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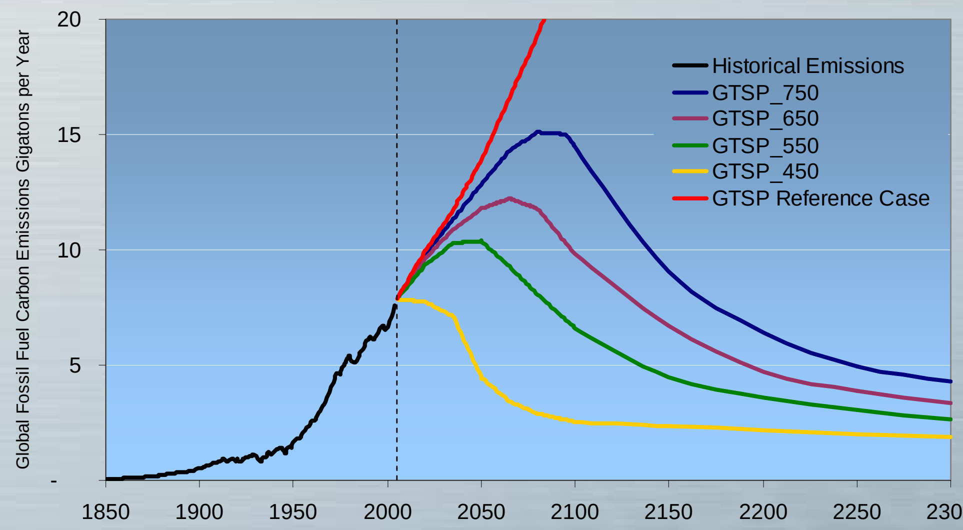
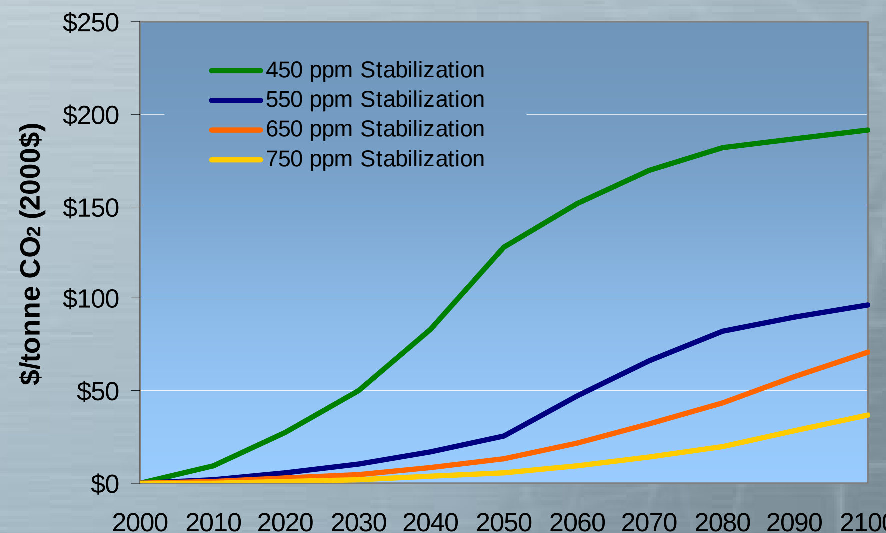
Climate change is a long-term strategic problem with implications for today

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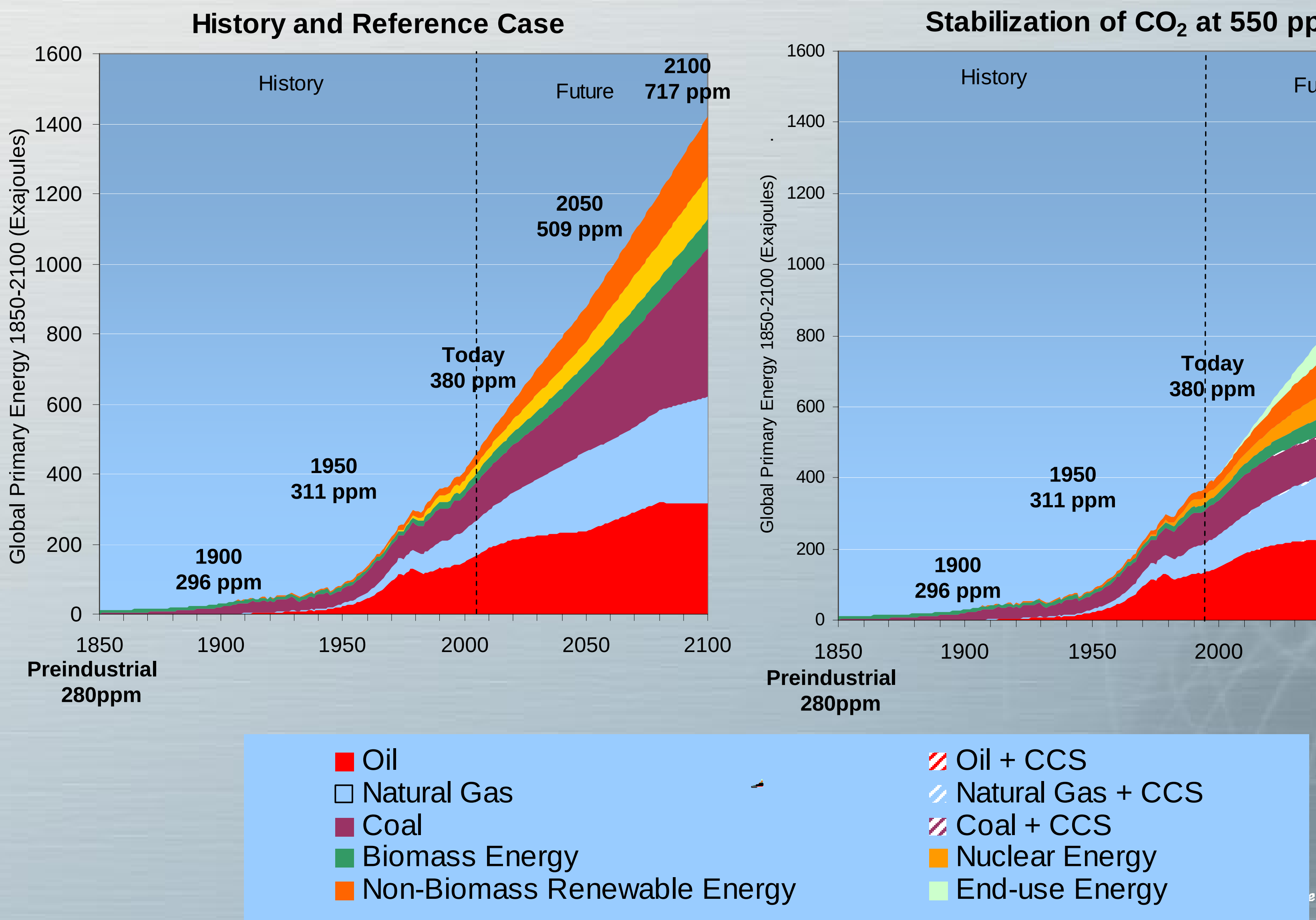
Stabilization of CO_2 concentrations means fundamental change to the global energy system



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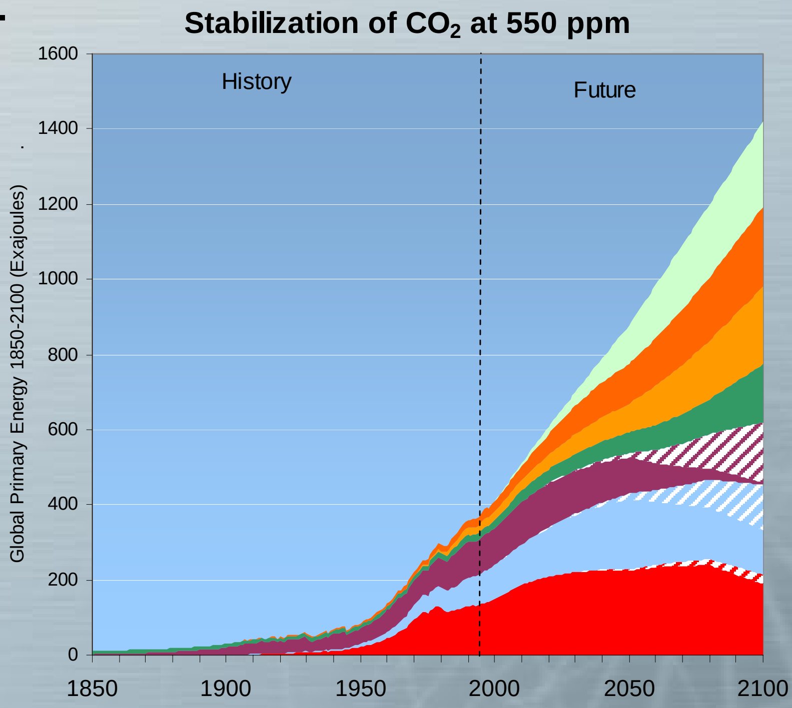
Stabilization of CO_2 concentrations means fundamental change to the global energy system…

