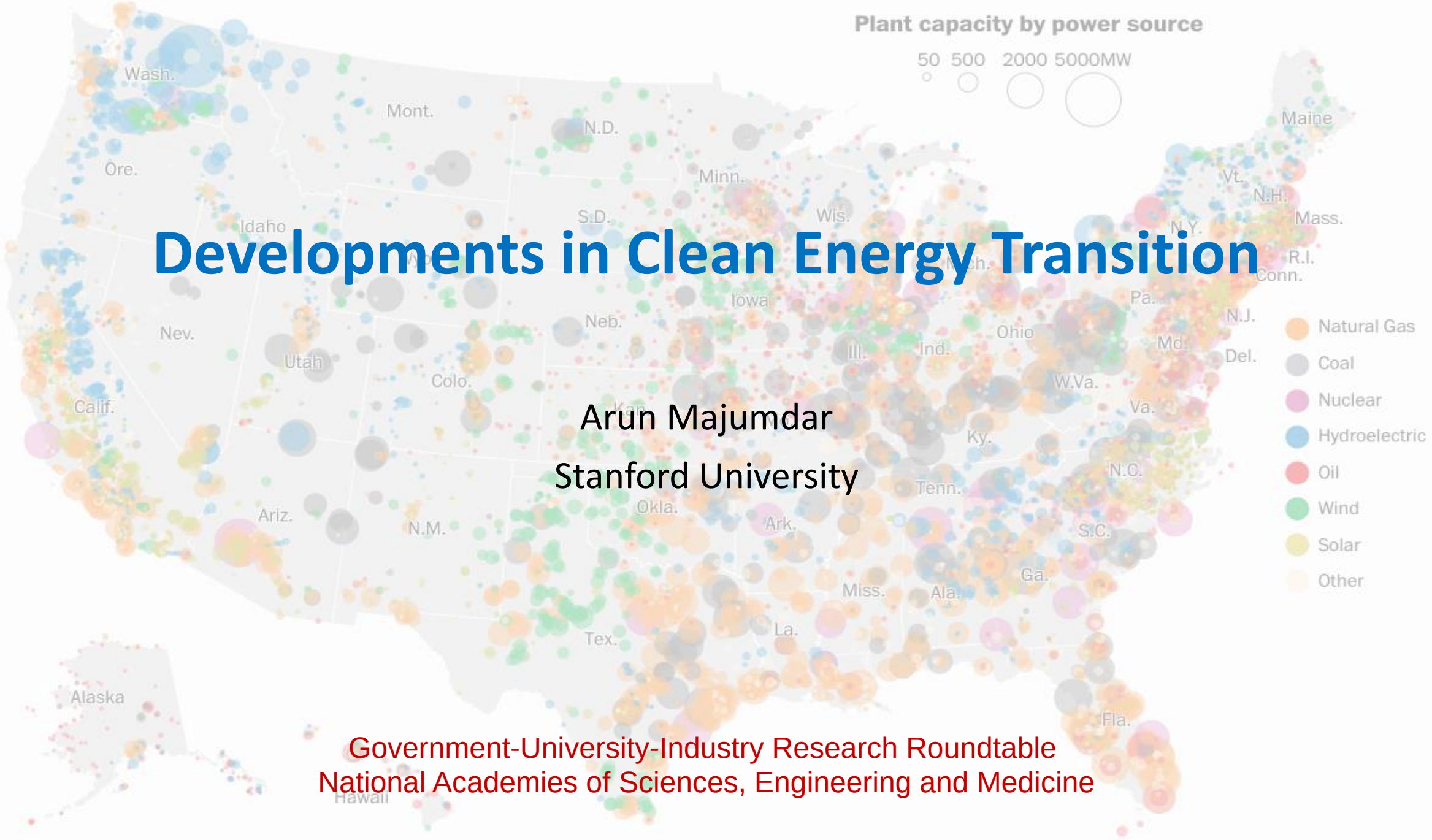


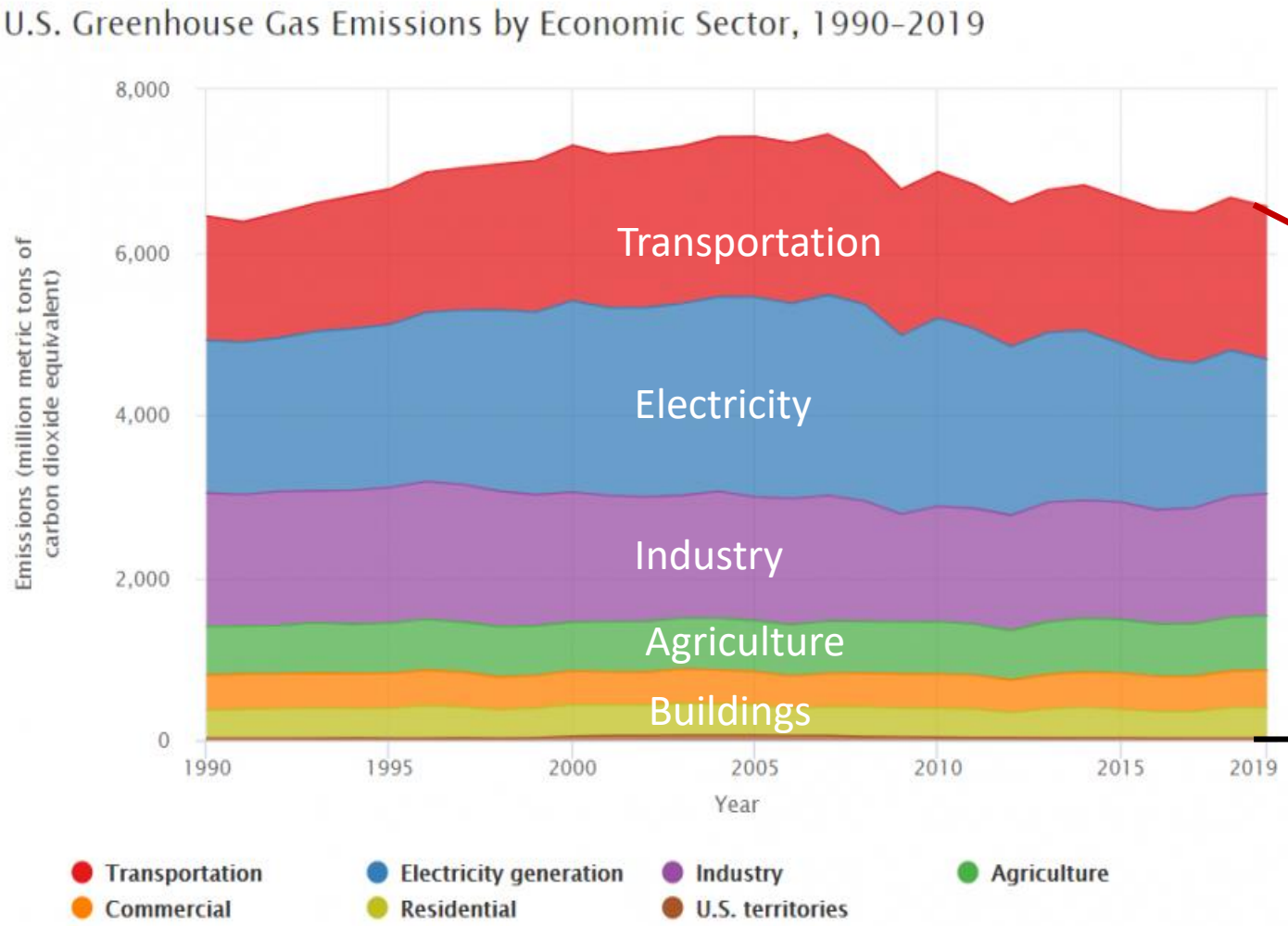
Developments in Clean Energy Transition

Arun Majumdar

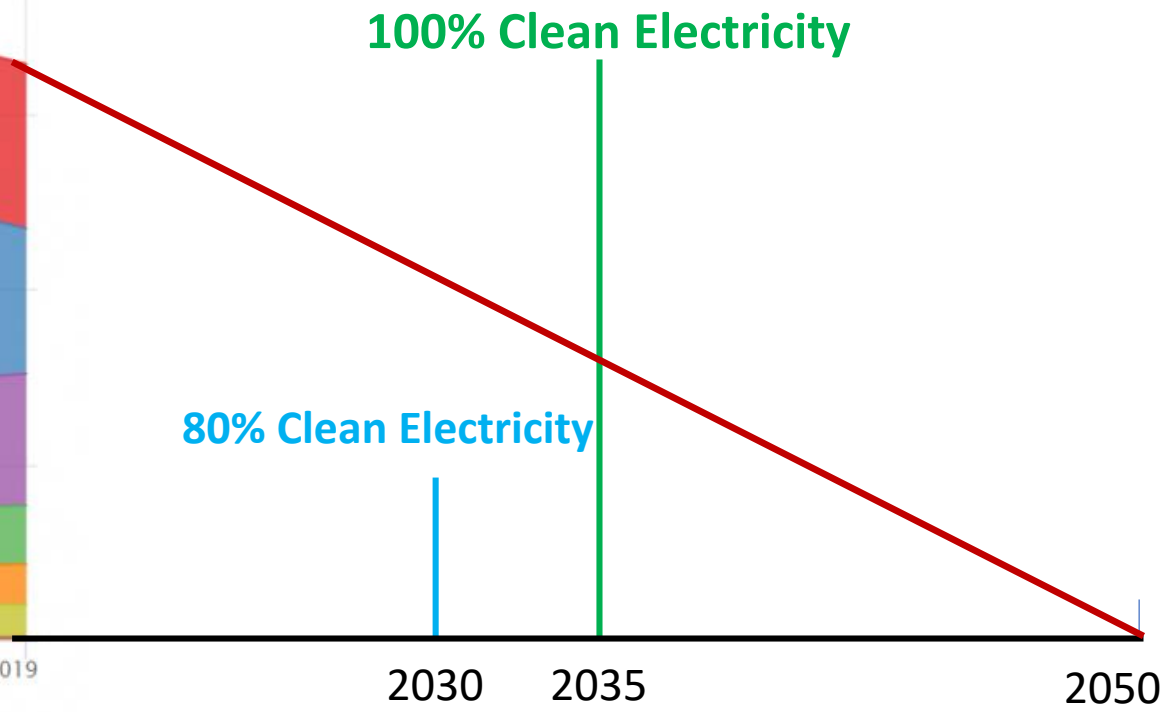
Stanford University

Government-University-Industry Research Roundtable
