



On the Potential Large-Scale Commercial Deployment of Carbon Dioxide Capture and Storage Technologies:

Findings from Phase 2 of the Global Energy Technology Strategy Project

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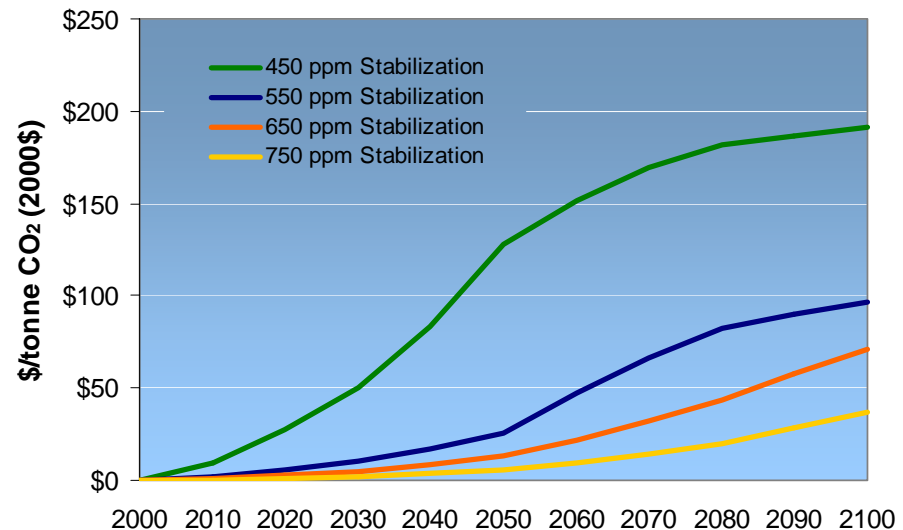
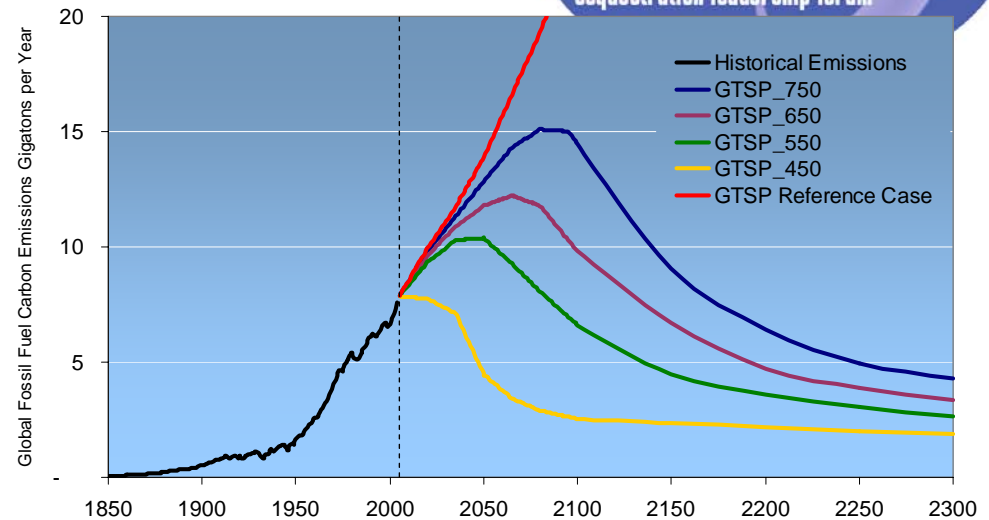
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Climate change is a long-term strategic problem with implications for today



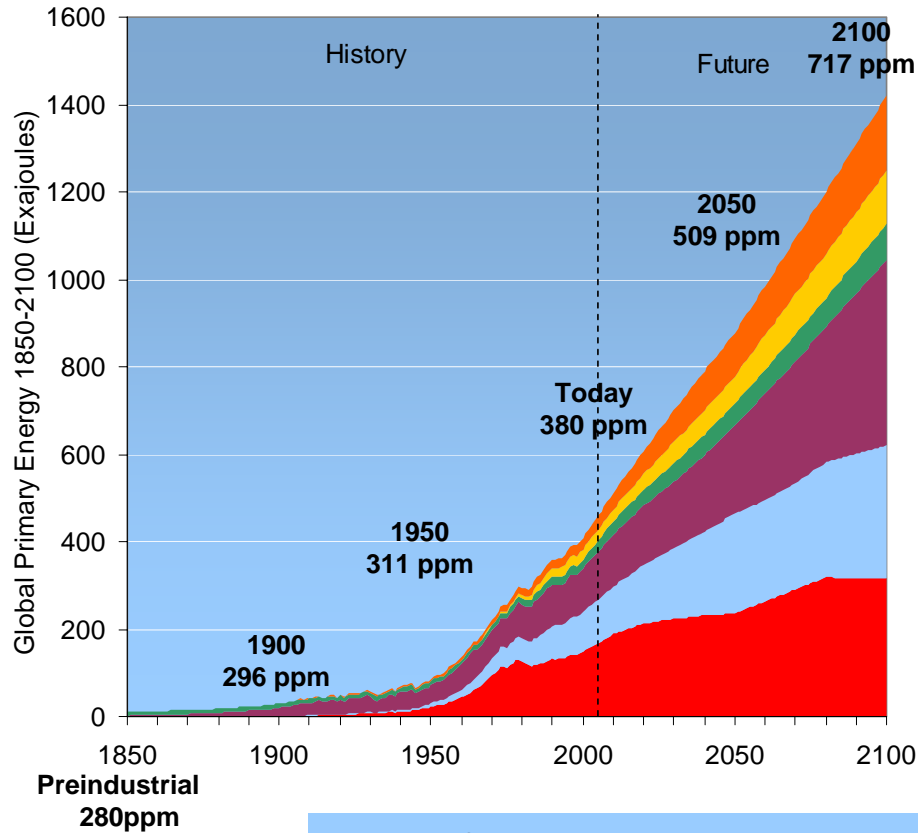
- Stabilizing atmospheric concentrations of greenhouse gases and not their annual emissions levels should be the overarching strategic goal of climate policy.
- This tells us that a fixed and finite amount of CO₂ can be released to the atmosphere over the course of this century.
 - We all share a planetary greenhouse gas emissions budget.
 - Every ton of emissions released to the atmosphere reduces the budget left for future generations.
 - As we move forward in time and this planetary emissions budget is drawn down, the remaining allowable emissions will become more valuable.
 - Emissions permit prices should steadily rise with time.



