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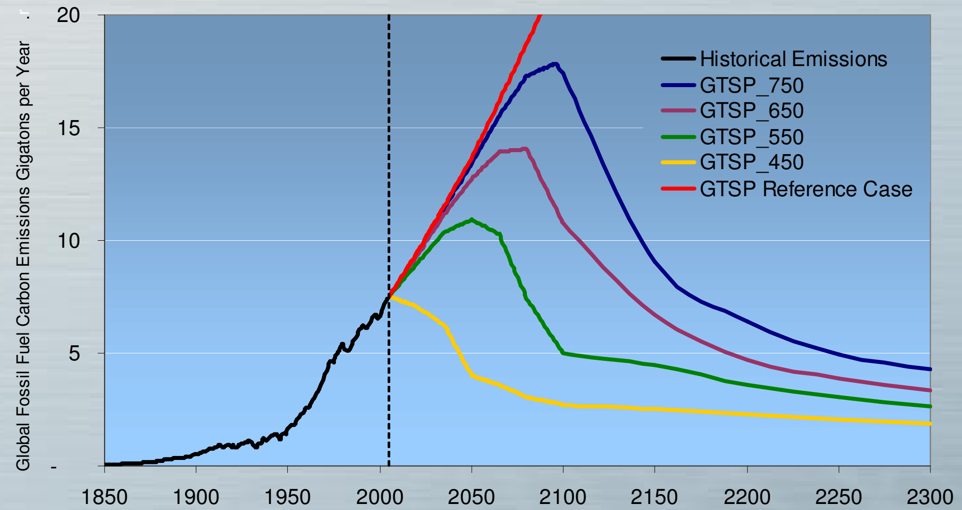
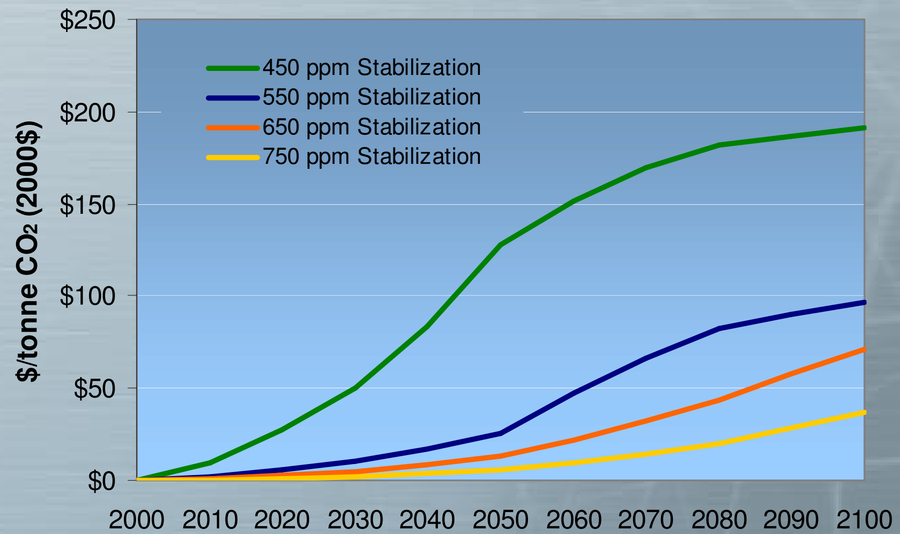
Climate change is a long-term strategic problem with implications for today

- 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 CO_2 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.





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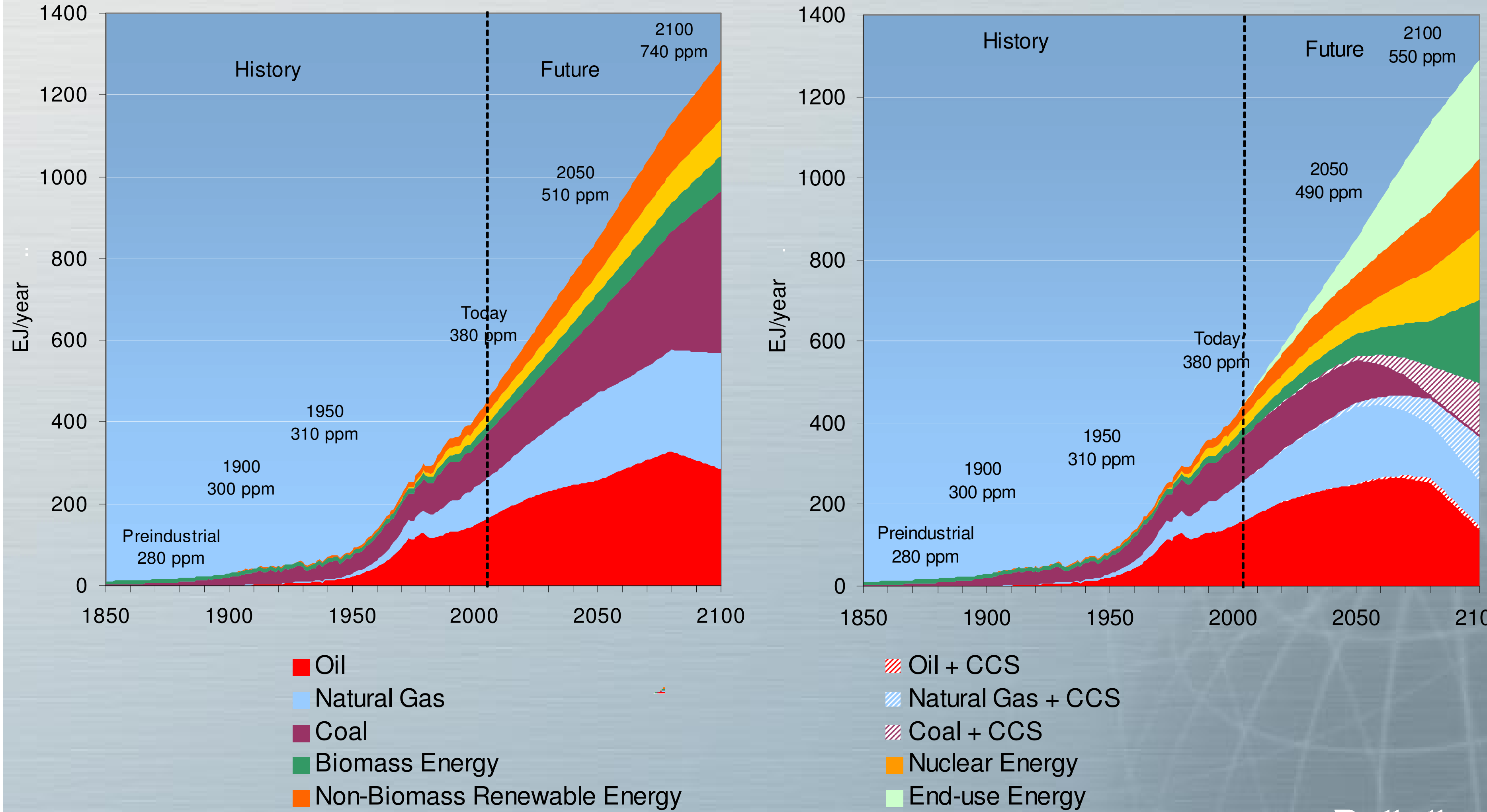
Stabilization of CO_2 concentrations means fundamental change to the global energy system