- 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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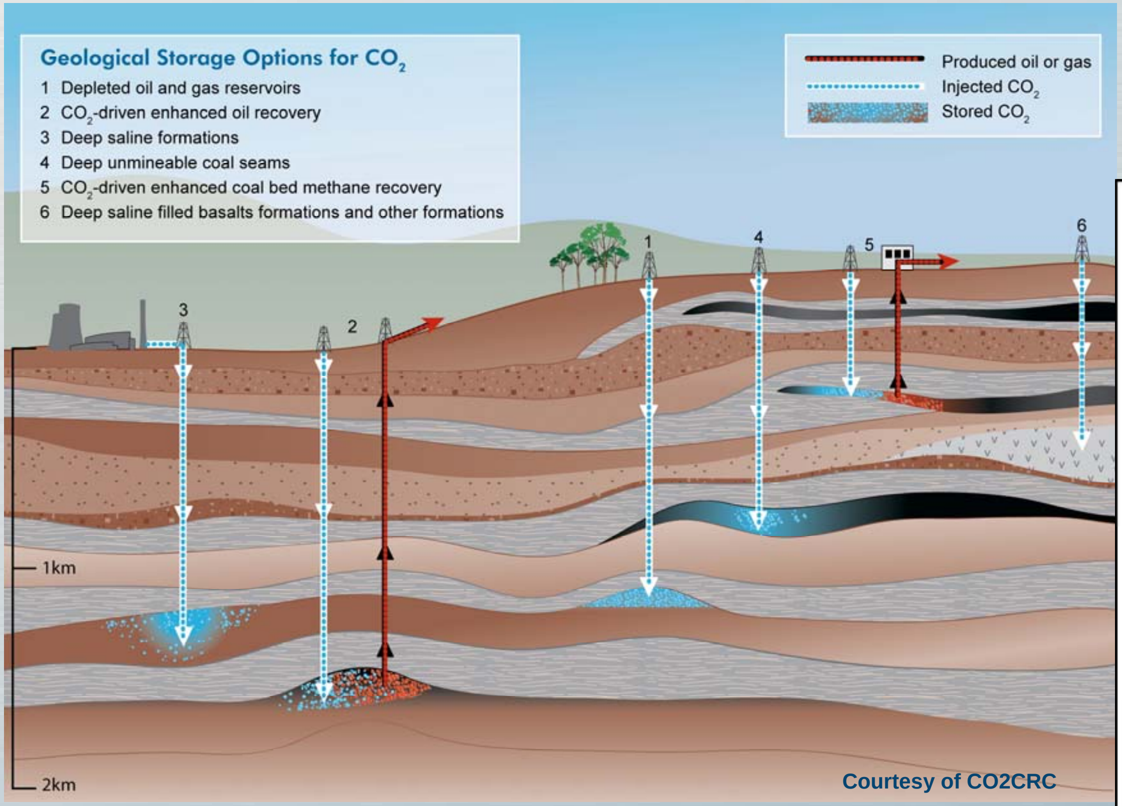
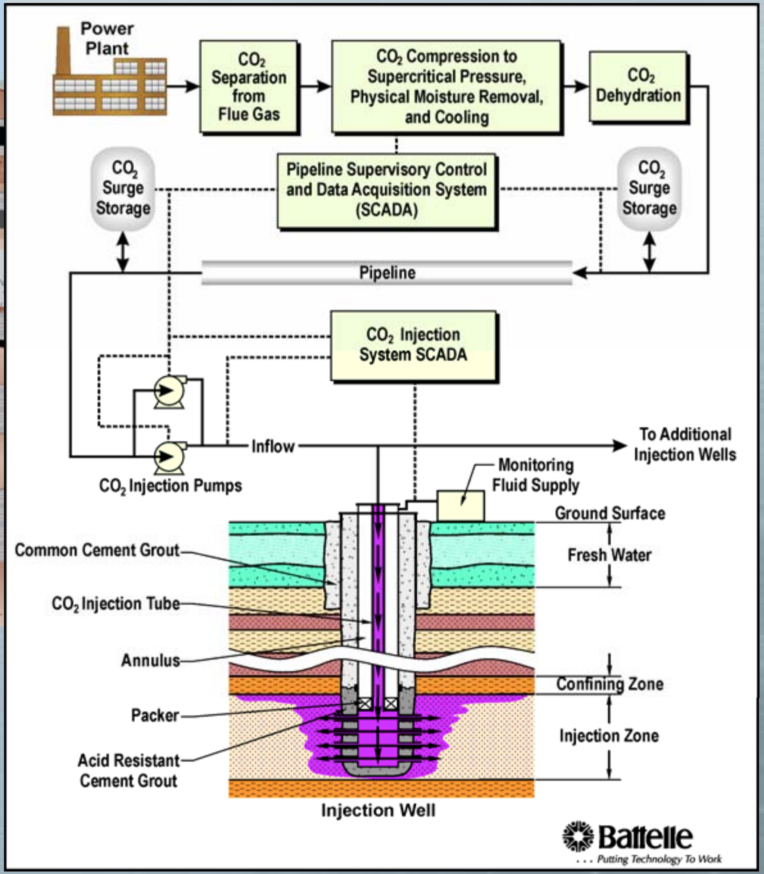
The Macroeconomic Role of CCS Technologies in Addressing Climate Change

- 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.

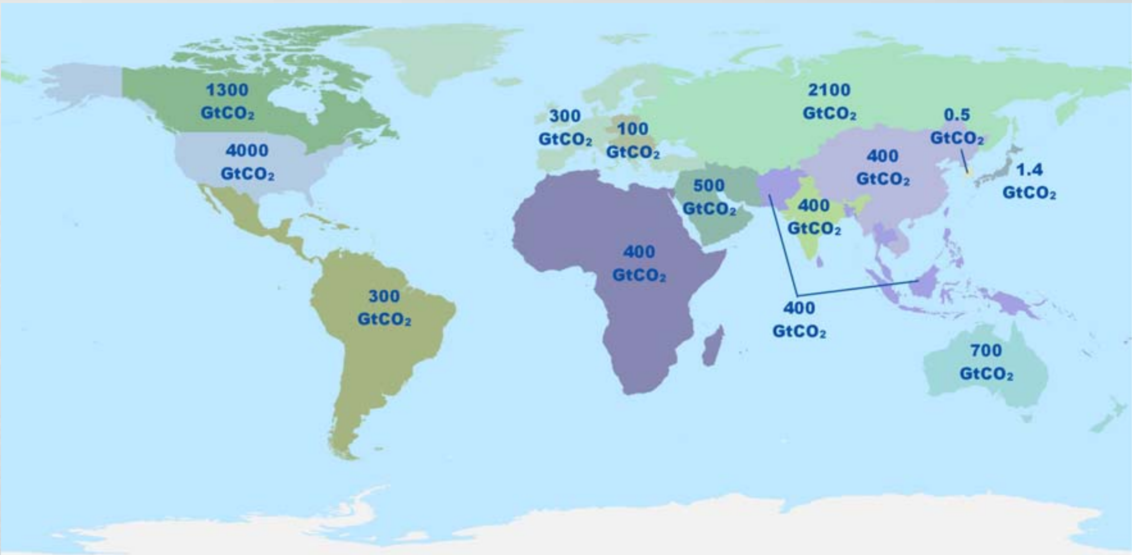
CO_2 Capture and Storage: Not Nearly this Simple

Overview of Carbon Dioxide Capture and Storage (CCS)