National Academies of Sciences, Engineering and Medicine

US Goals



Equity & Environmental Justice



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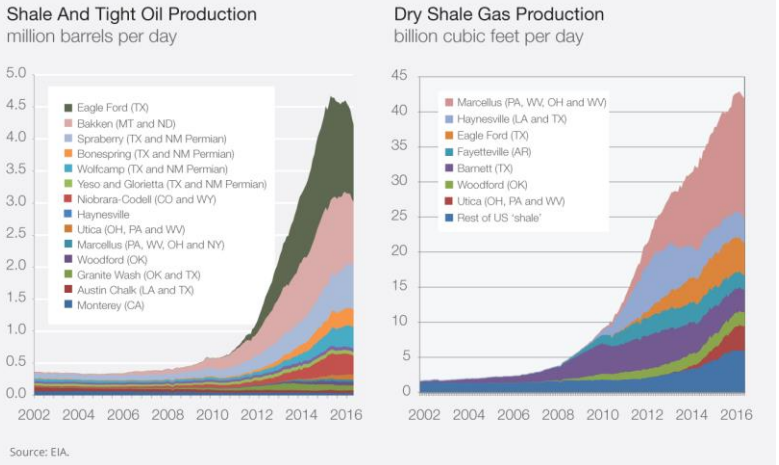
Energy Breakthroughs