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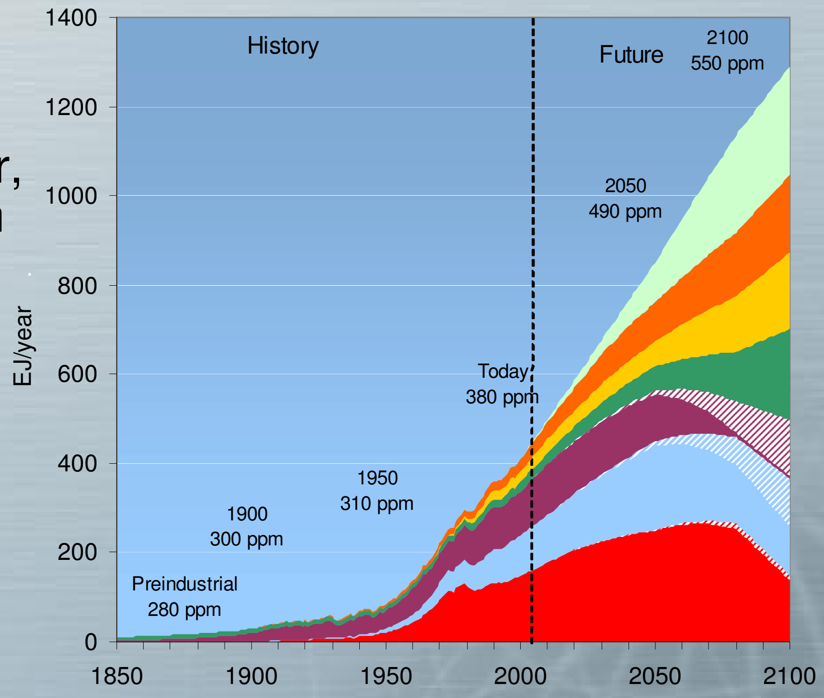
Stabilization of CO_2 concentrations means fundamental change to the global energy system…

- CO_2 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.



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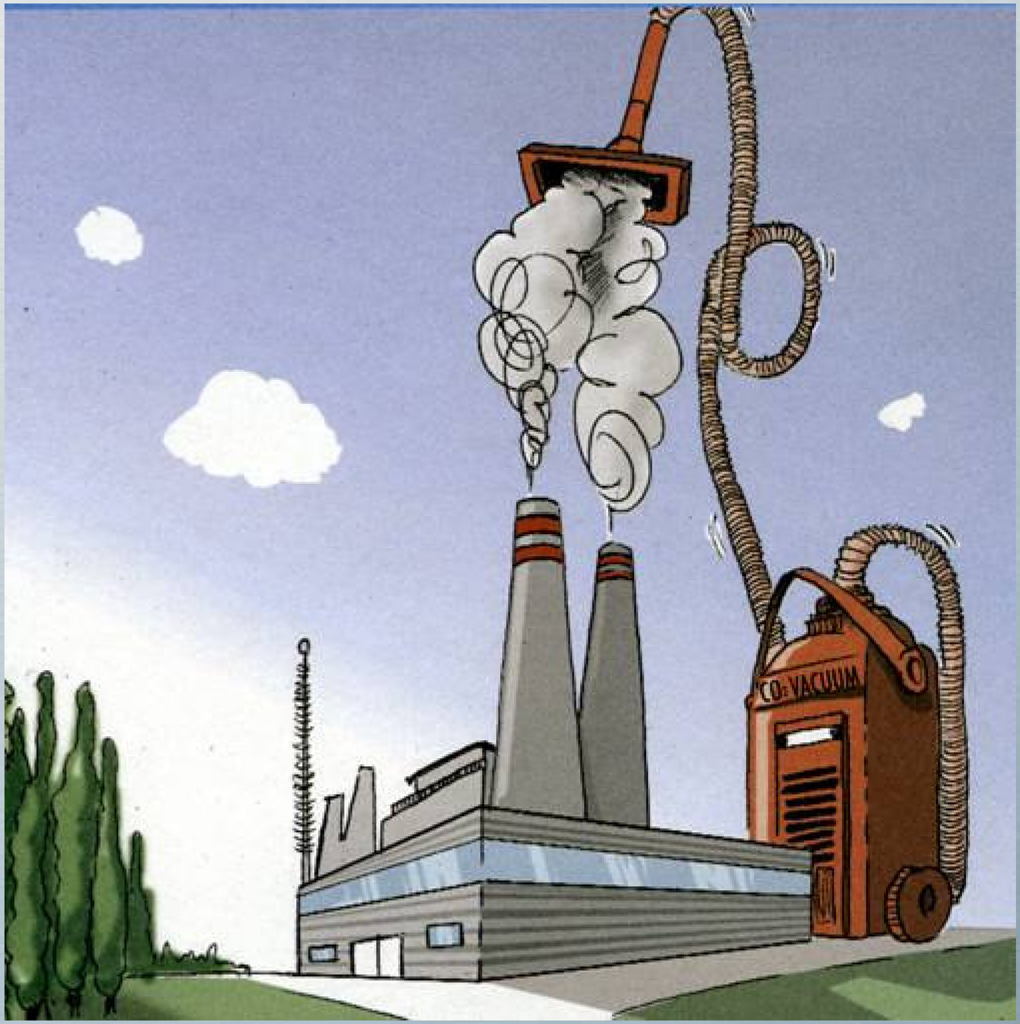
The Macroeconomic Role of CCS Technologies in Addressing Climate Change