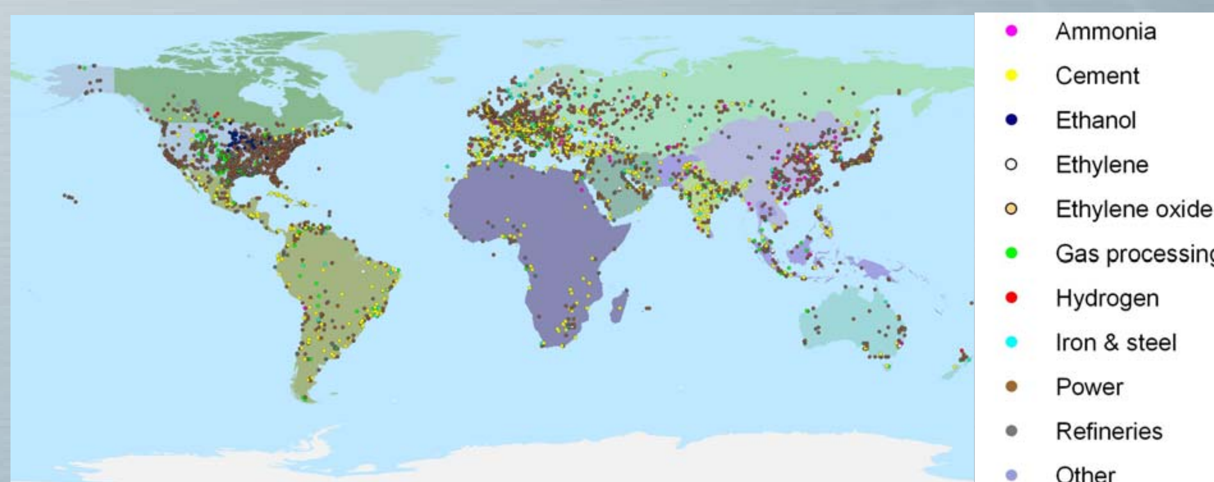


Global CO_2 Storage Capacity:
Abundant, Valuable and Very Heterogeneous Natural Resource



- 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



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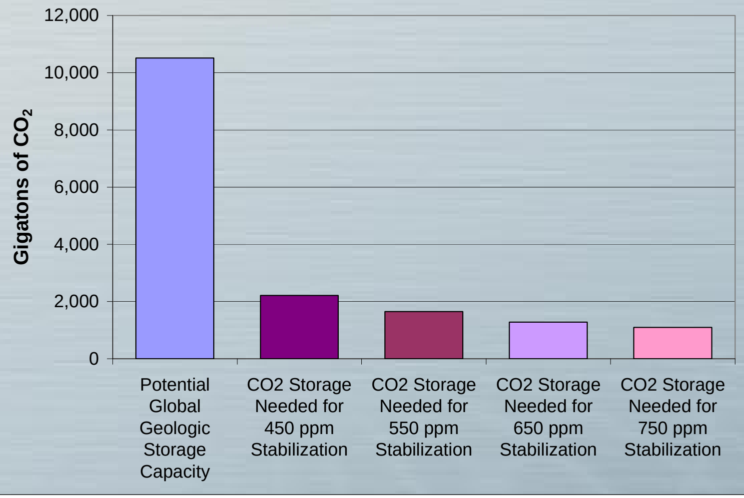
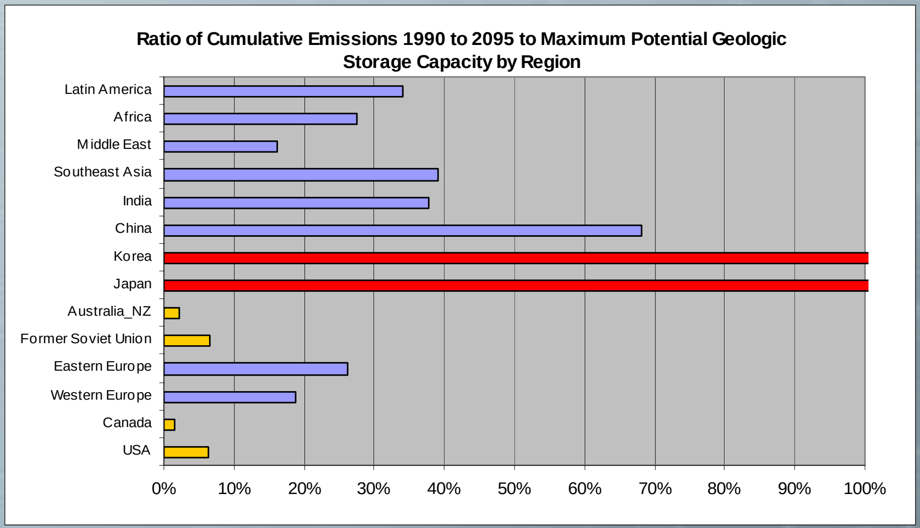
Global CO_2 Storage Capacity:
Abundant, Valuable and Very Heterogeneous Natural Resource

- 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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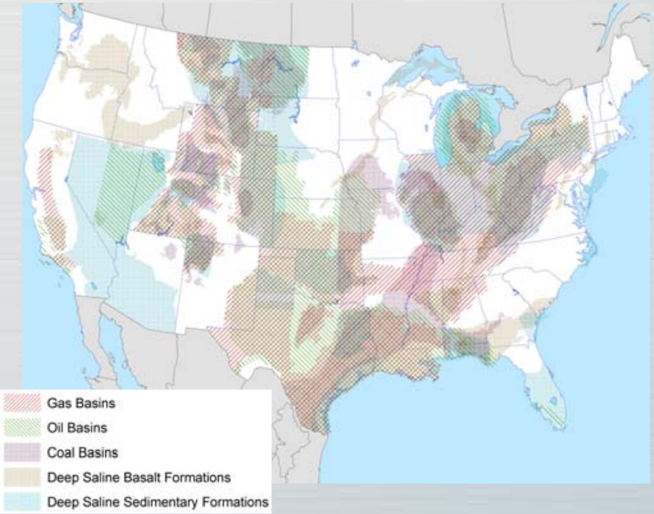
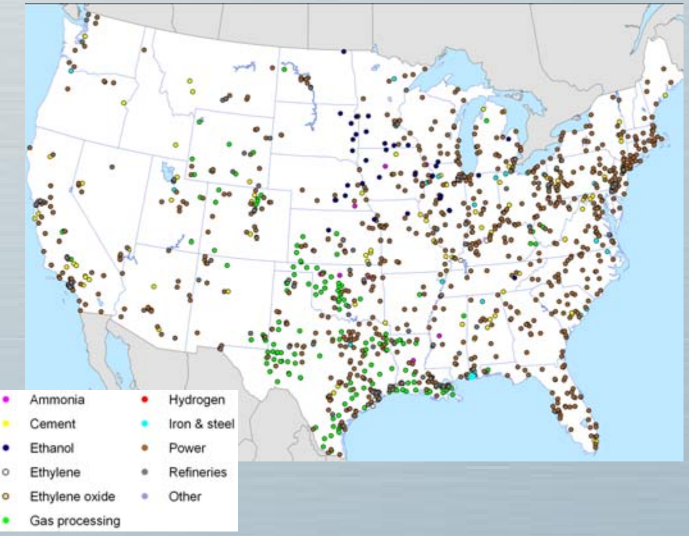
CCS Deployment Across the US Economy

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)

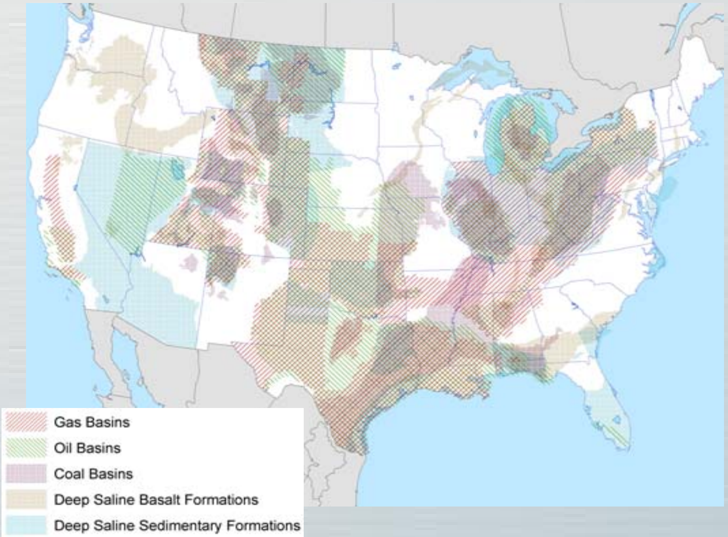


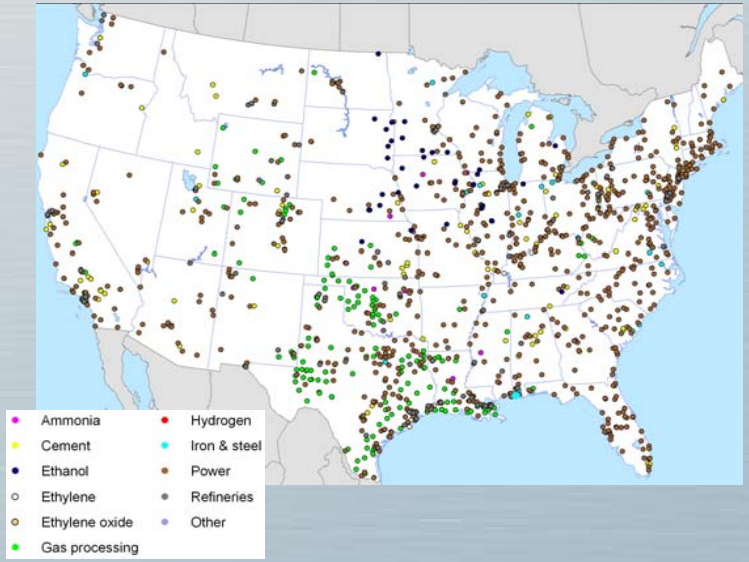
1,715 Large Sources (100+ $ktCO_2$/yr) with Total Annual Emissions = 2.9 $GtCO_2$