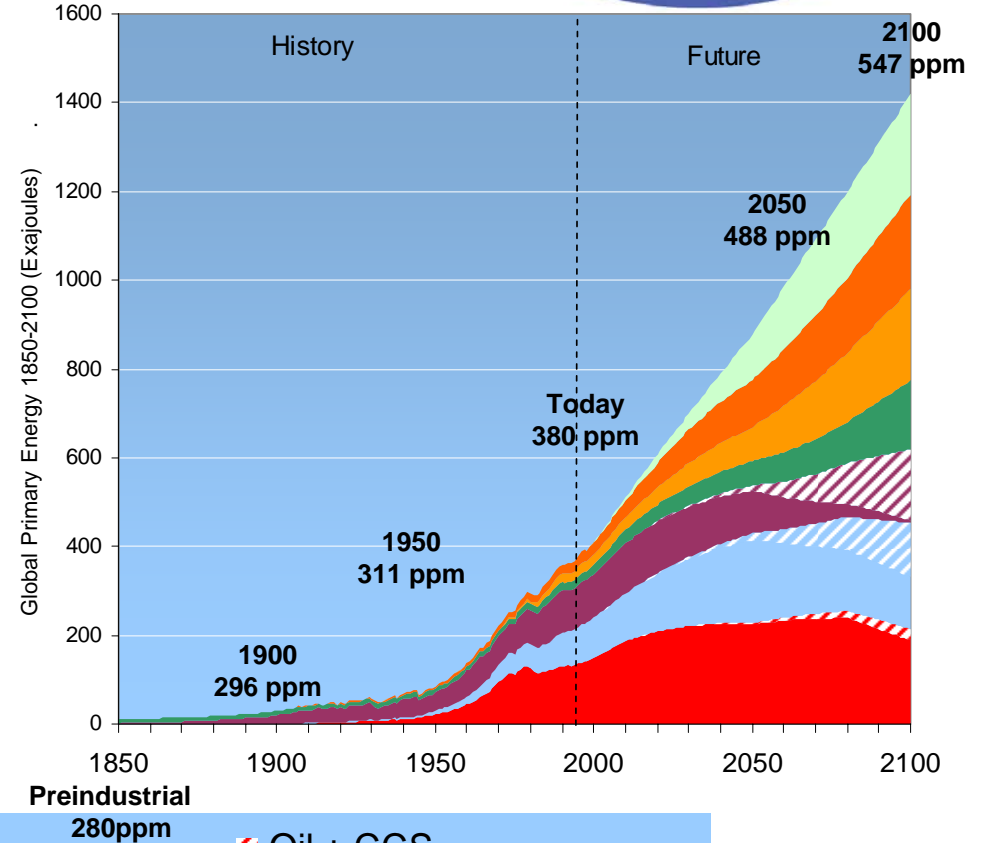
Stabilization of CO₂ concentrations means fundamental change to the global energy system



History and Reference Case



Stabilization of CO₂ at 550 ppm

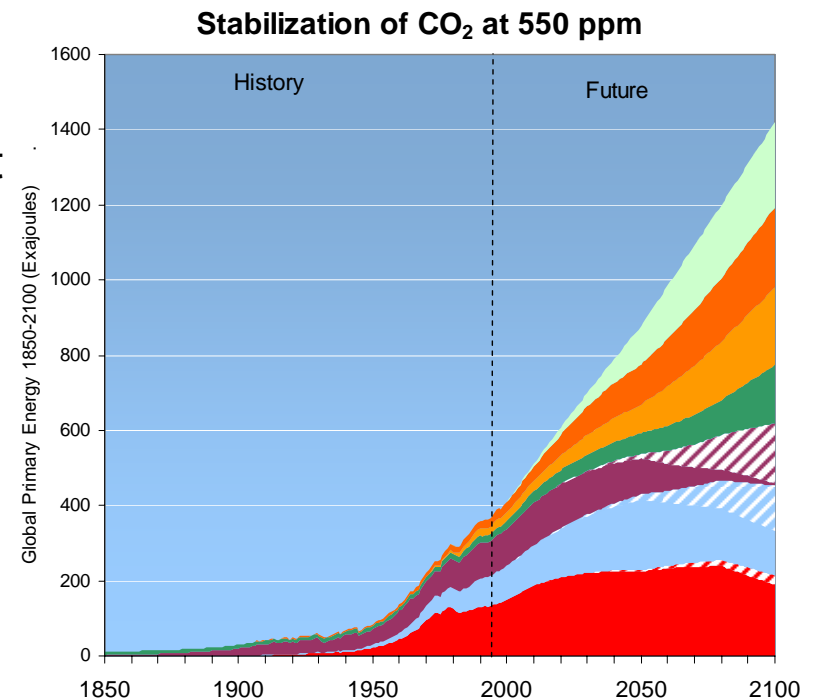


- Oil
- Natural Gas
- Coal
- Biomass Energy
- Non-Biomass Renewable Energy
- Oil + CCS
- Natural Gas + CCS
- Coal + CCS
- Nuclear Energy
- End-use Energy

Stabilization of CO₂ concentrations means fundamental change to the global energy system...