- Plenty of theoretical CO_2 storage capacity; however this natural resource is not evenly distributed around the world
- Knowing whether a country, region, or specific locale has suitable geologic CO_2 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.

CO_2 Capture and Storage: Not Nearly this Simple



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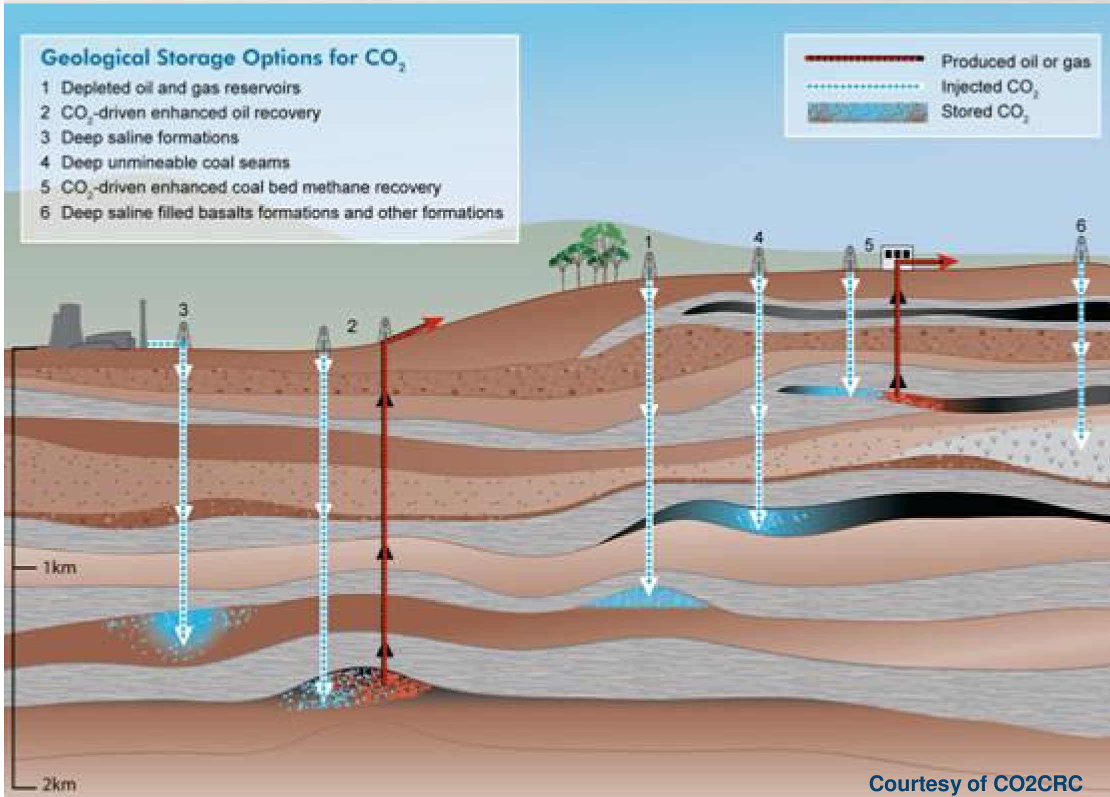
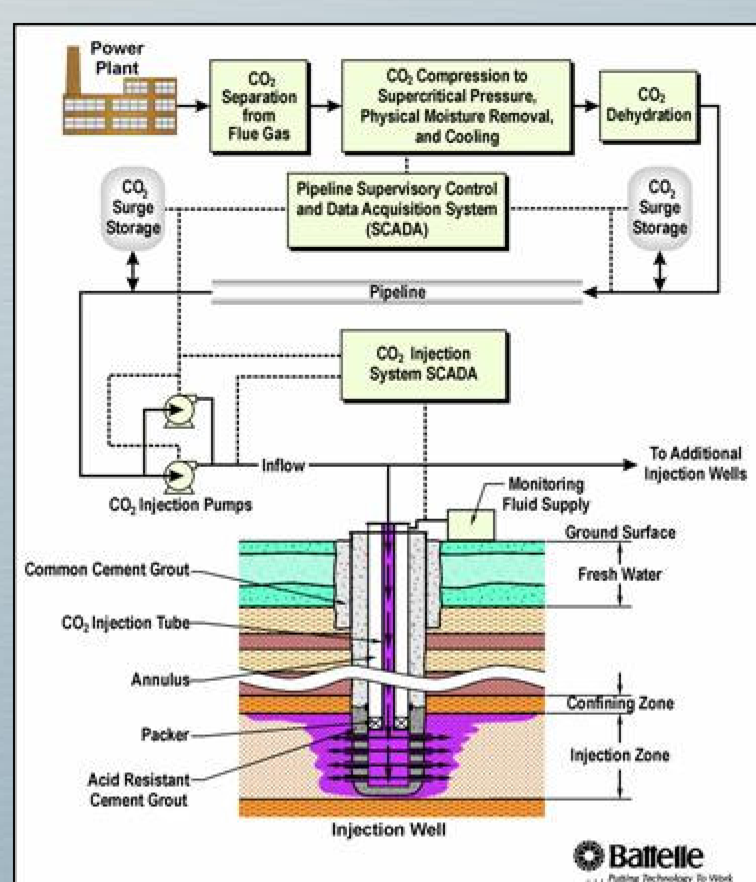
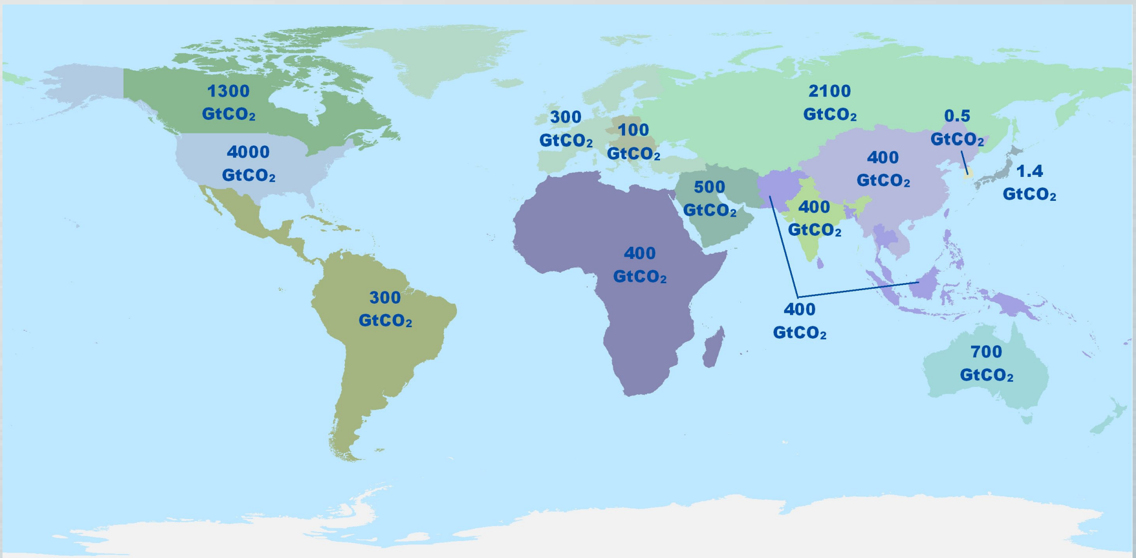
Overview of Carbon Dioxide Capture and Storage (CCS)