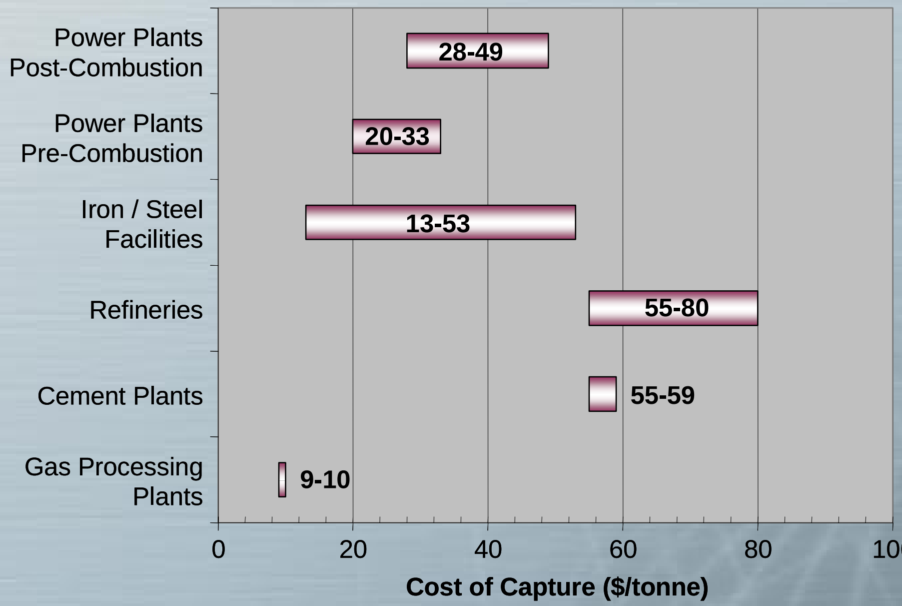
- 1,053 electric power plants
- 259 natural gas processing facilities
- 126 petroleum refineries
- 44 iron & steel foundries
- 105 cement kilns
- 38 ethylene plants
- 30 hydrogen production
- 19 ammonia refineries
- 34 ethanol production plants
- 7 ethylene oxide plants

CCS Deployment Across the US Economy

No uniform "CCS" technology. No homogenous market.







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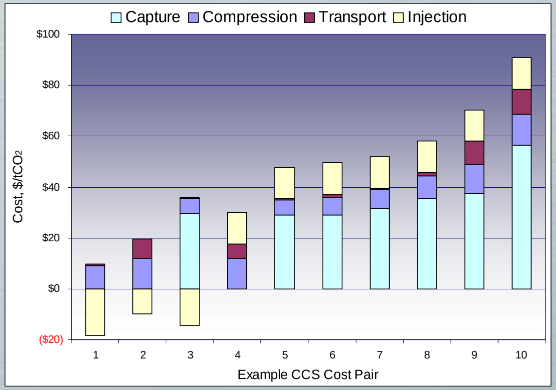
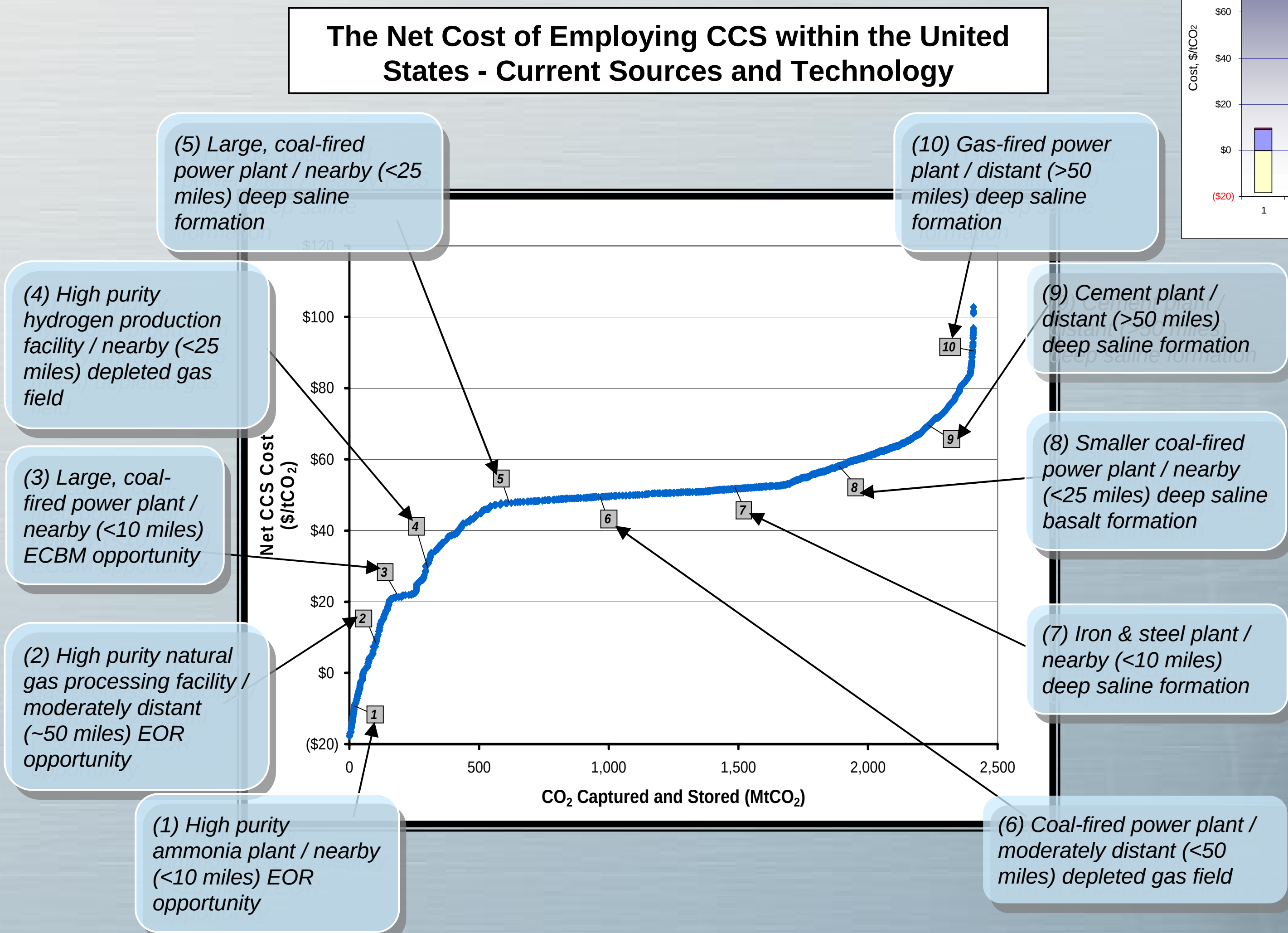
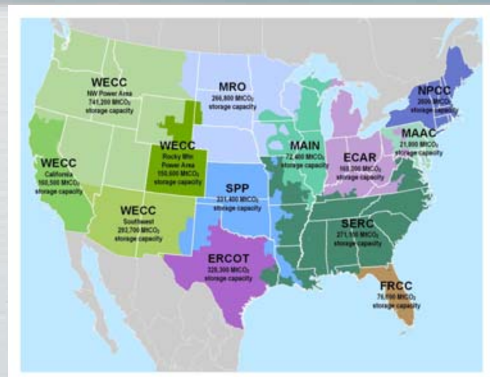
Many Industrial Facilities Are Likely to Adopt CCS before Electric Power Plants and This Will Impact How and When Electric Utilities Adopt CCS