- CO₂ capture and storage (CCS) plays a potentially large role assuming that the institutions make adequate provision for its use.
- Bioenergy crops have dramatic potential, but important land-use implications.
- Hydrogen could be a major new energy carrier, but requires important technology advances in fuel cells and storage.
- Nuclear energy could deploy extensively throughout the world but public acceptance, institutional constraints, waste, safety and proliferation issues remain.
- Wind & solar could accelerate their expansion particularly if energy storage improves.
- End-use energy technologies that improve efficiency and/or use energy carriers with low emissions can also play significant roles, e.g. continued electrification of the global economy.



The Macroeconomic Role of CCS Technologies in Addressing Climate Change

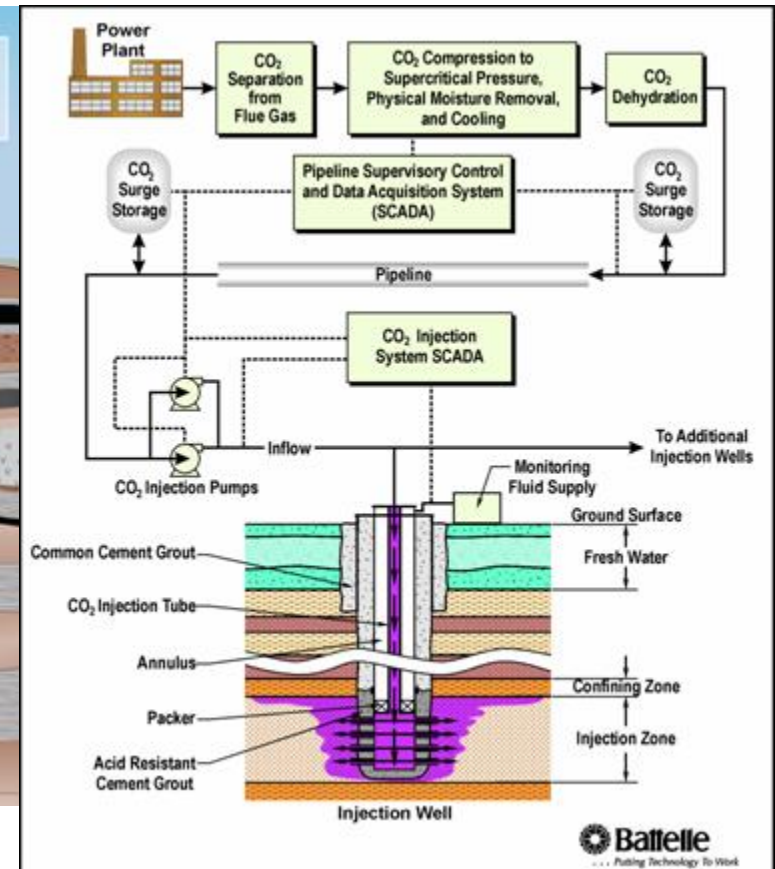
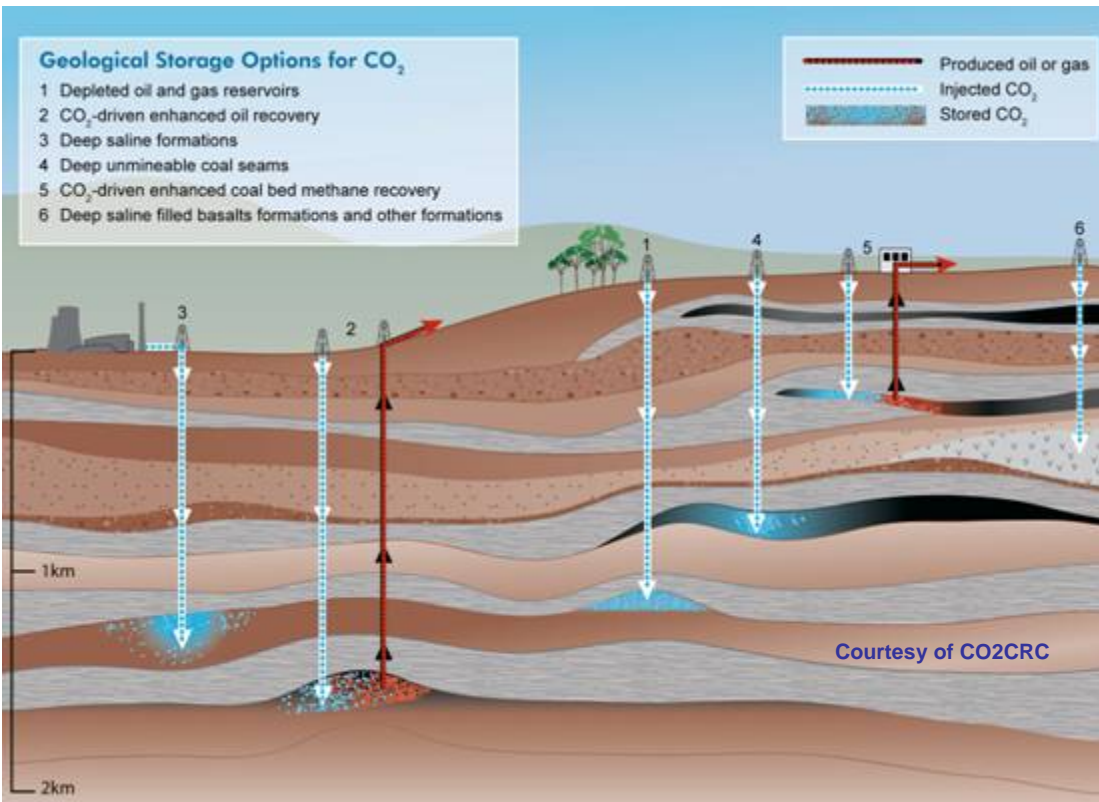


- Plenty of theoretical CO₂ storage capacity; however this natural resource is not evenly distributed around the world
- Knowing whether a country, region, or specific locale has suitable geologic CO₂ storage reservoirs provides a powerful insight into how that region's energy infrastructure will evolve in a greenhouse gas constrained world.
- The potential market for CCS technologies is and will remain very heterogeneous.
- Baseload coal-fired power plants and potential coal-to-liquids facilities are the largest potential market for CCS technologies.
- The potential deployment of CCS technologies could be massive.