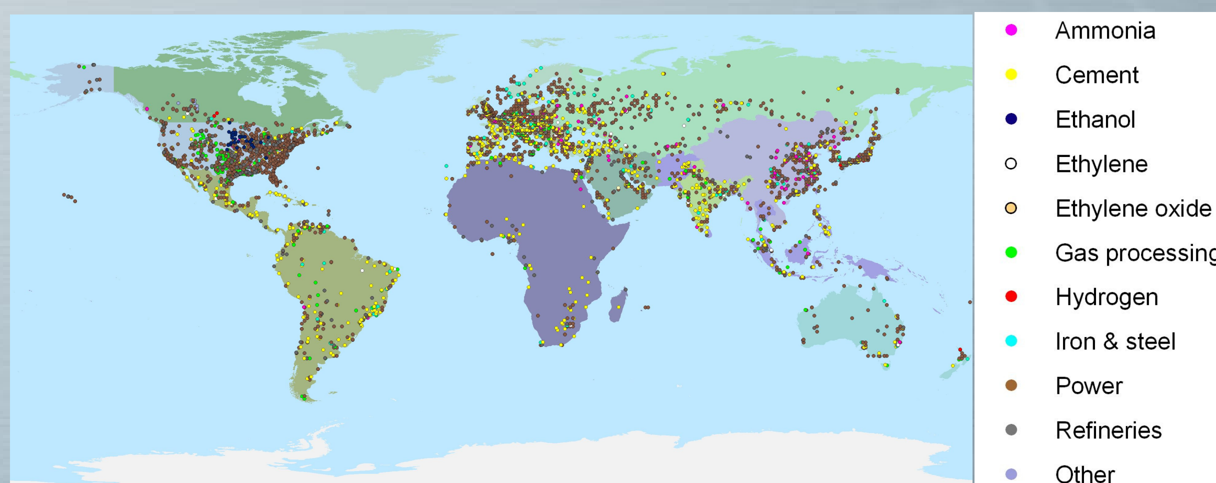


Global CO_2 Storage Capacity:
Abundant, Valuable and Very Heterogeneous Natural Resource



- 11,000 $GtCO_2$ of potentially available storage capacity
- U.S., Canada and Australia likely have sufficient CO_2 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 CO_2 Point Sources
- 14.9 $GtCO_2$/year
- >60% of all global anthropogenic CO_2 emissions