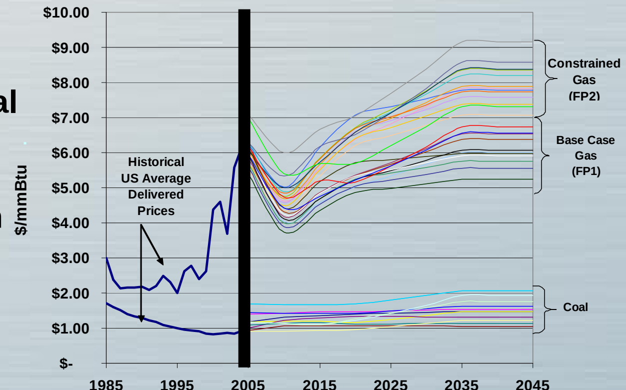


The US Electric Utility Sector is going through and will continue to go through significant changes all of which impact the adoption of CCS technologies

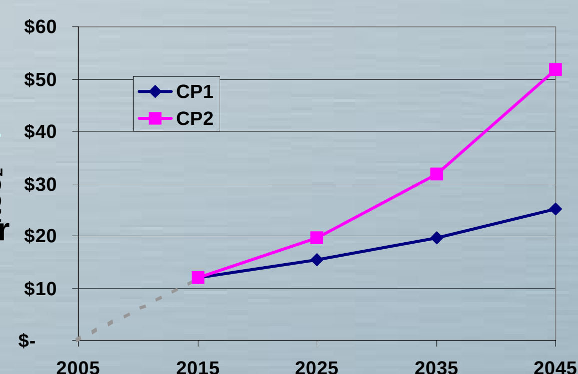
Most NERC Regions have significant CO_2 storage potential



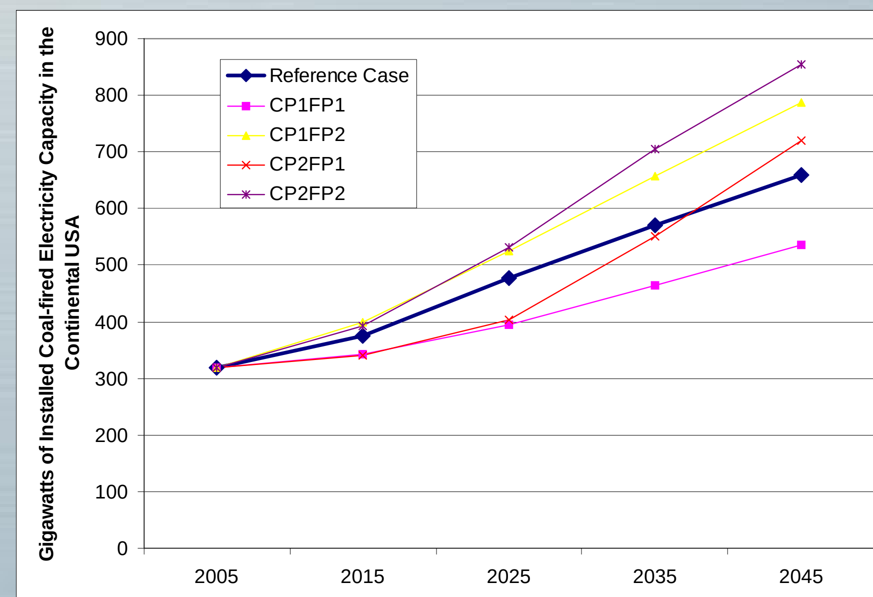
Current and projected natural gas prices have fundamentally altered dispatch economics



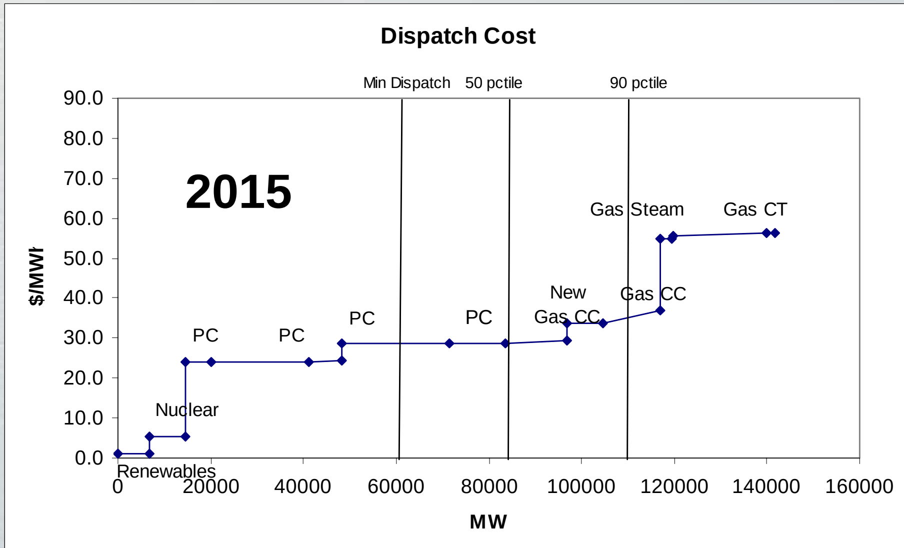
The possible imposition of constraints on CO_2 emissions represents an additional factor that will fundamentally alter dispatch

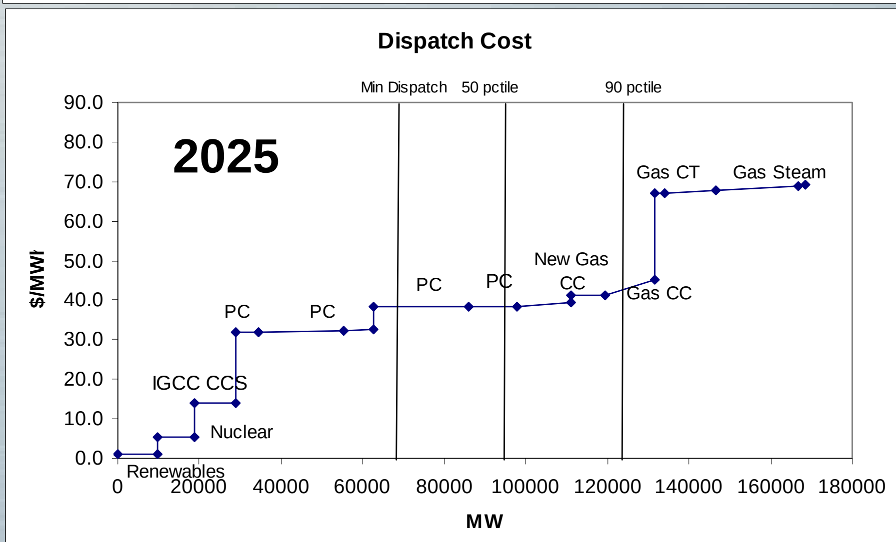


Coal-fired electricity capacity could even expand beyond the no climate policy reference case



Existing and New CO_2-Venting Fossil Plants will still have Value (ECAR CP1FP1 as an Example)





- In the near term, only conventional (i.e., venting power plants) are capable of generating competitively priced electricity.
- ECAR investment to 2015 is limited to gas CCs and CTs for intermediate and peaking.
- While by 2025
  - The modeled carbon tax is sufficient to induce some builds of IGCC+CCS where low-cost storage is available.
  - Once built, running an IGCC + CCS is cheaper than a PC plant and paying the carbon tax for the vented CO_2, but
  - Existing PC plants are still economically viable means of generating electricity.