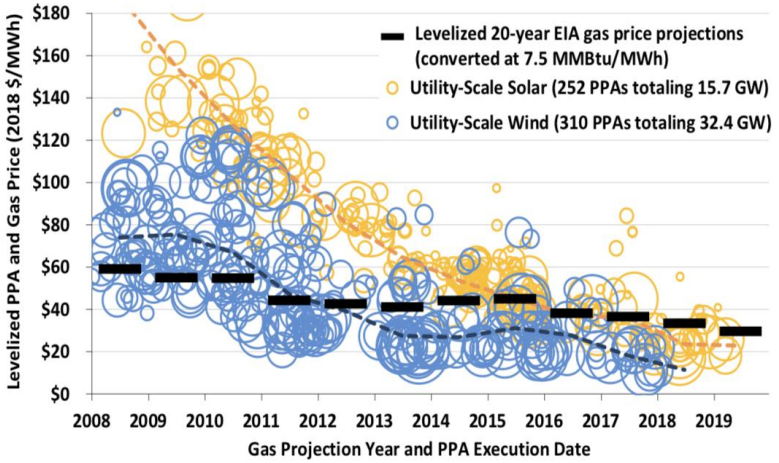
Unconventional Gas

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

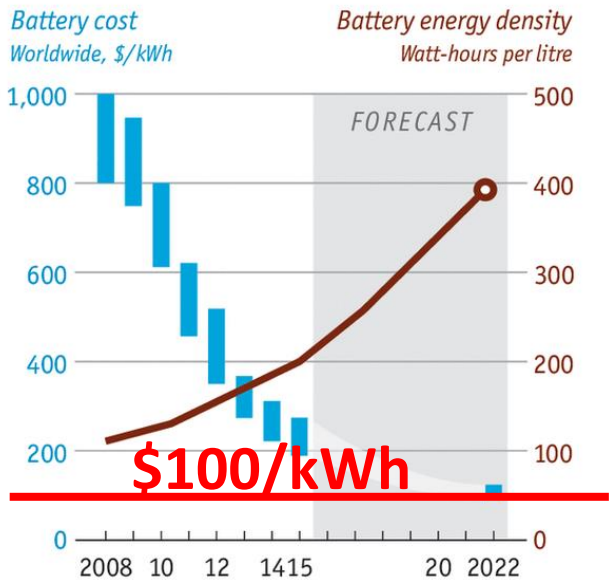


Source: EIA.