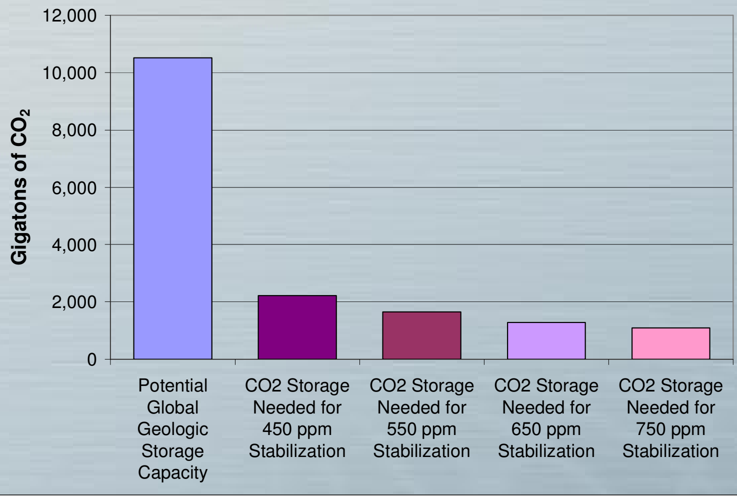


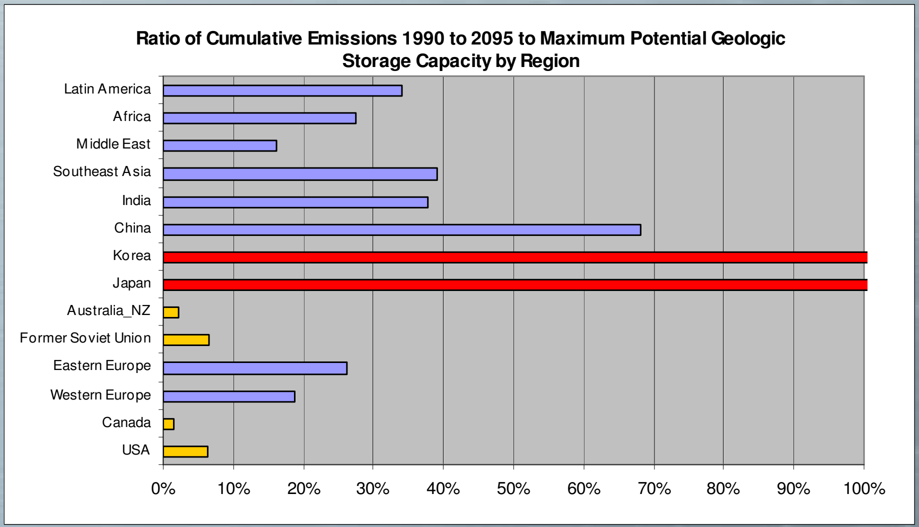
Global CO_2 Storage Capacity:

Abundant, Valuable and Very Heterogeneous Natural Resource

- There appears to be sufficient global theoretical storage capacity to easily accommodate the demand for CO_2 storage for stabilization scenarios ranging from 450-750ppmv.

- However, geologic CO_2 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.





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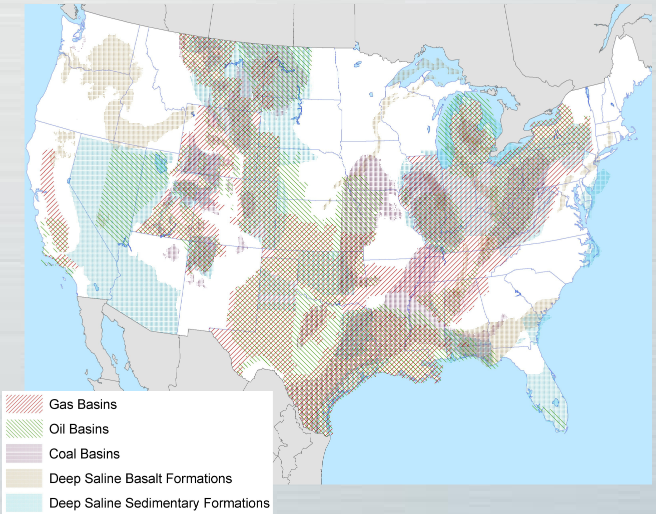
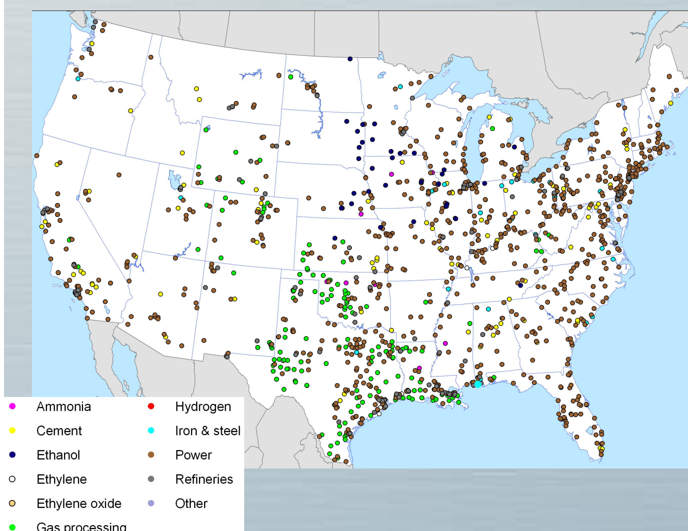
CCS Deployment Across the US Economy

Large CO_2 Storage Resource and Large Potential Demand for CO_2 Storage



3,900+ $GtCO_2$ Capacity within 230 Candidate Geologic CO_2 Storage Reservoirs

- 2,730 $GtCO_2$ in deep saline formations (DSF) with perhaps close to another 900 $GtCO_2$ in offshore DSFs
- 240 Gt CO_2 in on-shore saline filled basalt formations
- 35 $GtCO_2$ in depleted gas fields
- 30 $GtCO_2$ in deep unmineable coal seams with potential for enhanced coalbed methane (ECBM) recovery
- 12 $GtCO_2$ in depleted oil fields with potential for enhanced oil recovery (EOR)



1,715 Large Sources (100+ $ktCO_2$/yr) with Total Annual Emissions = 2.9 $GtCO_2$