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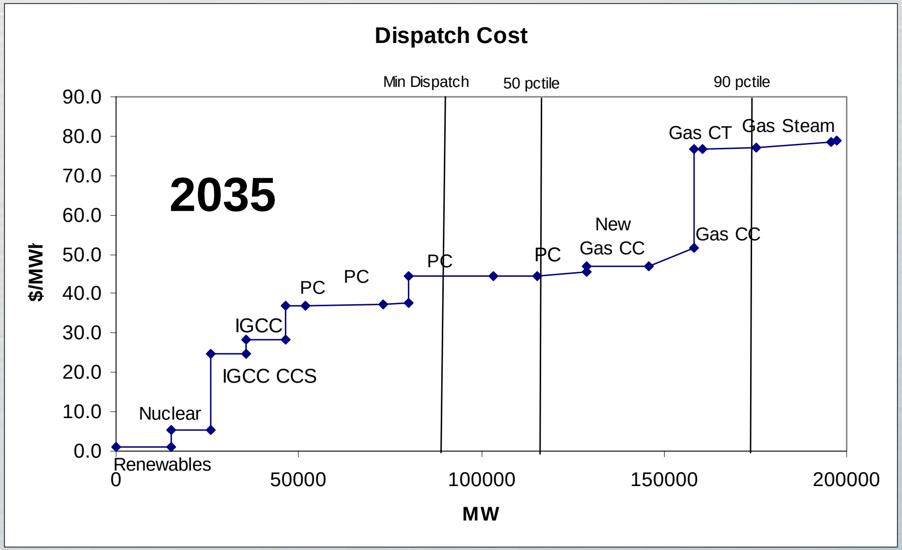
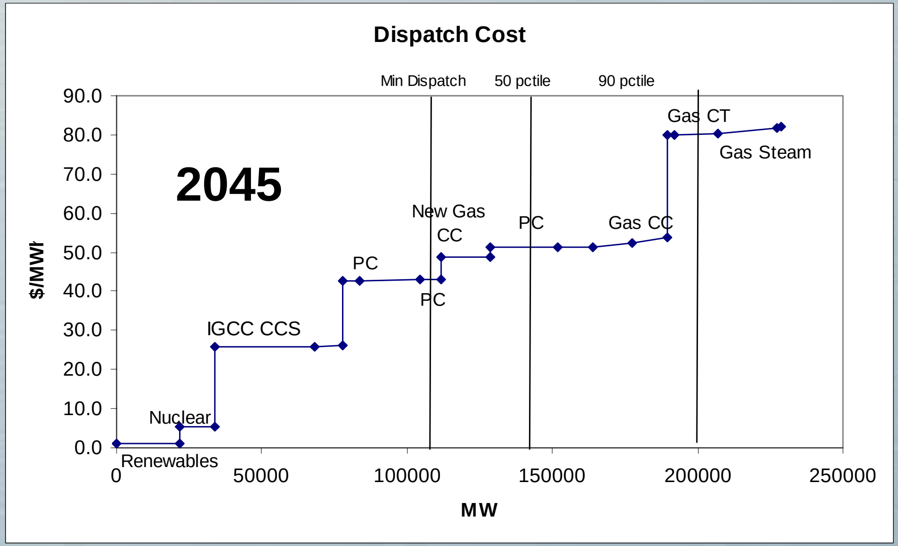
IGCC+CCS Eventually Displaces PC as the Baseload is De-Carbonized (ECAR CP1FP1 as an Example)





- In 2035, some conventional venting PC plants remain in the baseload, but more are reduced to lower levels of operation.
  - Additional IGCC that vents CO_2 is built, with the option to add CCS in the future.
- While in the 2045 period
  - Carbon taxes sufficient to induce retrofitting of IGCC with CCS as well as more new builds of IGCC+CCS.
  - PC capacity loses more dispatch, and some falls behind gas CC capacity in the dispatch order.
  - Nuclear and renewables continue to grow in the baseload.

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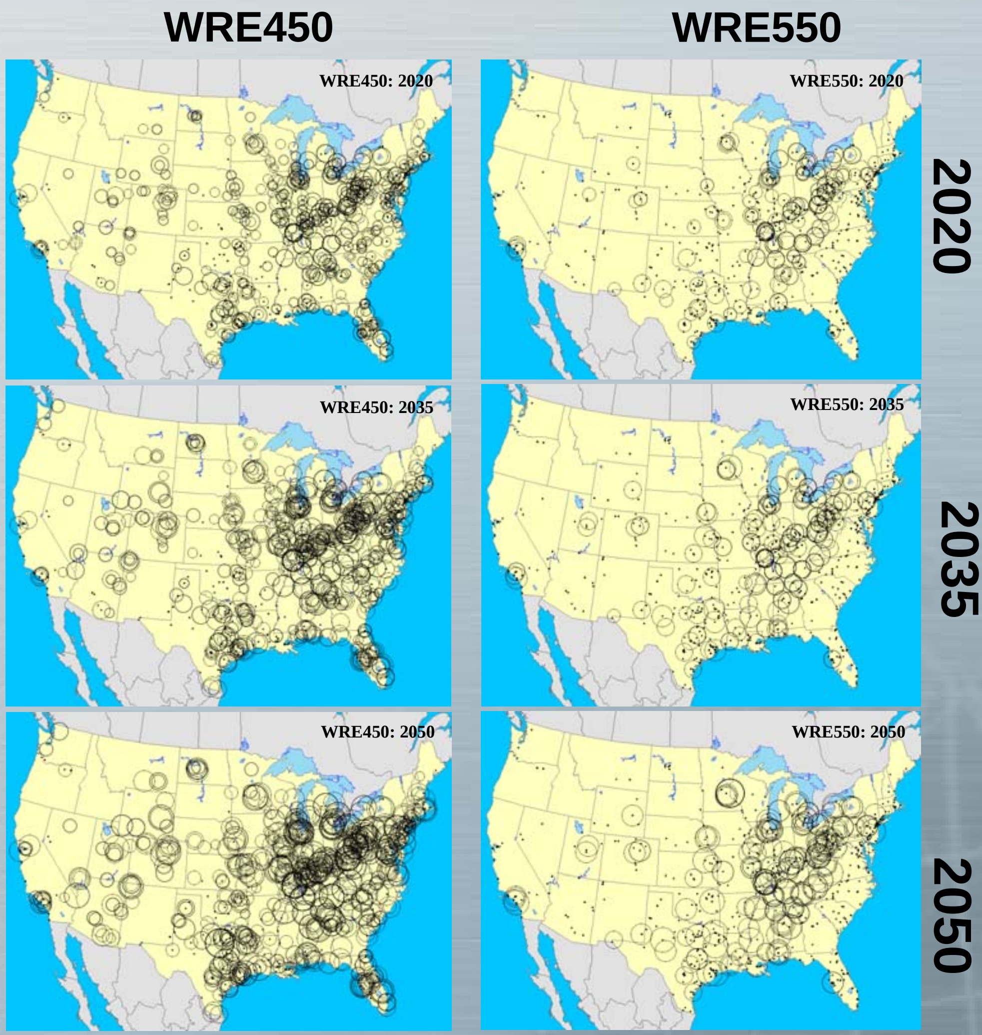
It is important to realize that we are in the *earliest stages* of the deployment of CCS technologies.