Renewable Electricity



Battery Electric Vehicles



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ENERGY

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

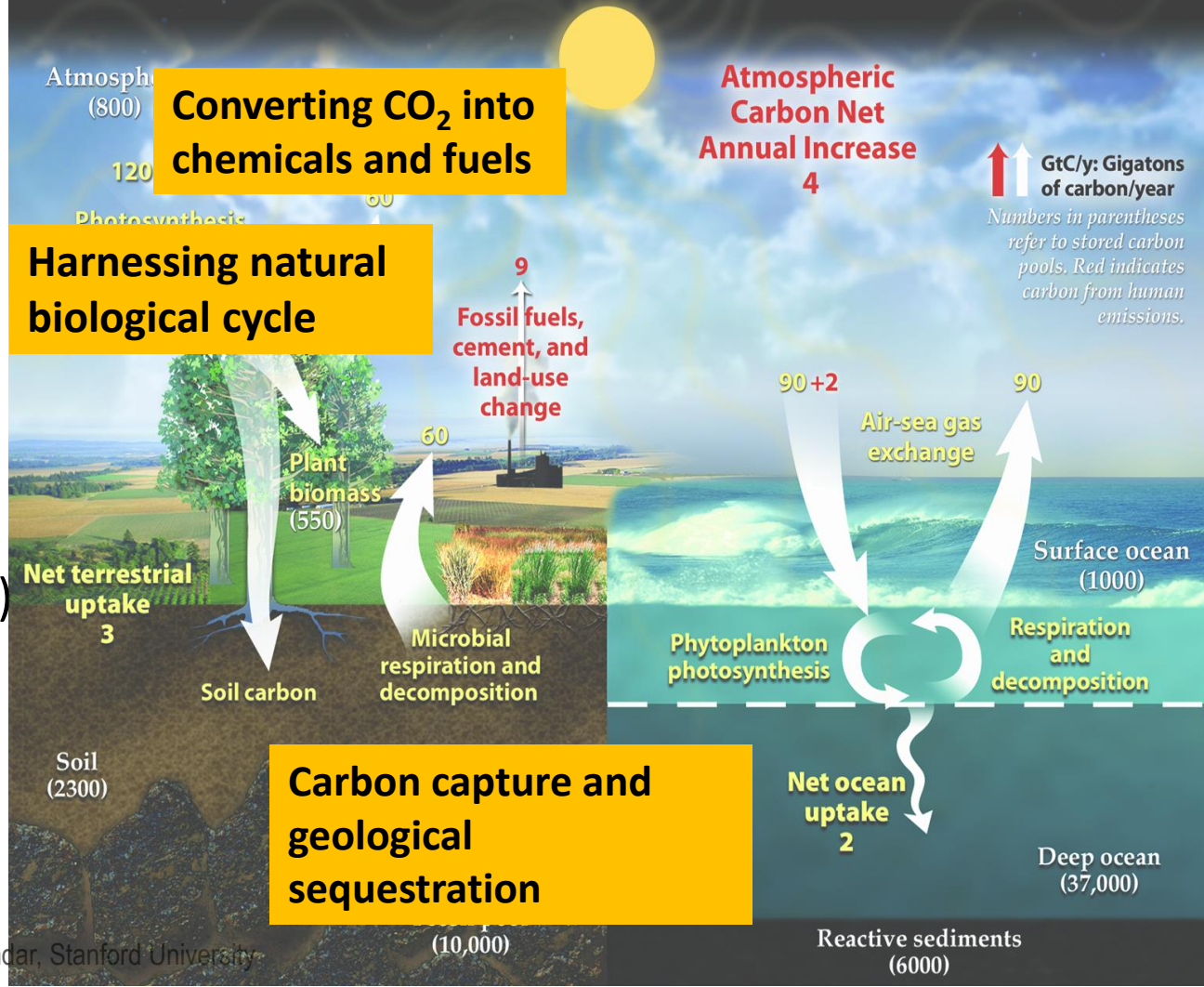
Decarbonizing food
& agriculture

Carbon Management at GigaTonne Scale

Converting CO_2 into chemicals and fuels

Harnessing natural biological cycle

Carbon capture and geological sequestration

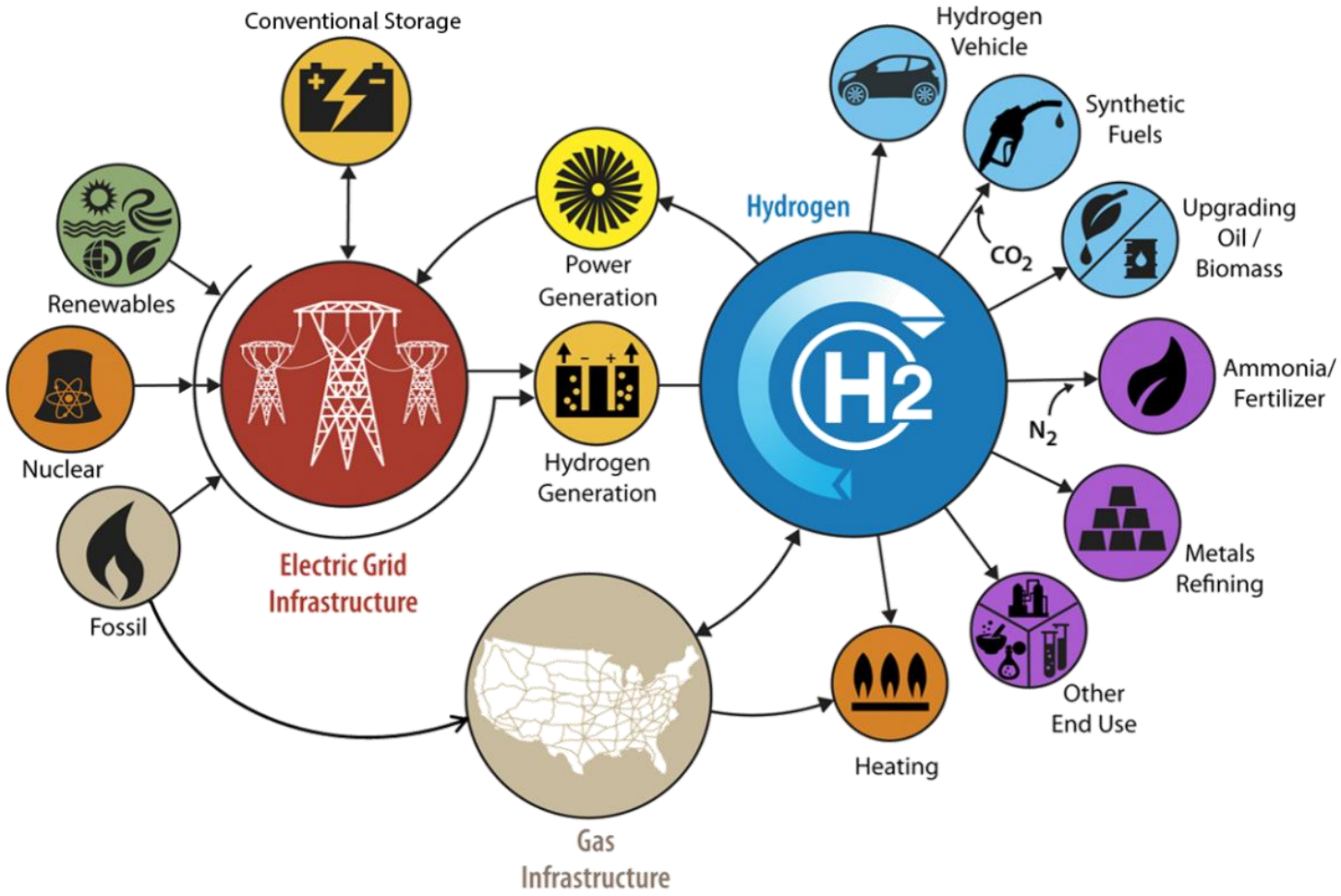


Department of Energy

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

JUNE 7, 2021

First Earthshot



Hydrogen Techno-economics (Target = $1/kg-$H_2$)

Steam

Gray Hydrogen
(95% of Today)

Hydrogen + CO_2 Emissions

$1/kg-$H_2$
$7.5/MMBTU

CO_2 Capture (CO_2 Pipelines)

Blue Hydrogen

GHG-Free H_2

$1.50-1.75/kg-$H_2$

Potentially $1.25/kg-$H_2$

Water

Electrolysis

Green Hydrogen

GHG-Free Hydrogen

Today $3-5/kg-$H_2$

Potentially $1-2/kg-$H_2$

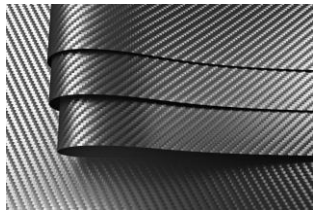
- Bulk H_2 Pipelines Unlikely to Happen; Ammonia!
- On-Site H_2 Production Most Likely and use Electricity, Natural Gas and CO_2 Infrastructure for moving feedstock and waste