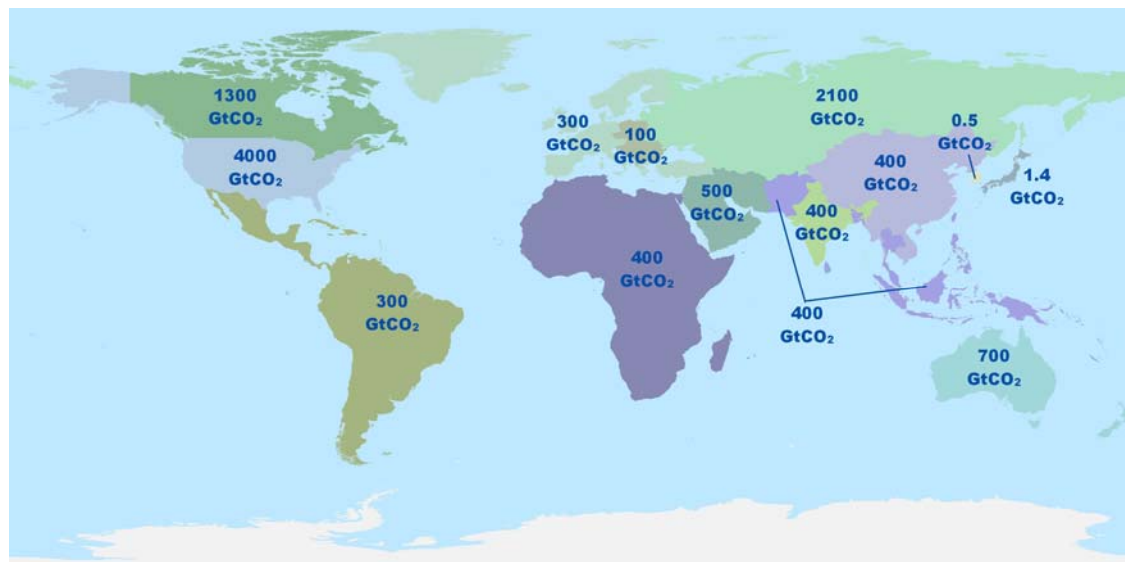
CO₂ Capture and Storage: Not Nearly this Simple



Overview of Carbon Dioxide Capture and Storage (CCS)



Global CO₂ Storage Capacity: *Abundant, Valuable and Very Heterogeneous Natural Resource*



•11,000 GtCO₂ of potentially available storage capacity

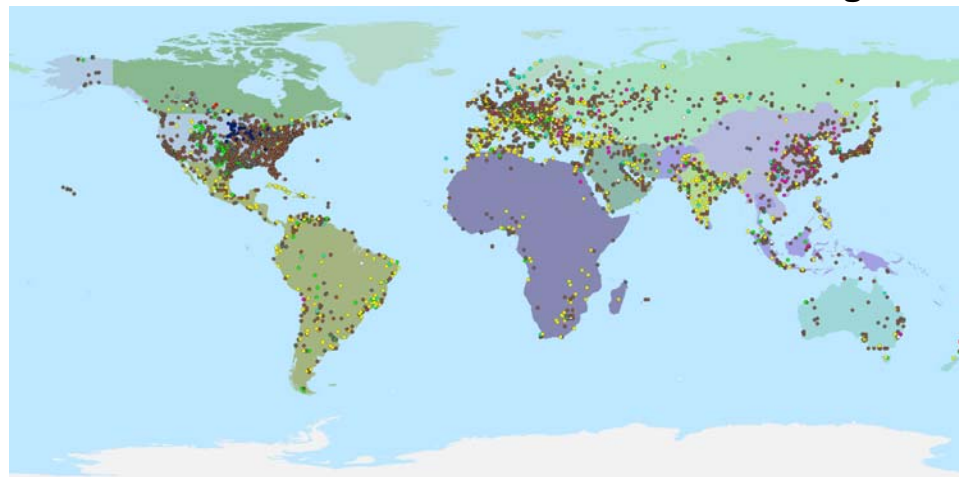
•U.S., Canada and Australia likely have sufficient CO₂ storage capacity for this century

•Japan and Korea's ability to continue using fossil fuels likely constrained by relatively small domestic storage reservoir capacity

