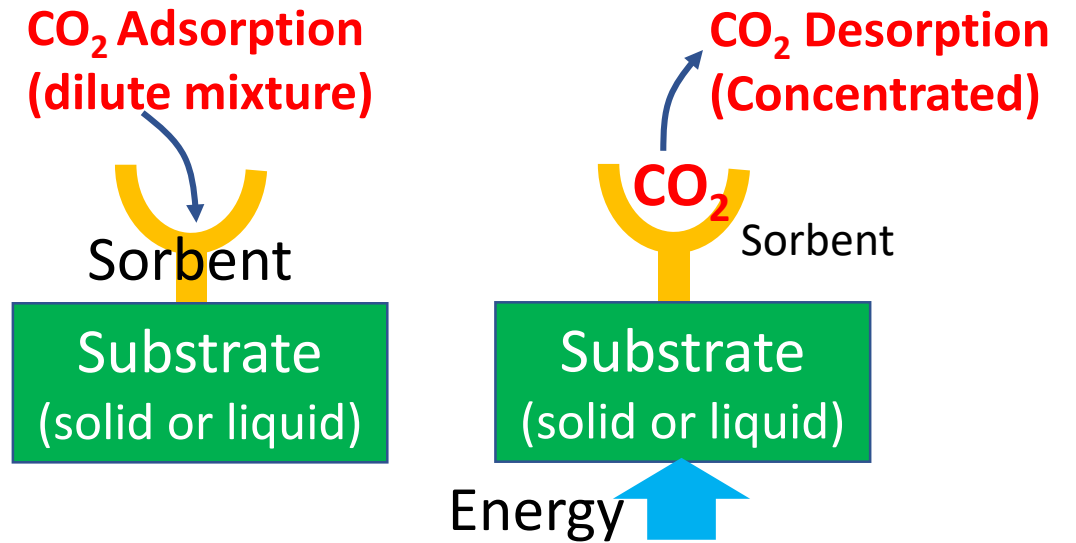
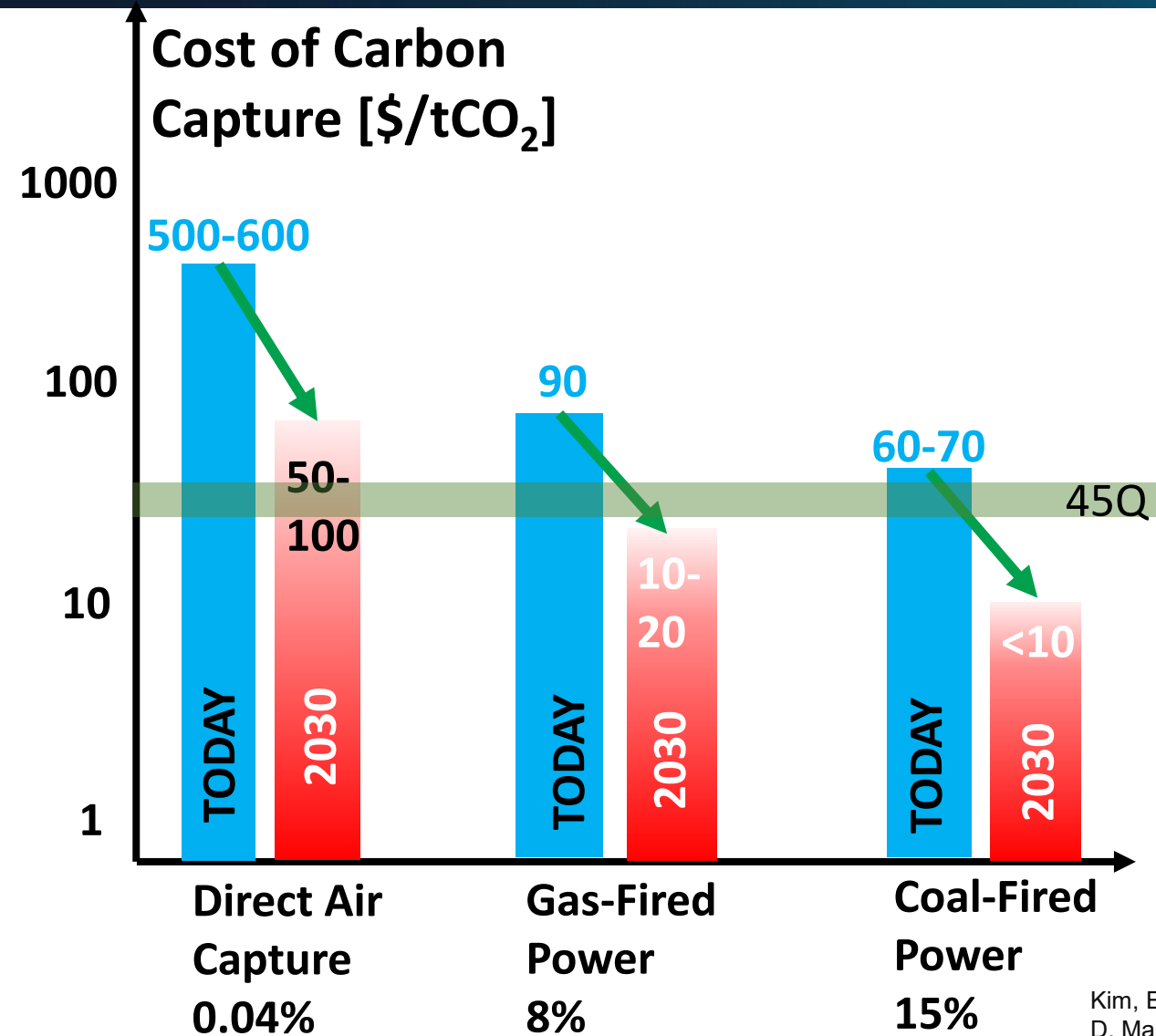
First Earthshot