- 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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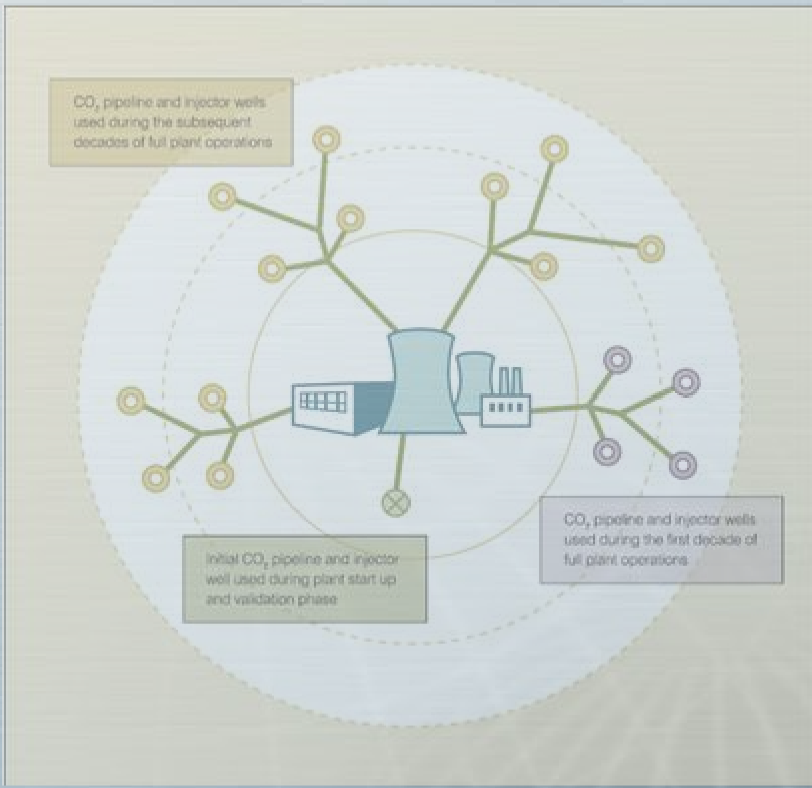
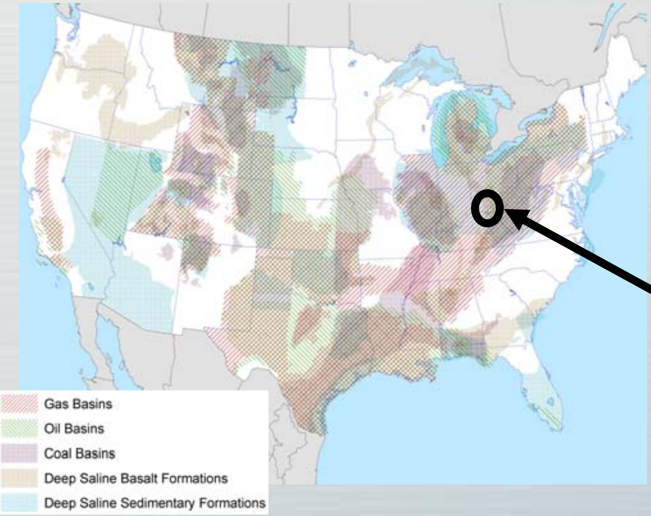
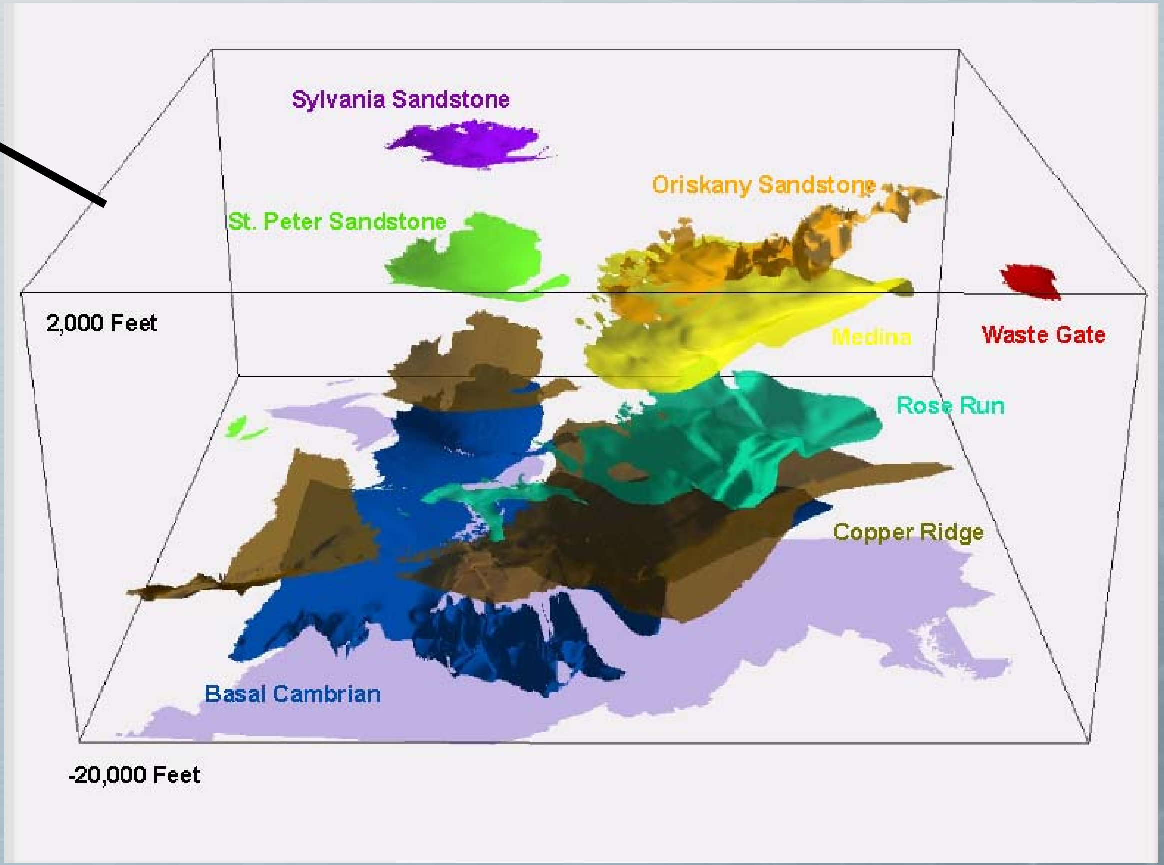
Geologic CO_2 Storage: Selected Basic Engineering and Operational Issues

- 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 when CO_2 Storage Becomes Necessary





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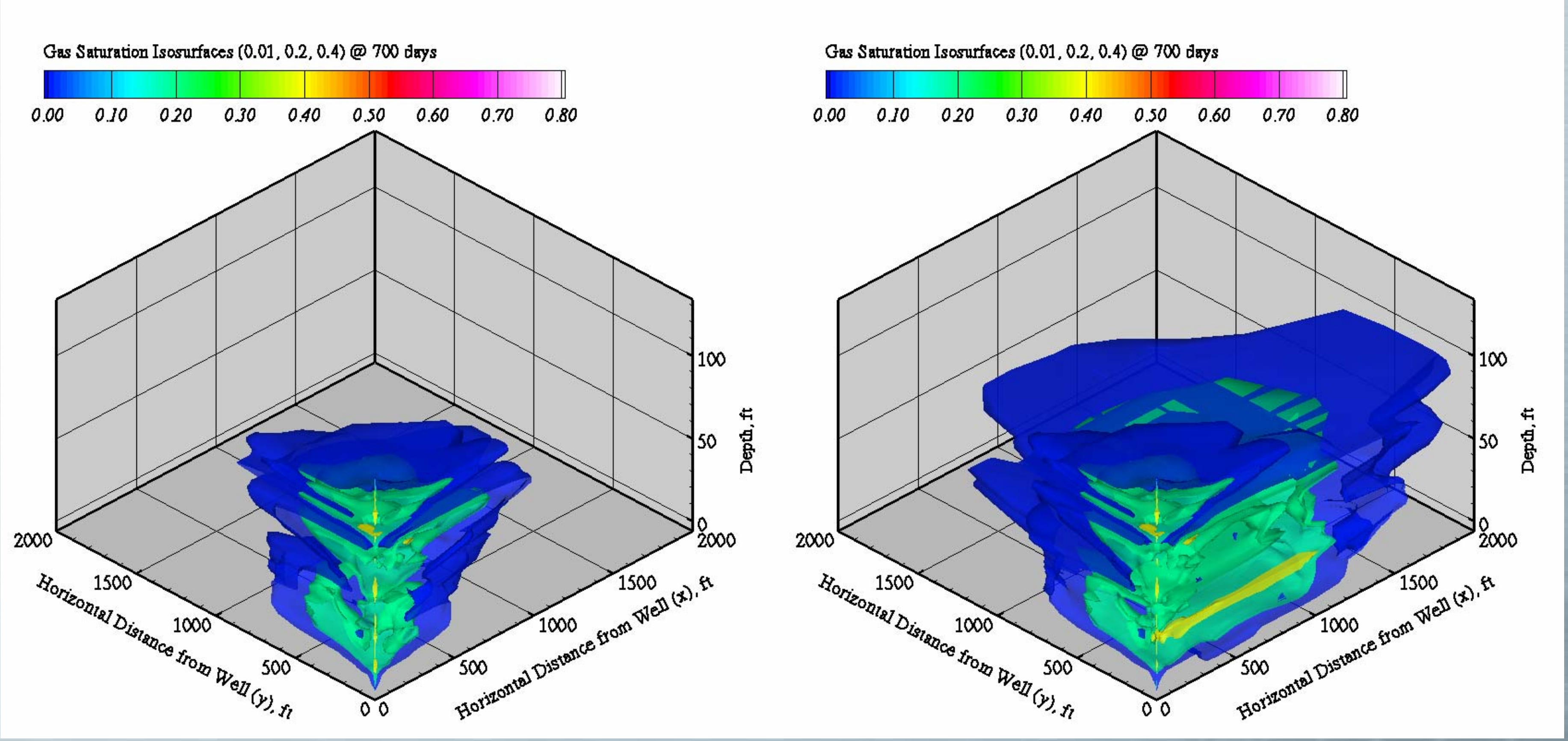