•~8100 Large CO₂ Point Sources

• 14.9 GtCO₂/year

•>60% of all global anthropogenic CO₂ emissions

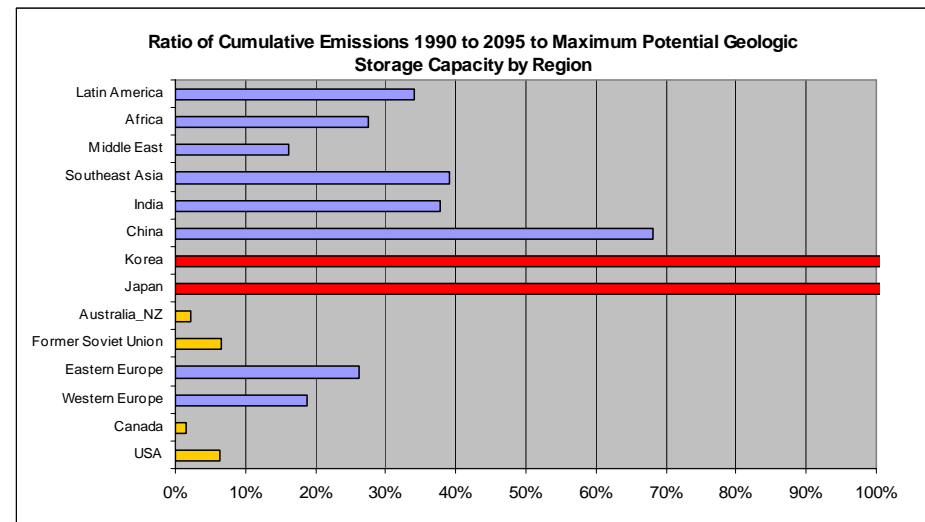
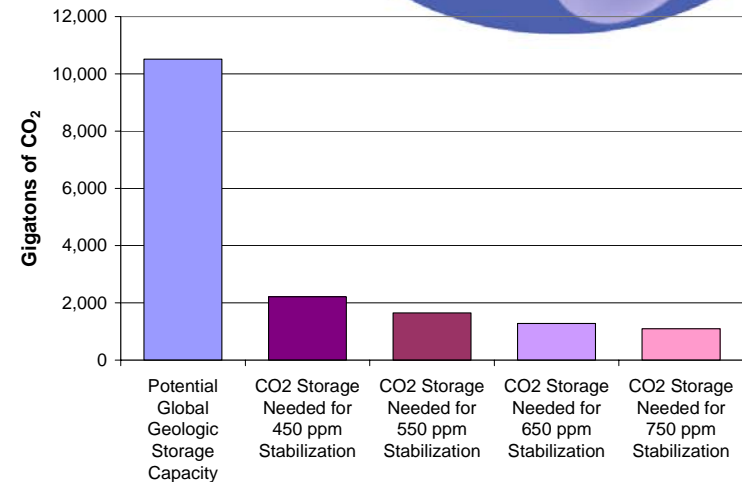


- Ammonia
- Cement
- Ethanol
- Ethylene
- Ethylene oxide
- Gas processing
- Hydrogen
- Iron & steel
- Power
- Refineries
- Other

Global CO₂ Storage Capacity: *Abundant, Valuable and Very Heterogeneous Natural Resource*

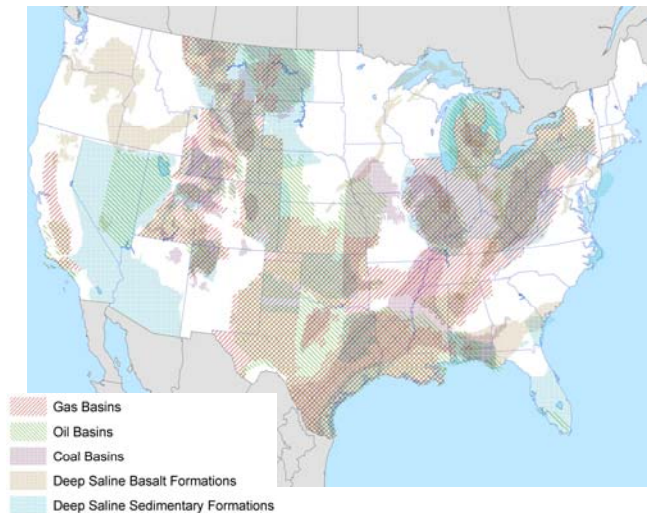


- There appears to be sufficient global theoretical storage capacity to easily accommodate the demand for CO₂ storage for stabilization scenarios ranging from 450-750ppmv.
- However, geologic CO₂ storage reservoirs, like many other natural resources, are not homogenous in quality nor in their distribution:
 - Some regions will be able to use CCS for a very long time and likely with fairly constant and possibly declining costs.
 - In other regions, CCS appears to be more of a transition technology.



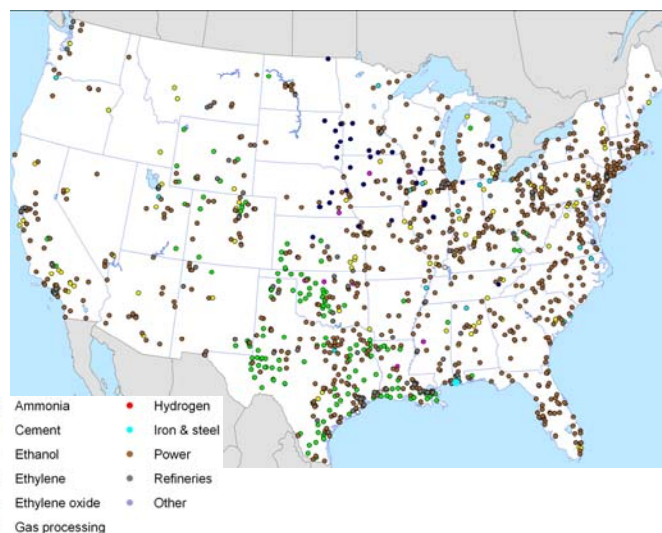
CCS Deployment Across the US Economy

Large CO₂ Storage Resource and Large Potential Demand for CO₂ Storage



3,900+ GtCO₂ Capacity within 230 Candidate Geologic CO₂ Storage Reservoirs

- 2,730 GtCO₂ in deep saline formations (DSF) with perhaps close to another 900 GtCO₂ in offshore DSFs
- 240 Gt CO₂ in on-shore saline filled basalt formations
- 35 GtCO₂ in depleted gas fields
- 30 GtCO₂ in deep unmineable coal seams with potential for enhanced coalbed methane (ECBM) recovery
- 12 GtCO₂ in depleted oil fields with potential for enhanced oil recovery (EOR)