- 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

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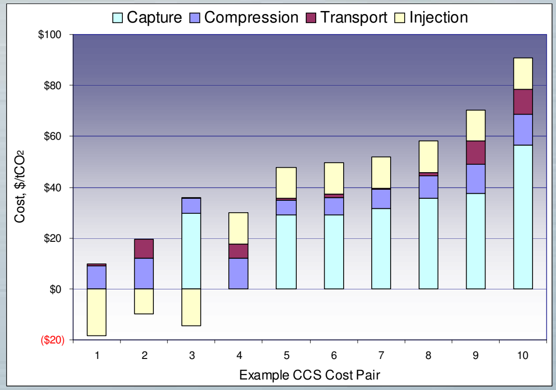
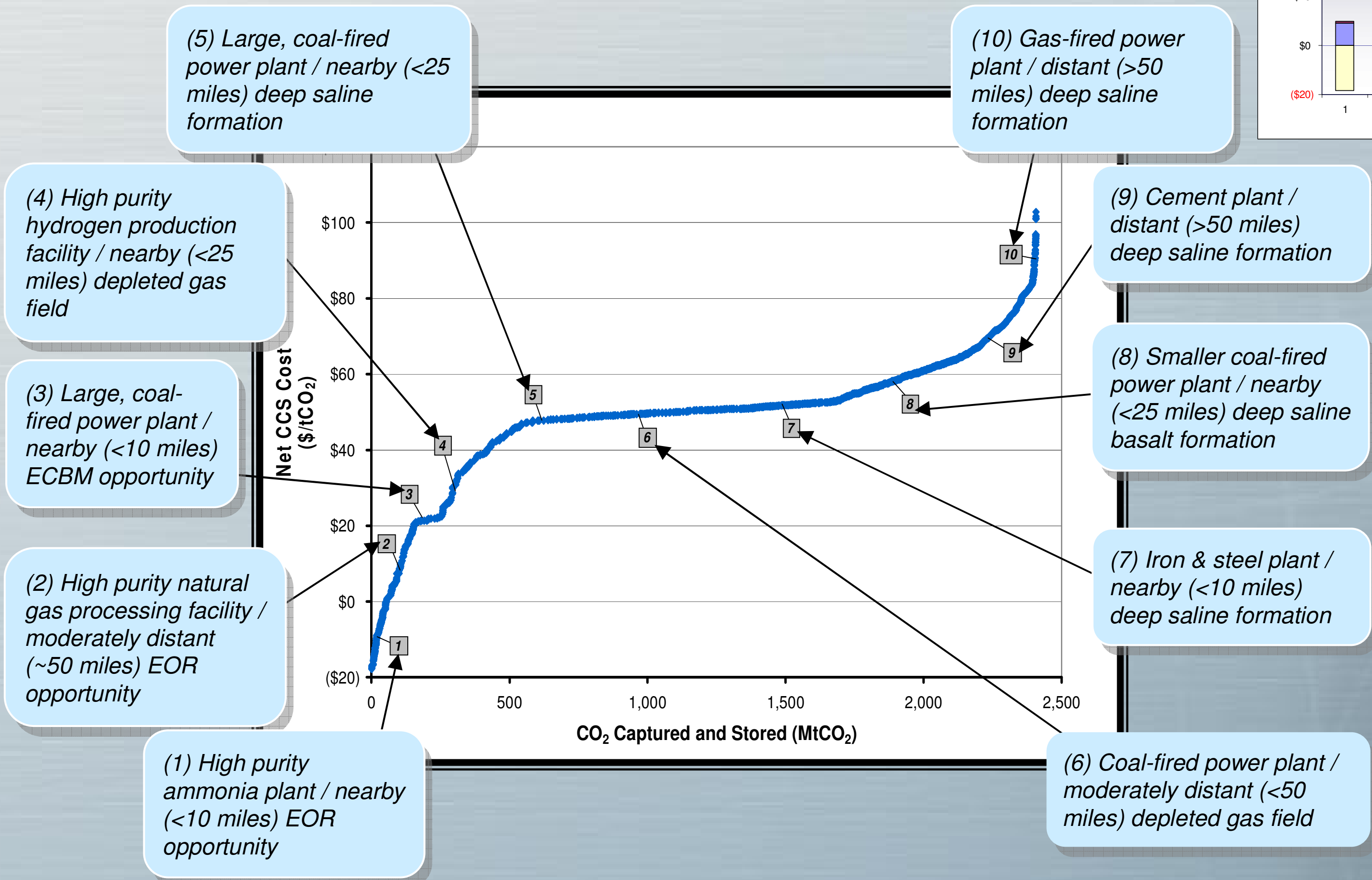
CCS Deployment Across the US Economy

Differentiated CCS Adoption Across Economic Sectors



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



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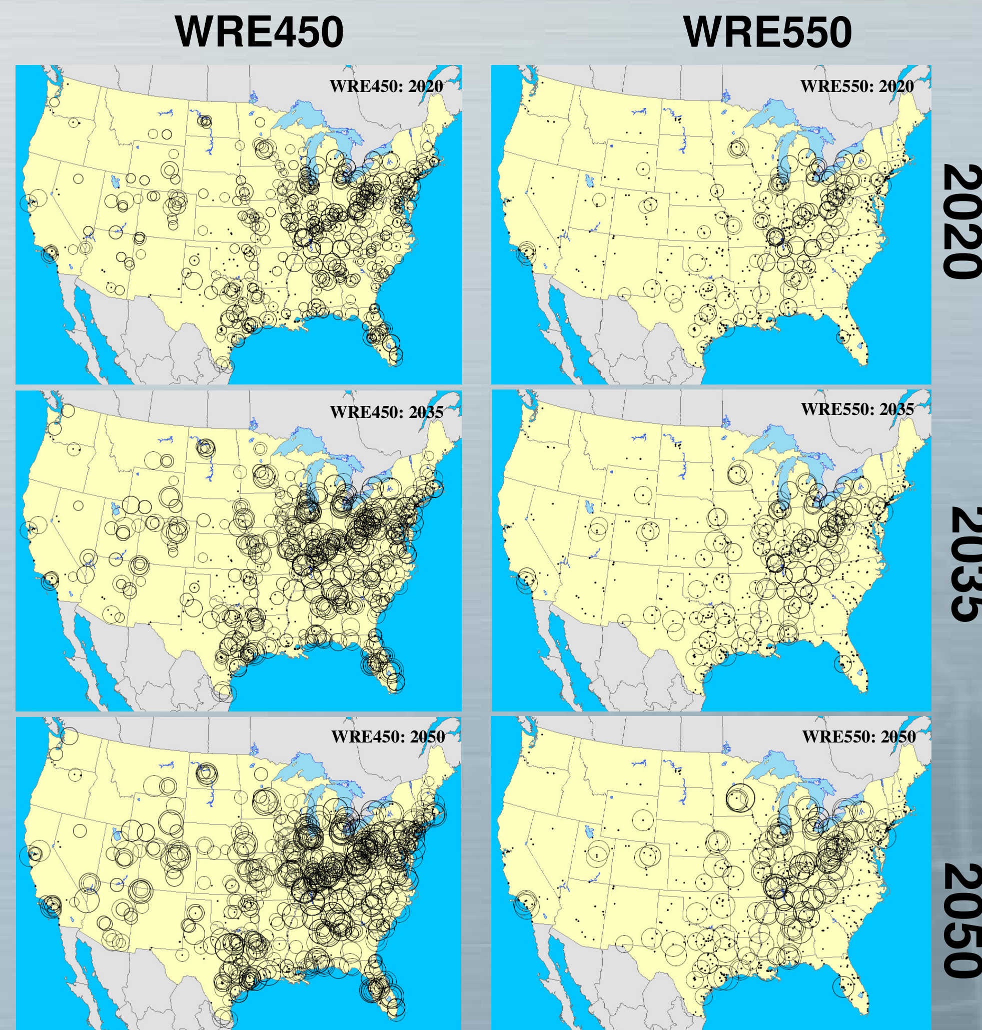
It is important to realize that we are in the *earliest stages* of the deployment of CCS technologies.