Vertical Well Configuration for the Rose Run Formation

700 days

Horizontal Well Configuration for the Rose Run Formation

STOMP Subsurface Transport Over Multiple Phases

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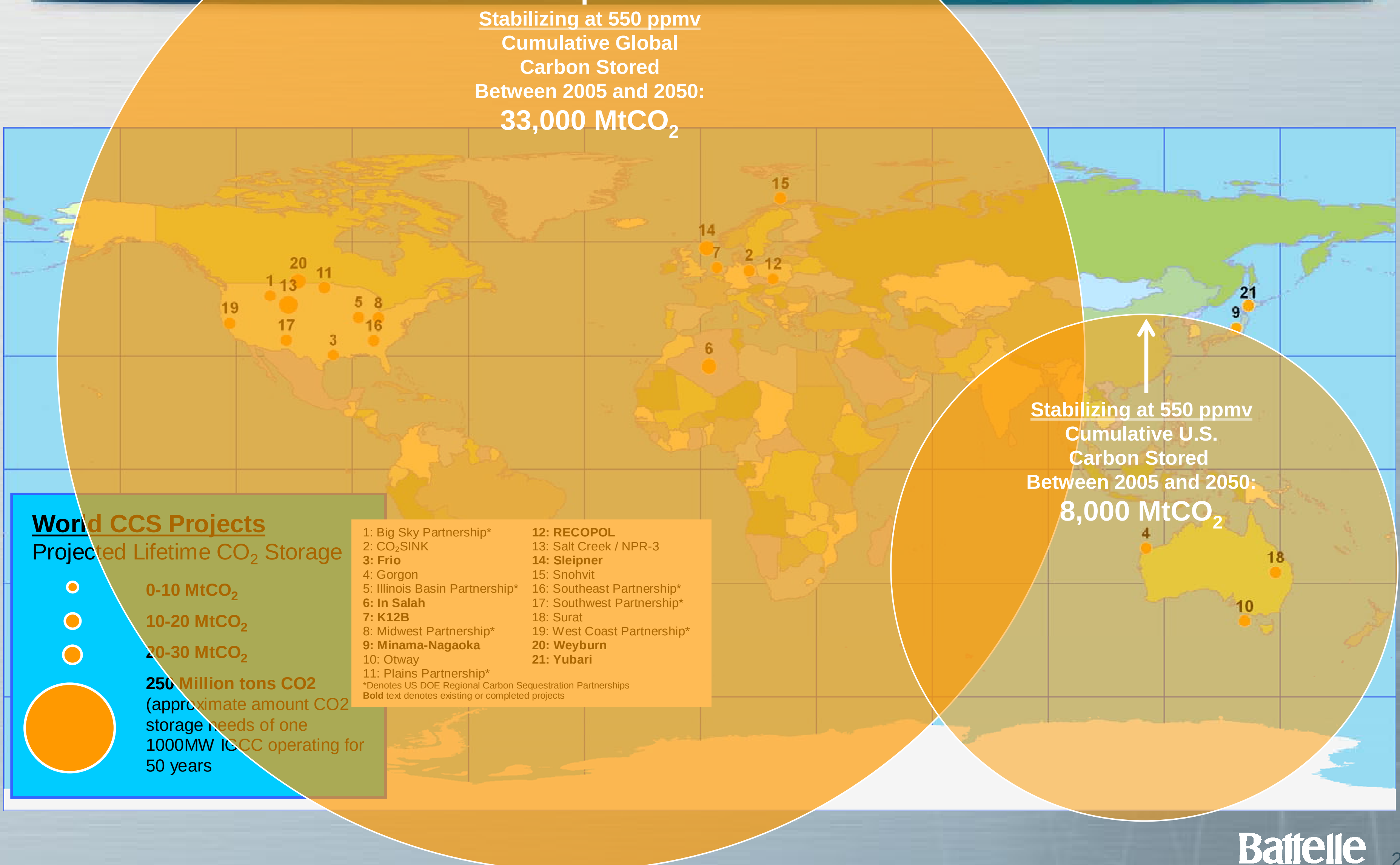
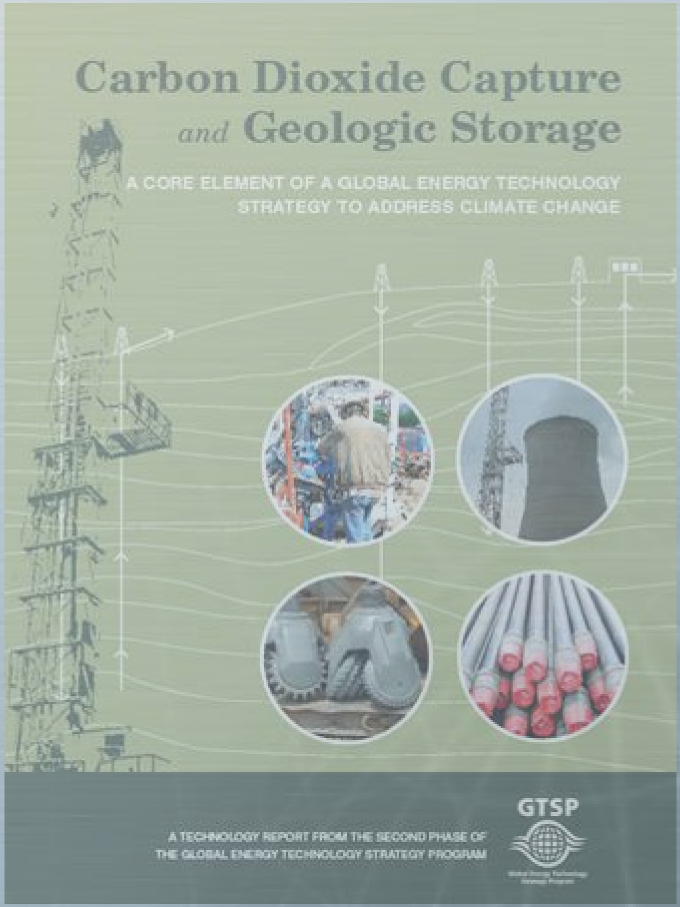
The Scope of the Scale-up Challenge

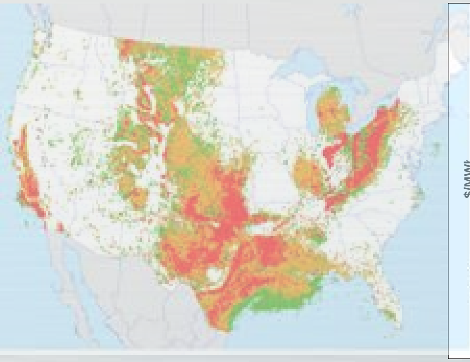


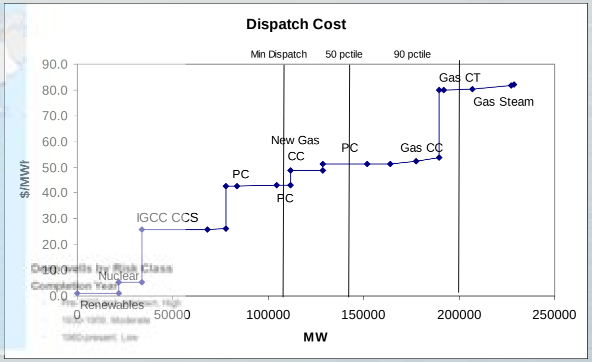
GTSP Phase II Capstone Report on Carbon Dioxide Capture and Storage

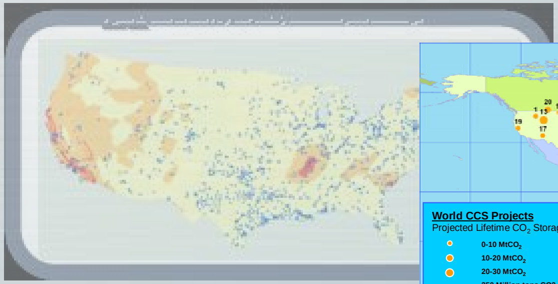
- CCS technologies have tremendous potential value for society.
- CCS is, at its core, a climate-change mitigation technology and therefore the large-scale deployment of CCS is contingent upon the timing and nature of future GHG emission control policies.
- The next 5-10 years constitute a critical window 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.

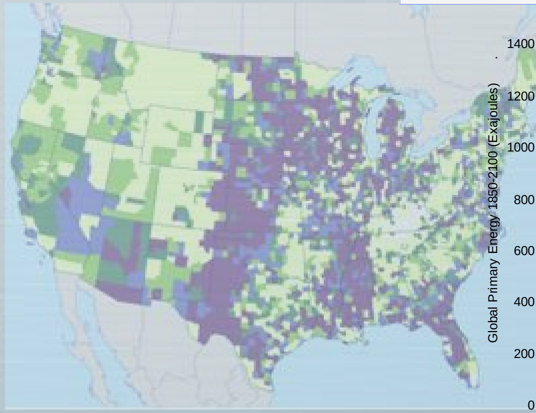


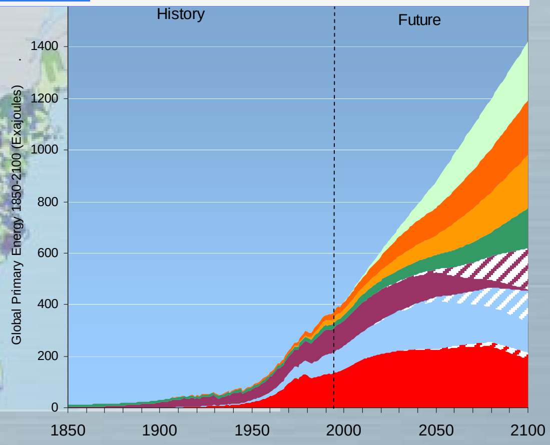
CO_2 Capture and Storage: Not Nearly this Simple











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