GHG-Free Hydrogen (Target = \$1/kg-H₂)



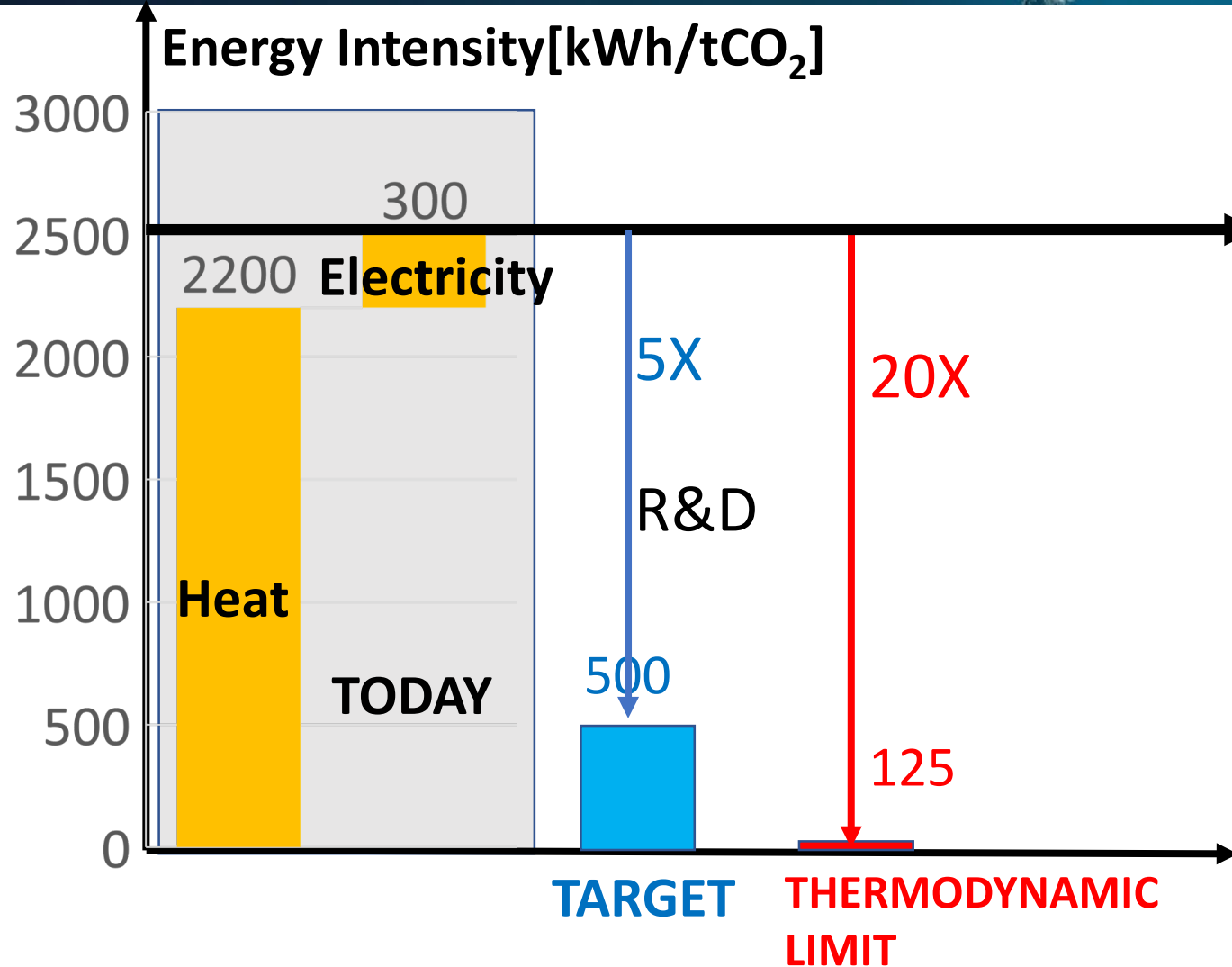
Carbon Capture



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 CO₂ 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