Pyrolysis

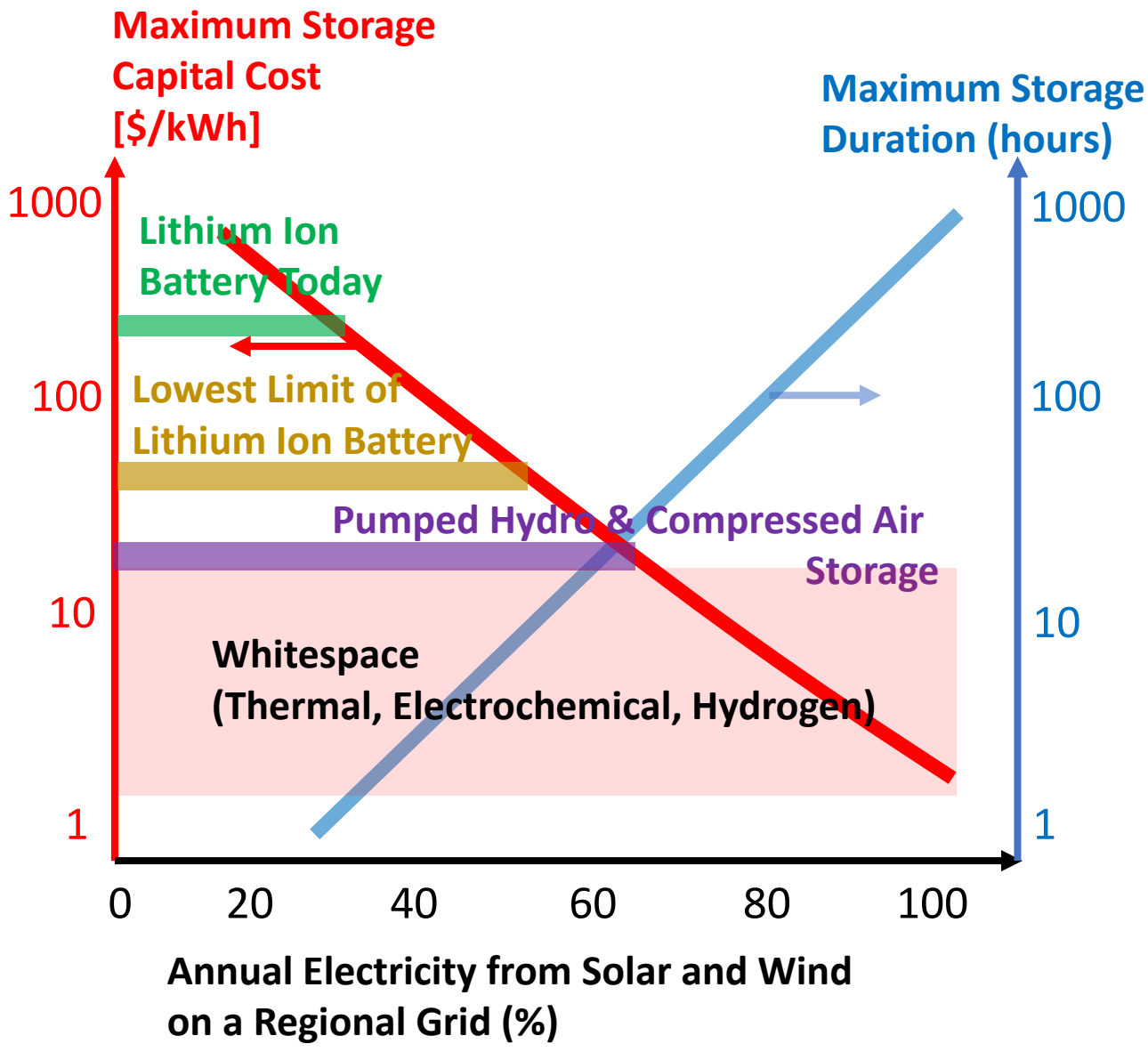
GHG-Free Hydrogen

Potentially $1/kg-$H_2$ or less

Solid Carbon
Black or Fiber

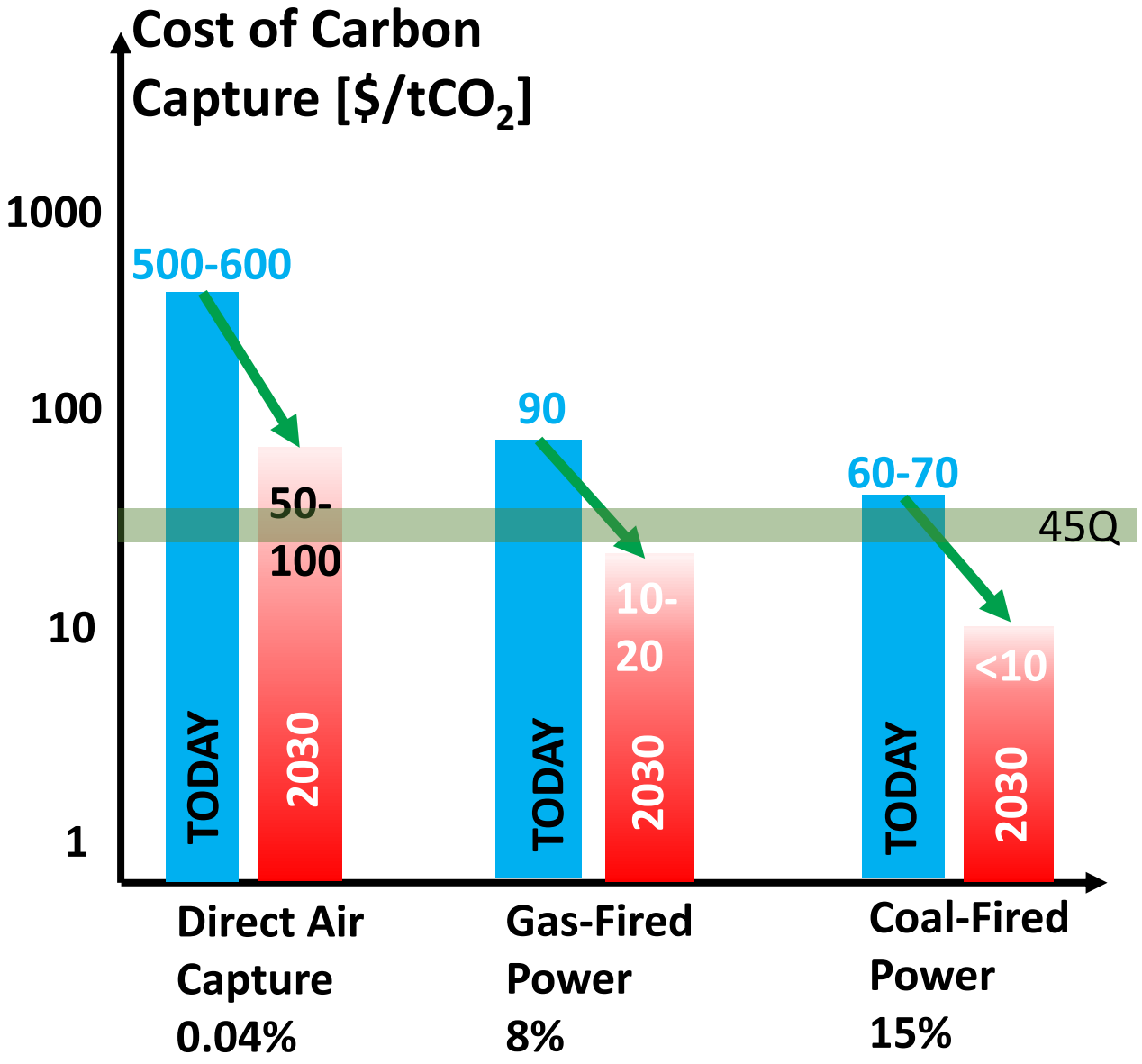


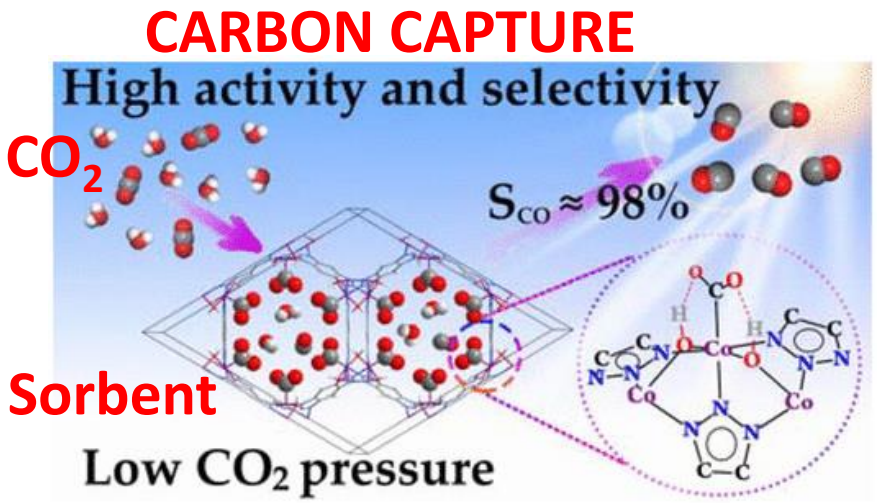