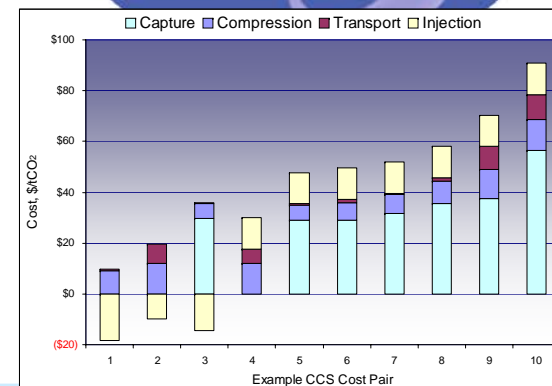
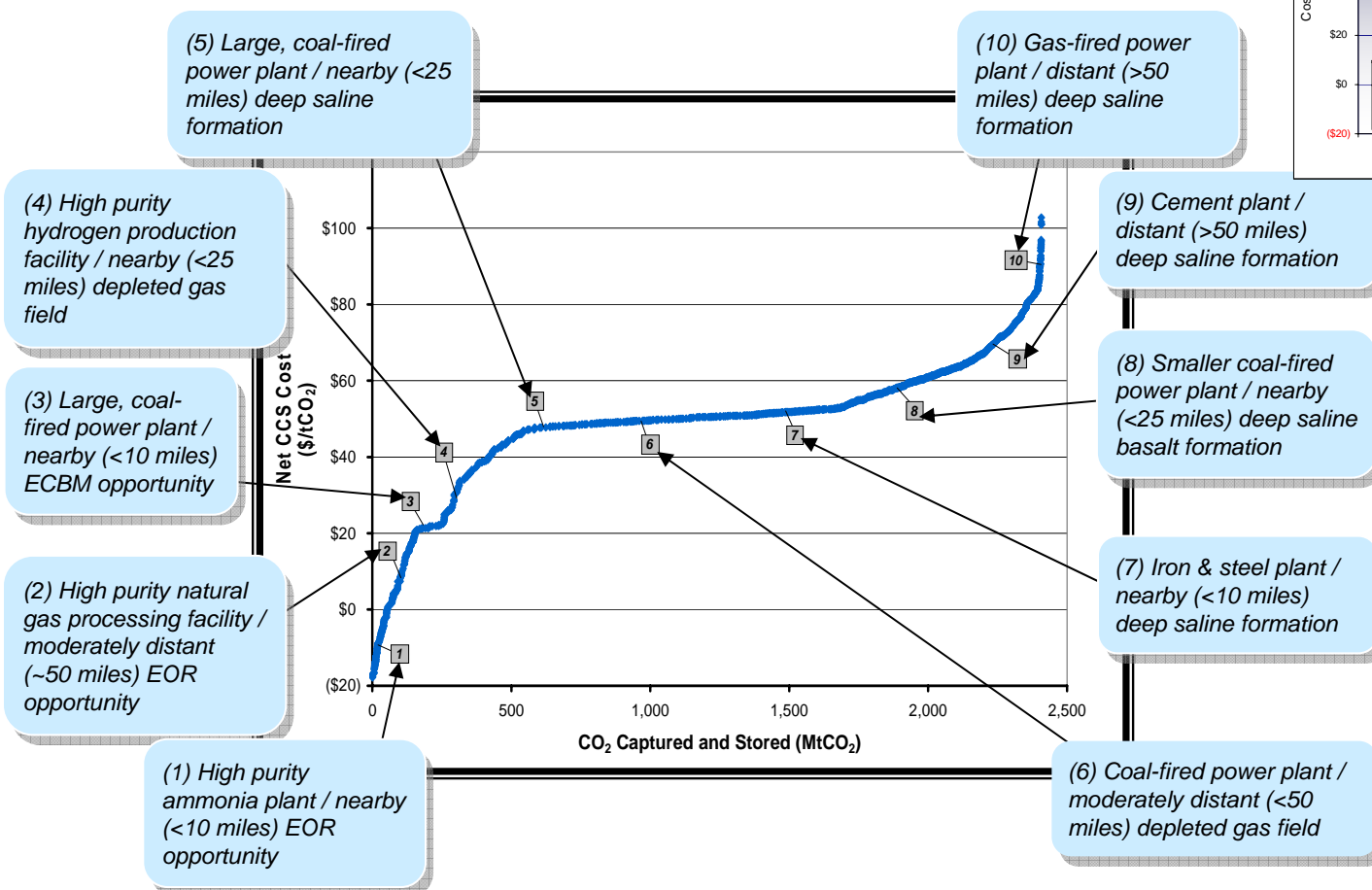
1,715 Large Sources (100+ ktCO₂/yr) with Total Annual Emissions = 2.9 GtCO₂

- 1,053 electric power plants
- 259 natural gas processing facilities
- 126 petroleum refineries
- 44 iron & steel foundries
- 105 cement kilns
- 38 ethylene plants
- 30 hydrogen production
- 19 ammonia refineries
- 34 ethanol production plants
- 7 ethylene oxide plants

CCS Deployment Across the US Economy *Differentiated* CCS Adoption Across Economic Sectors