- 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 CO_2, 24-7-365.
  - 1,000s of miles of dedicated CO_2 pipelines.
  - 100s of millions of tons of CO_2 being injected into the subsurface annually.

- The deployment across the rest of the world could be at least another order of magnitude.



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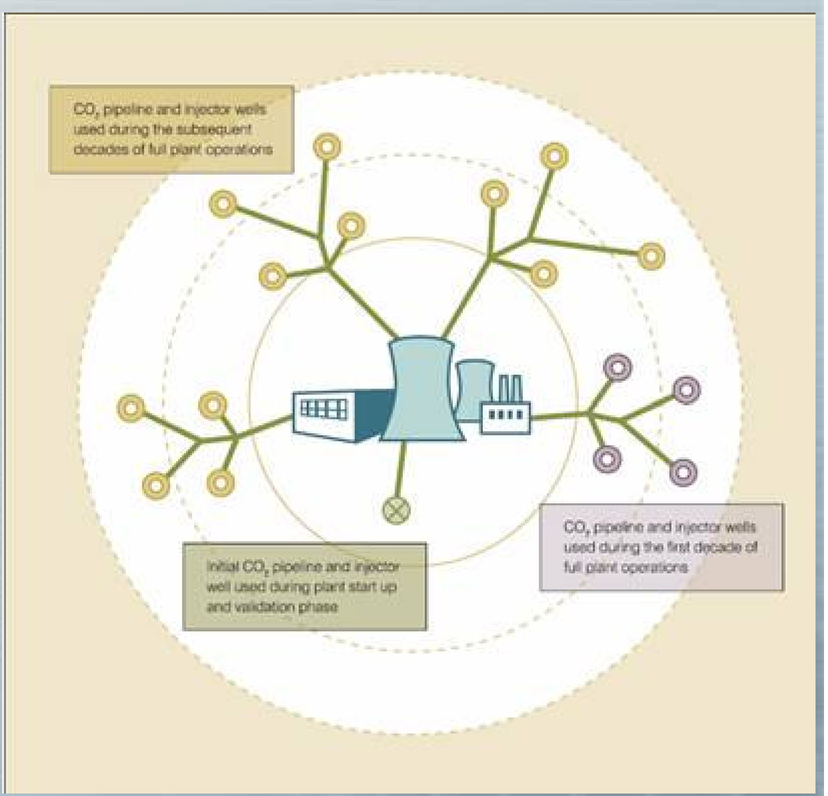
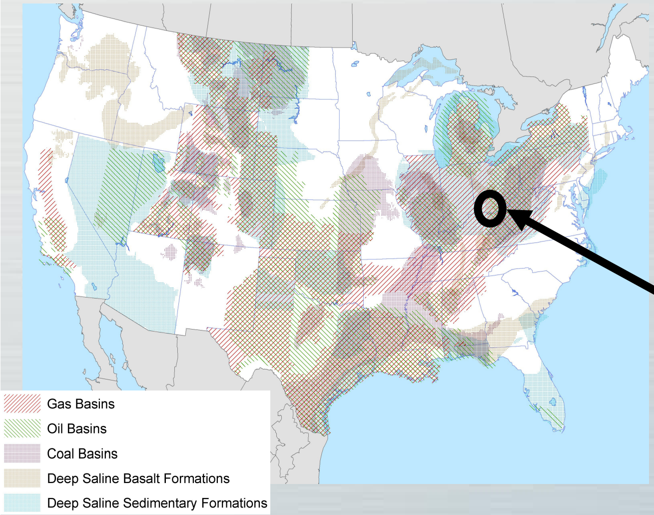
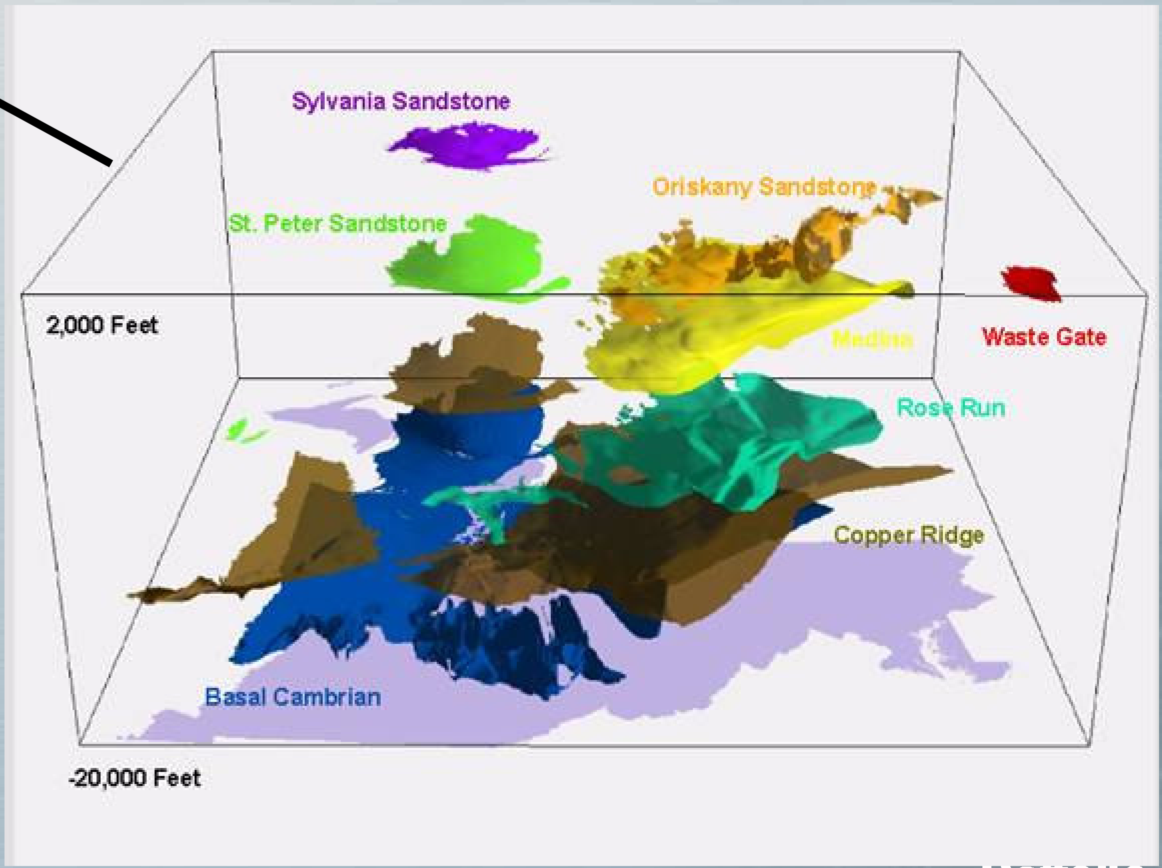
Geologic CO_2 Storage: Selected Basic Engineering and Operational Issues