Long-Duration Grid-Scale Storage

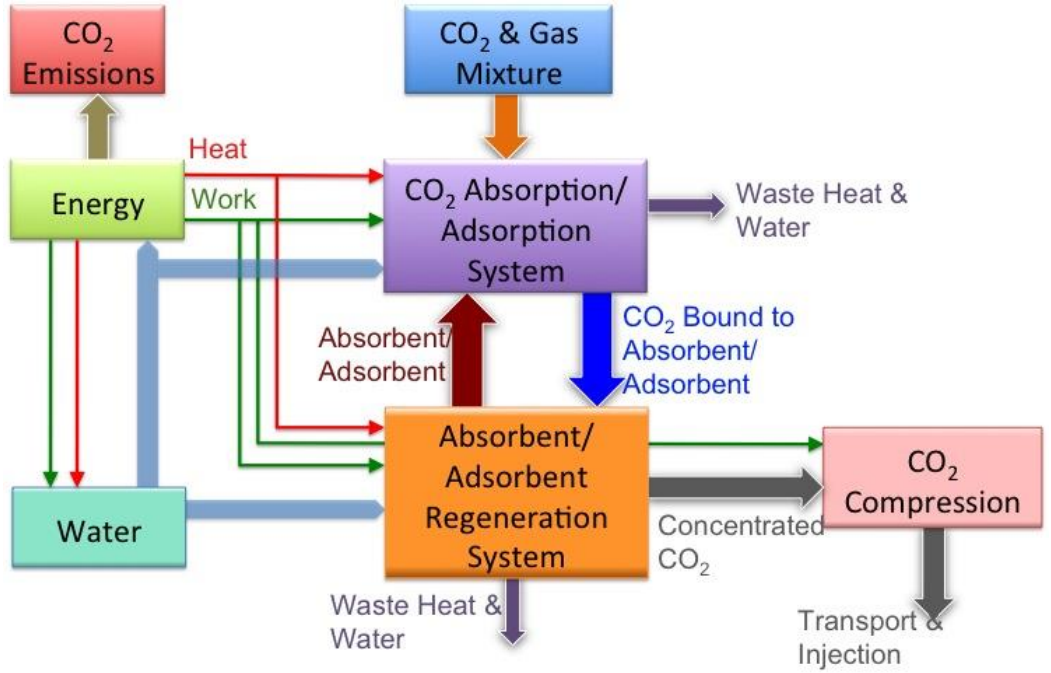


P. Albertus, J.S. Manser, S. Litzelman, "Long-duration electricity storage applications, economics, technology," *Joule* **4**, 21-32 (2020)