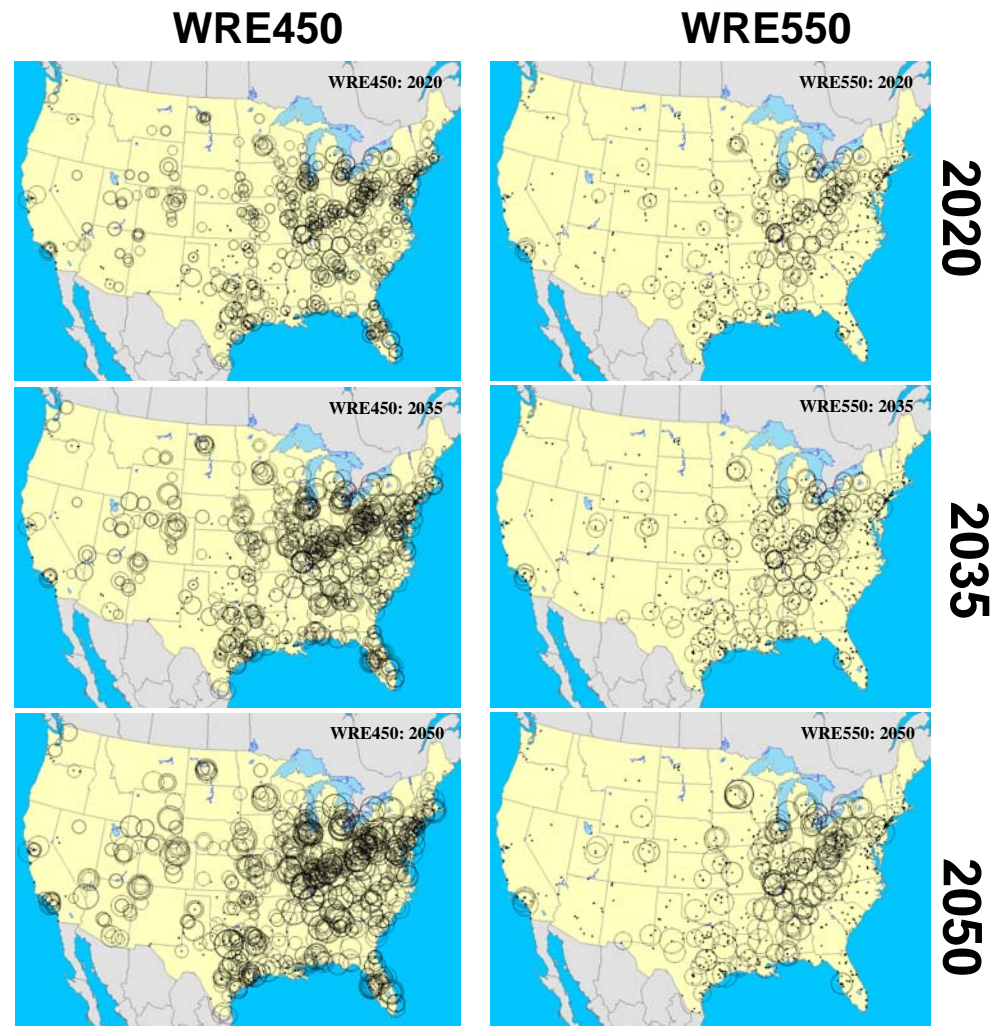
The Net Cost of Employing CCS within the United States - Current Sources and Technology



It is important to realize that we are in the *earliest stages* of the deployment of CCS technologies.



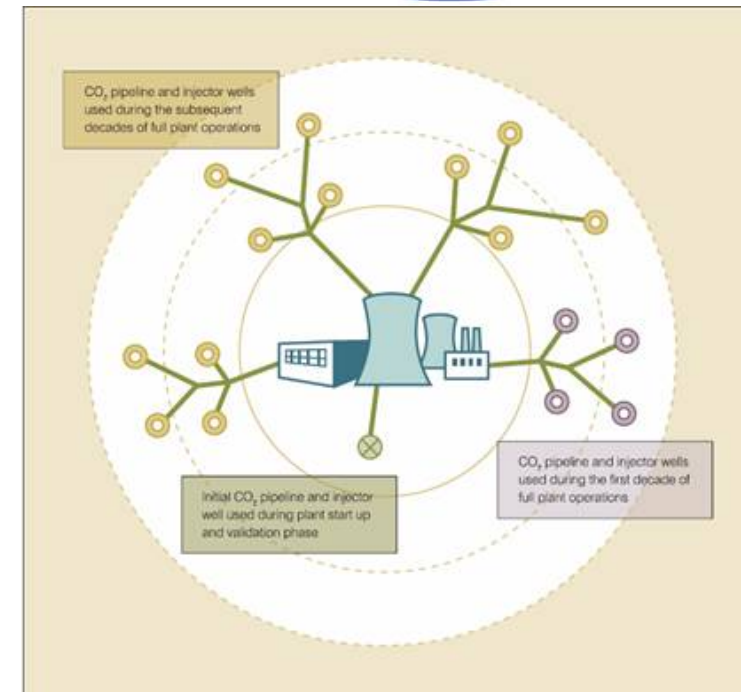
- The potential deployment of CCS technologies could be truly massive. The potential deployment of CCS in the US could entail:
 - 1,000s of power plants and industrial facilities capturing CO₂, 24-7-365.
 - 1,000s of miles of dedicated CO₂ pipelines.
 - 100s of millions of tons of CO₂ being injected into the subsurface annually.
- The deployment across the rest of the world could be at least another order of magnitude.