- The cost of capturing CO_2 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 CO_2-driven enhanced oil recovery similar to the demands placed upon deep geologic formation that is being used to isolate large quantities of CO_2 from the atmosphere fore 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 CO_2 storage on a day-to-day basis? What criteria and metrics will this regulator use?

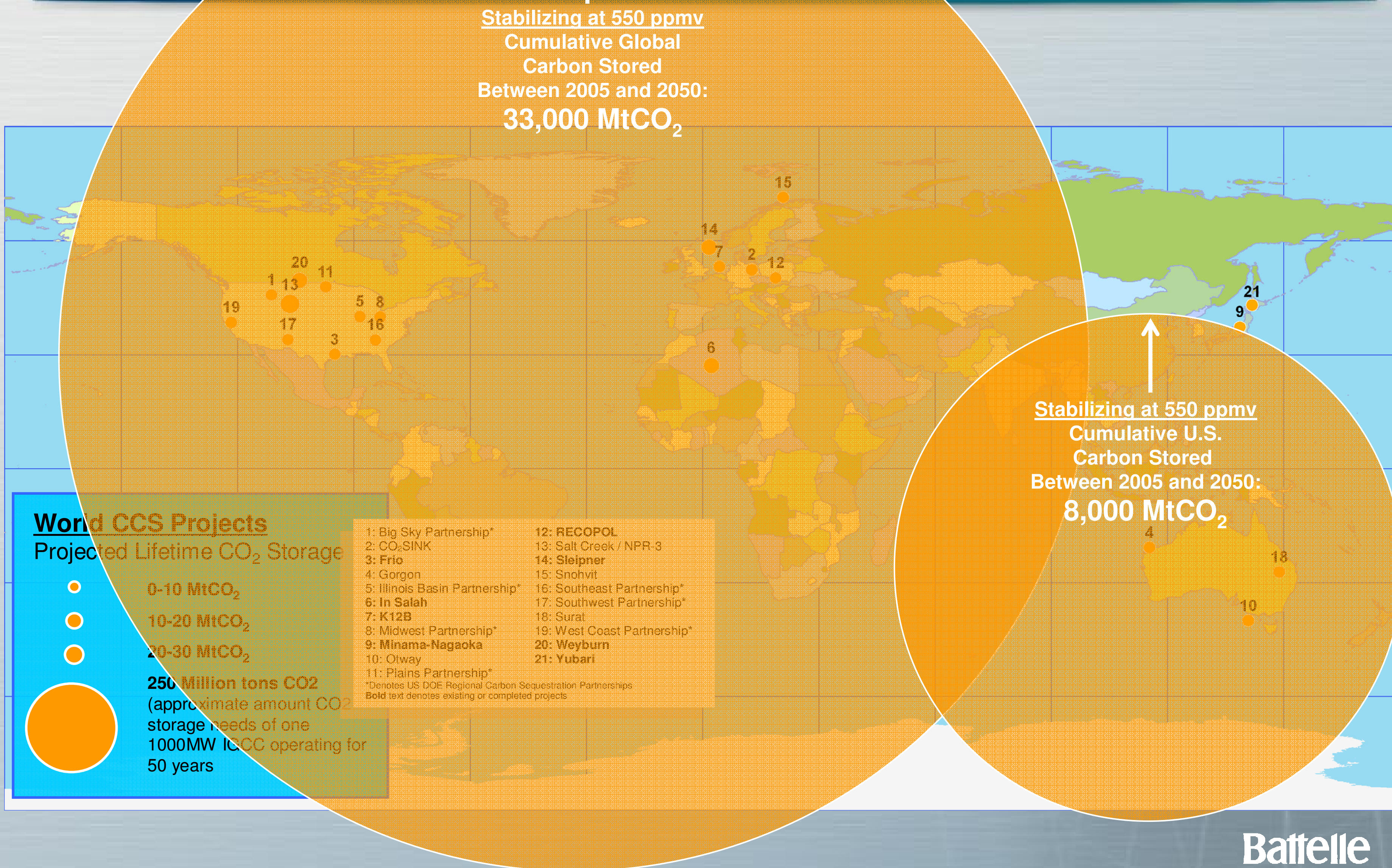


The Challenge Is to Take Theoretical Storage Potential and Turn It into a Bankable Asset that Can Be Counted on when CO_2 Storage Becomes Necessary





The Scope of the Scale-up Challenge



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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.