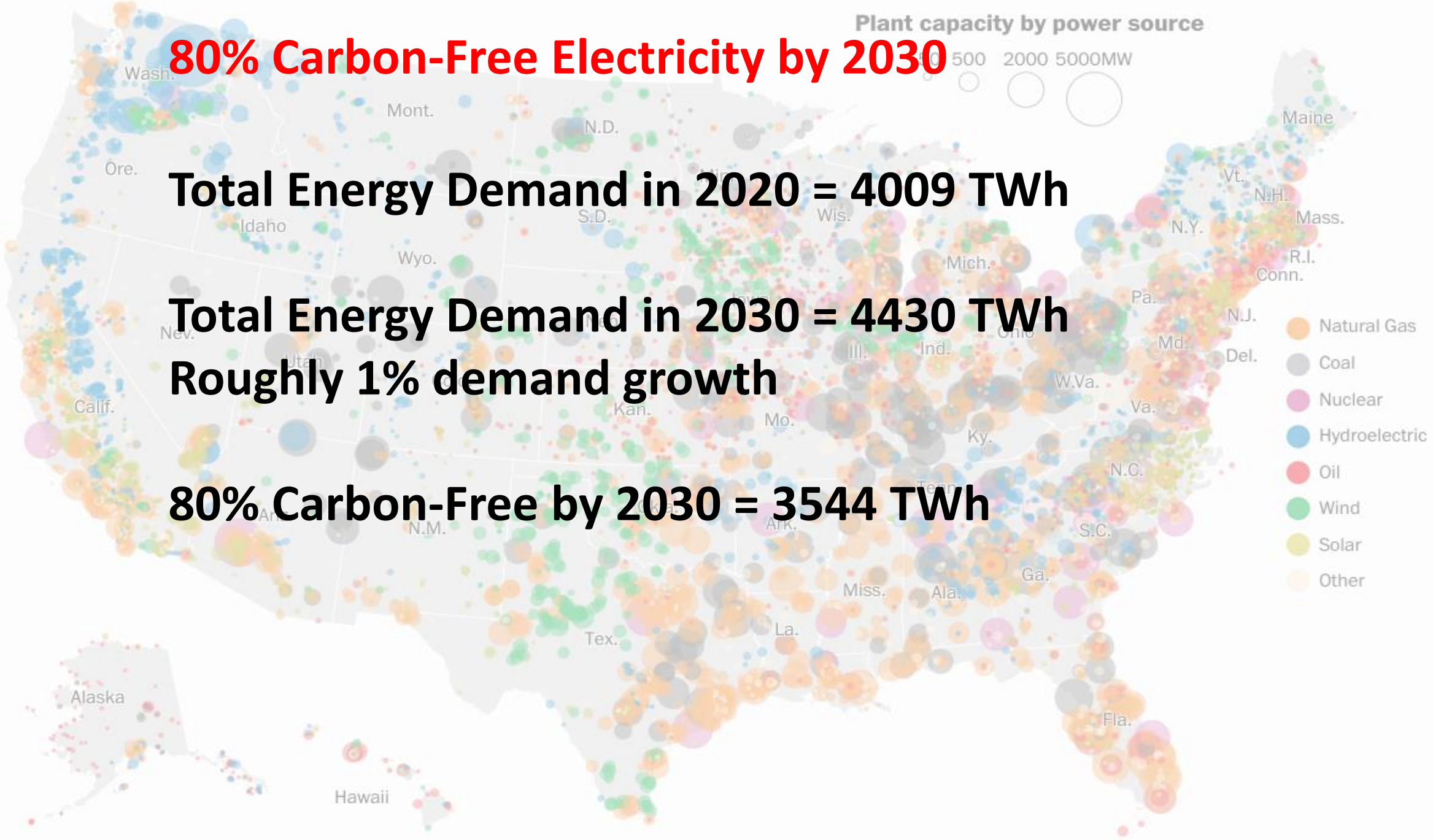
Carbon Capture







80% Carbon-Free Electricity by 2030

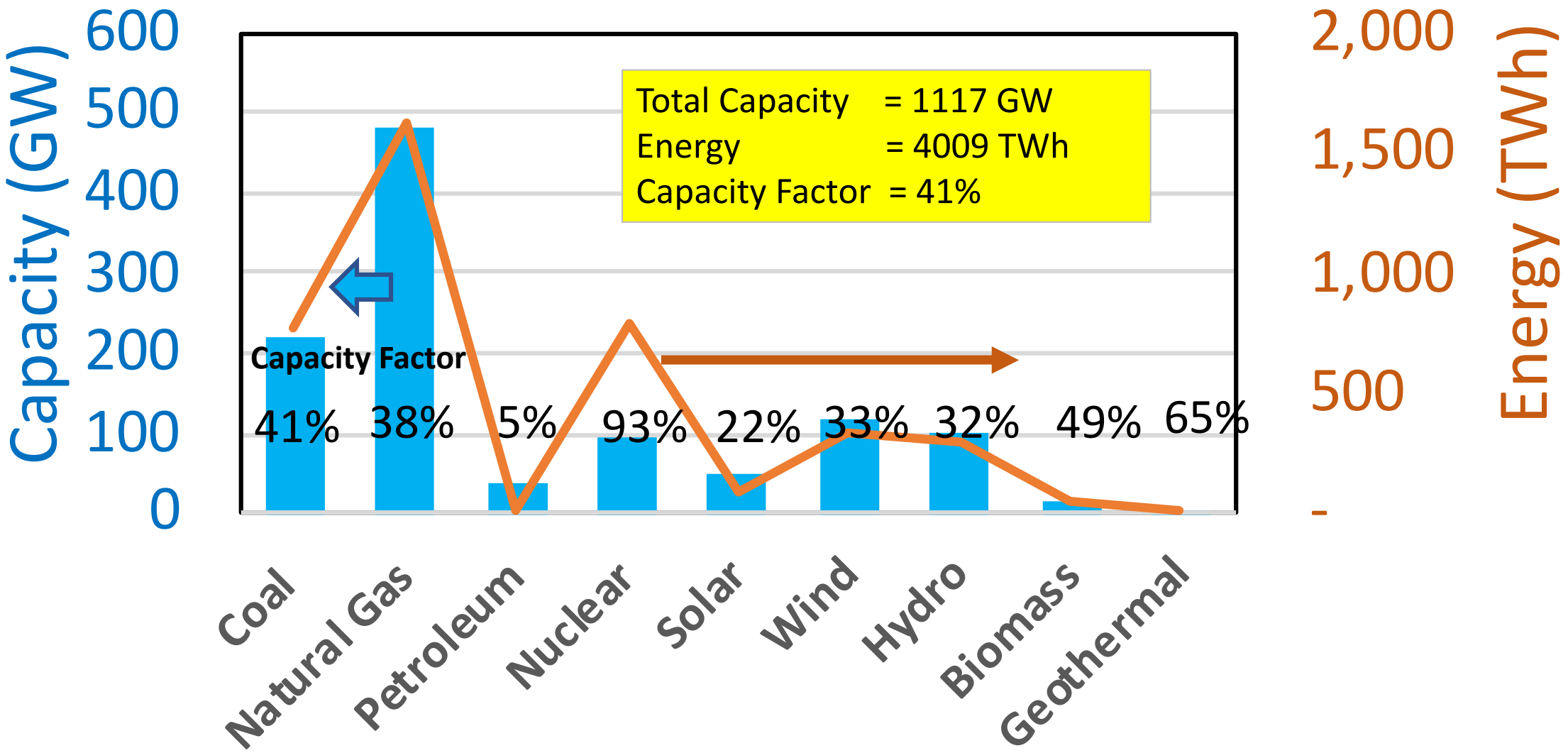


Total Energy Demand in 2020 = 4009 TWh

Total Energy Demand in 2030 = 4430 TWh
Roughly 1% demand growth

80% Carbon-Free by 2030 = 3544 TWh

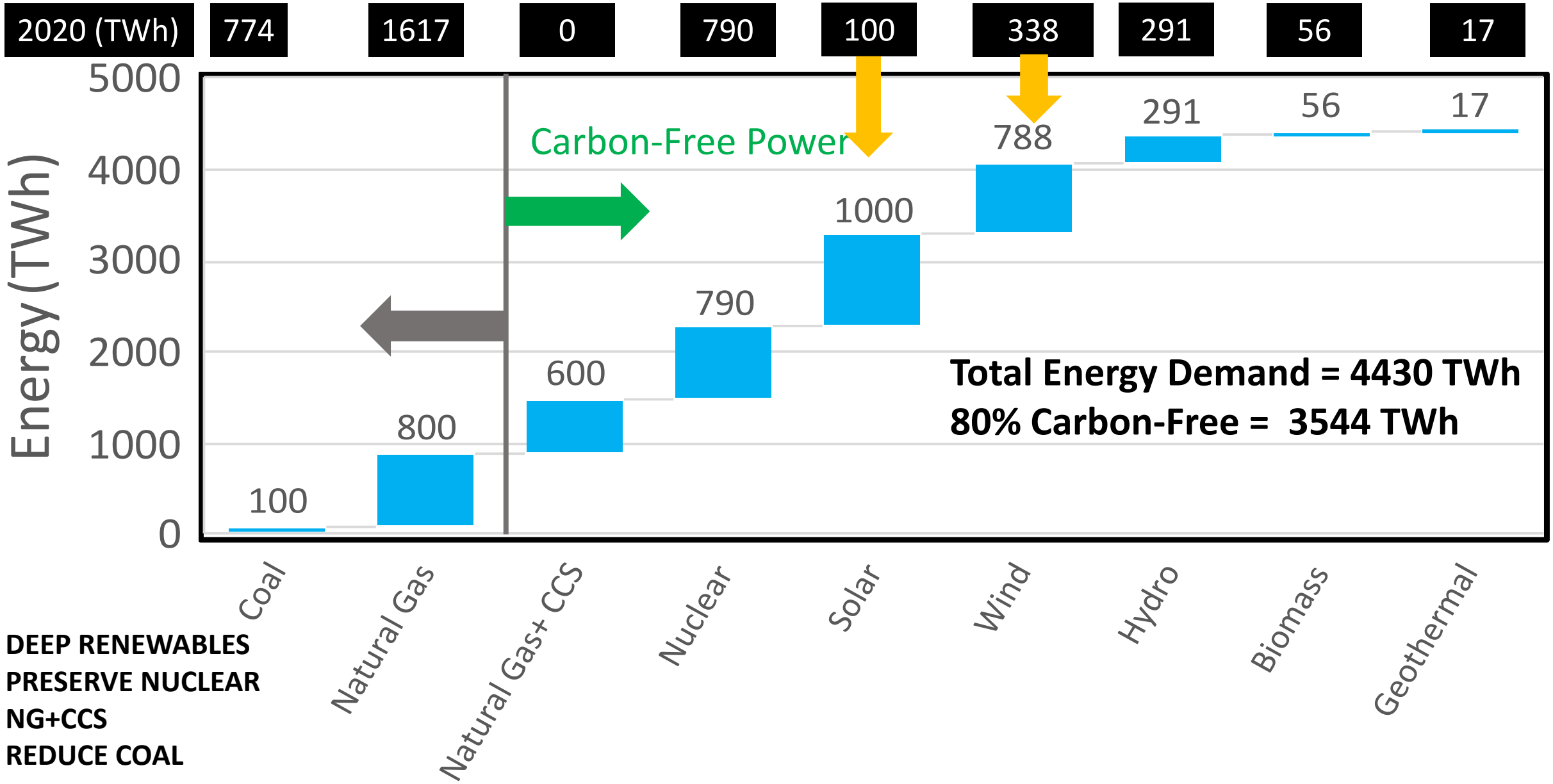
US Power Generation 2020



Source: EIA

10X SOLAR

80% Carbon-Free Energy by 2030



DEEP RENEWABLES
PRESERVE NUCLEAR
NG+CCS
REDUCE COAL

Key Messages & Policy Options

- A direct [revenue neutral carbon tax] or indirect [clean energy standards] reasonable price on carbon [>$50/tCO$_2$]
- Energy efficiency to reduce total demand (TWh)
  - Whole building performance standards (kWh/m^2-year)
  - Industrial energy efficiency standards
- Preserve current nuclear, try adding new nuclear
  - Payment for current nuclear plants
  - Market for small modular nuclear
- Aggressive deployment of solar and wind
  - Transmission line infrastructure
  - R&D and Incentives for long-duration storage
- Need natural gas with CCS for balancing grid
  - R&D to reduce CCS cost
  - Increase 45Q to incentivize new markets
  - Carve out 45Q for Direct Air Capture
  - Authorize FERC to permit and regulate interstate CO2 pipelines
  - Expedite permitting for CO2 sequestration
- Hydrogen for Hard-to-Abate Sectors
  - R&D to develop technology and reduce cost of electrolyzers and pyrolyzers
  - Markets for solid carbon
  - Incentivize ammonia infrastructure as carrier of H_2

We must not leave anyone behind in this energy transition