Geologic CO₂ Storage: Selected Basic Engineering and Operational Issues



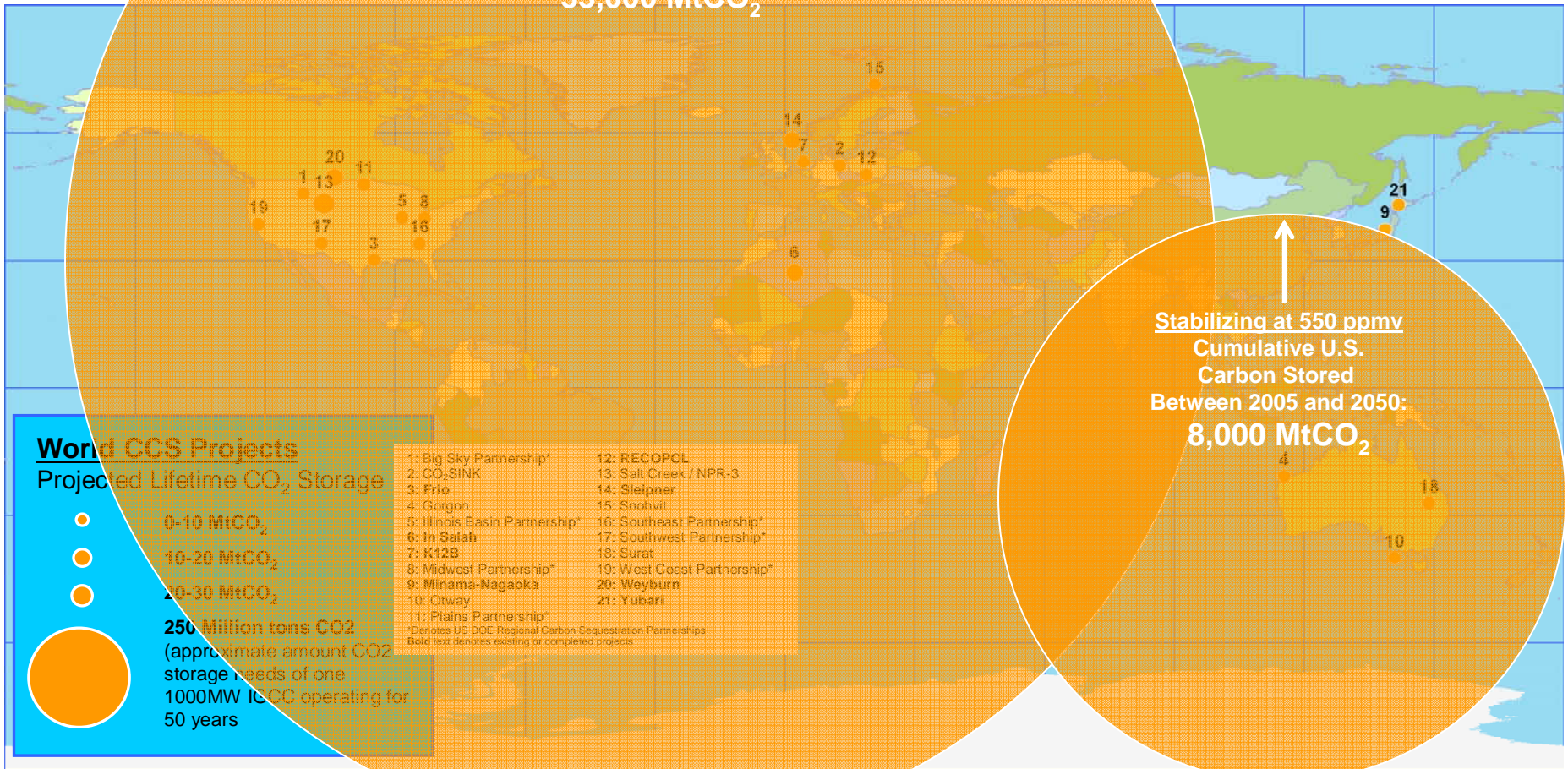
- The cost of capturing CO₂ is **not** the single biggest obstacle standing in the way of CCS deployment.
- No one has ever attempted to determine what it means to store 100% of a large power plant's emissions for 50+ years.
 - How many injector wells will be needed? How close can they be to each other?
 - Can the same injector wells be used for 50+ years?
 - Are the operational characteristics that make a field a good candidate CO₂-driven enhanced oil recovery similar to the demands placed upon deep geologic formation that is being used to isolate large quantities of CO₂ from the atmosphere for the long term?
 - What measurement, monitoring and verification (MMV) "technology suites" should be used and does the suite vary across different classes of geologic reservoirs and/or with time?
 - How long should post injection monitoring last?
 - What are realistic, field deployable remediation options if leakage from the target storage formation is detected?
 - Who will regulate CO₂ storage on a day-to-day basis? What criteria and metrics will this regulator use?



The Scope of the Scale-up Challenge



Stabilizing at 550 ppmv
 Cumulative Global
 Carbon Stored
 Between 2005 and 2050:
33,000 MtCO₂



Stabilizing at 550 ppmv
 Cumulative U.S.
 Carbon Stored
 Between 2005 and 2050:
8,000 MtCO₂

World CCS Projects

Projected Lifetime CO₂ Storage

- 0-10 MtCO₂
- 10-20 MtCO₂
- 20-30 MtCO₂
- 250 Million tons CO₂**
 (approximate amount CO₂
 storage needs of one
 1000MW IGCC operating for
 50 years)

- | | |
|--------------------------------|-----------------------------|
| 1: Big Sky Partnership* | 12: RECOPOL |
| 2: CO ₂ SINK | 13: Salt Creek / NPR-3 |
| 3: Frio | 14: Sleipner |
| 4: Gorgon | 15: Snohvit |
| 5: Illinois Basin Partnership* | 16: Southeast Partnership* |
| 6: In Salah | 17: Southwest Partnership* |
| 7: K12B | 18: Surat |
| 8: Midwest Partnership* | 19: West Coast Partnership* |
| 9: Minama-Nagaoka | 20: Weyburn |
| 10: Otway | 21: Yubari |
| 11: Plains Partnership* | |

*Denotes US DOE Regional Carbon Sequestration Partnerships
 Bold text denotes existing or completed projects

GTSP Phase II Capstone Report on Carbon Dioxide Capture and Storage



- CCS technologies have tremendous potential value for society.
- CCS is, at its core, a climate-change mitigation technology and therefore the large-scale deployment of CCS is contingent upon the timing and nature of future GHG emission control policies.
- The next 5-10 years constitute a critical window in which to amass needed real-world operational experience with CCS systems.
- The electric power sector is the largest potential market for CCS technologies and its potential use of CCS has its own characteristics that need to be better understood.
- Much work needs to be done to ensure that the potential large and rapid scale-up in CCS deployment will be safe and successful.

