Building a World that Buries Climate Change

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Carbon Capture and Storage

- What are we talking about?
  - A system engineered to capture, transport, and store carbon dioxide.
- Why?
  - Climate problem
  - Hydrocarbon economy and resources
  - Knowledge and path dependence
- What does CCS do?
  - Couples the organization of CO_2 emitting point sources with the geologic organization of amenable storage sites.

Scale of Problem

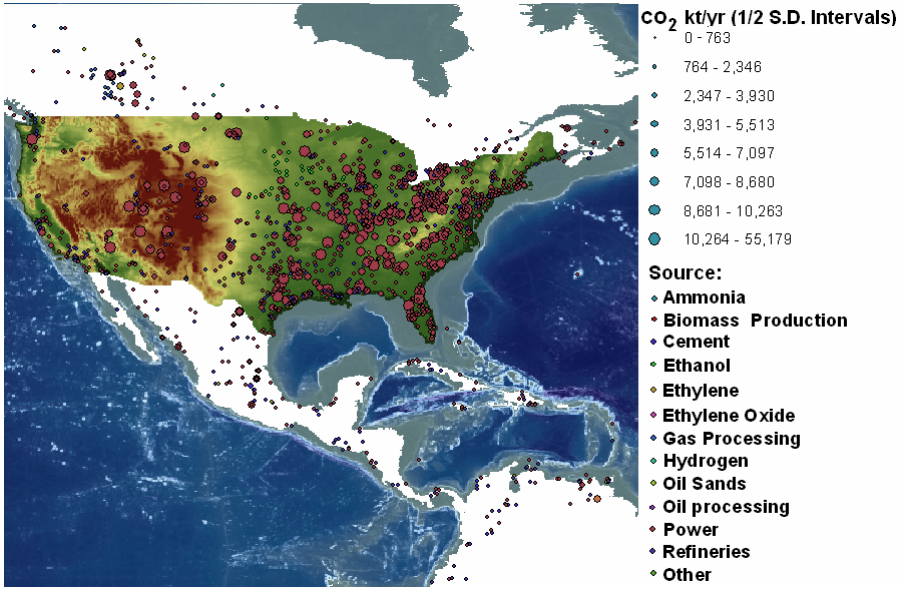
- A 'Typical' Pulverized Coal Power Plant[1]
  - Uses approximately 9.6 kg/s coal per MW
  - Produces approximately 4.7 kg/s CO_2 per MW
  - A 1 GW coal-fired power plant emits ~760 tCO_2 /hr
    - 380,000 m^3/hr (gas) = 1,600 m^3/hr (supercritical)[2]

- ~27.5 Gt_{CO2} emitted in 2005[3] = 5.9 x 10^{10} m^3.

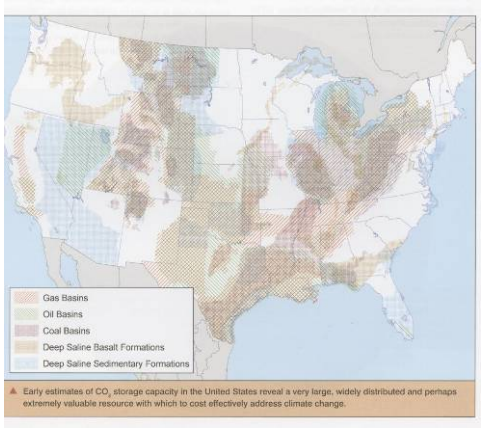
[1]Operating at 37% efficiency. [2]ρ_{CO2} ~2kg/m3 @ STP (~1.5x ρ_{air}), ~470 kg/m^3 @ critical point (~7.38 MPa, ~304 K)
[3]Not all from point sources: ~7.5 GtC in 2005 = 27.5 $GtCO_2$.

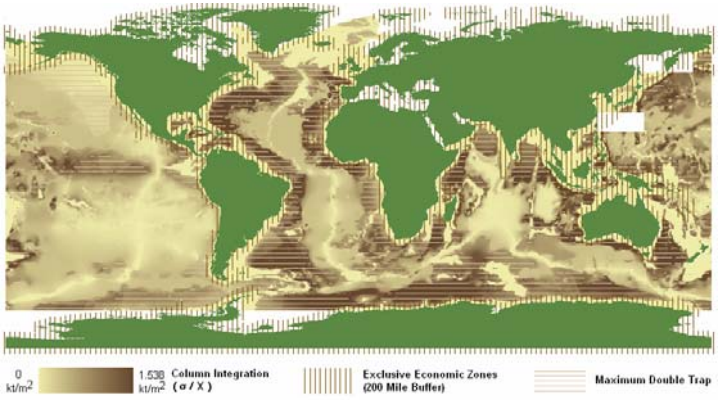
Industrial and Geologic Organization

Major CO_2 Point Sources[1]



Geologic Possibilities[2, 3]





[1] > 100 ktonne CO_2/year: 8341 in World; 1498 in USA. Data from (IEA GHG 2006); [2]Image from Dooley et al (2006); [3] Bielicki (2007)

Main Takeaways

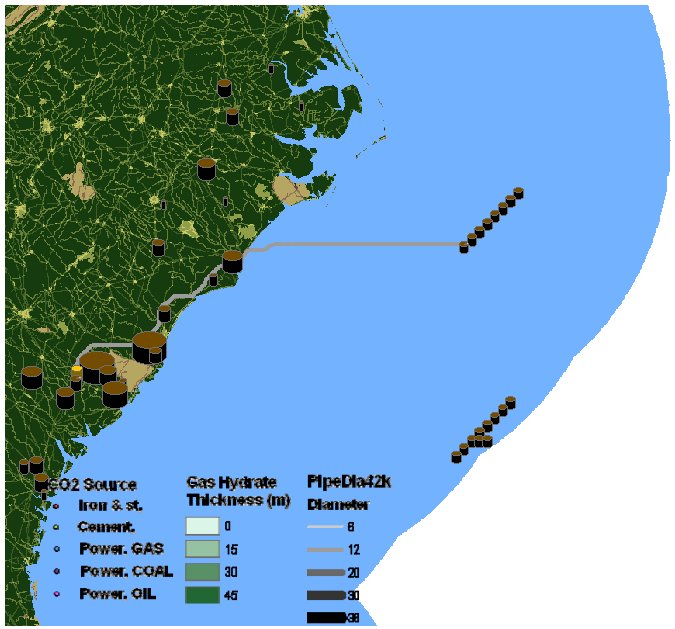
- CCS is hierarchically nested within technological, political, economic, and social systems.
- These systems influence and are influenced by CCS and each other.
- Co-evolution is necessary, and the character of it will likely have a large influence.

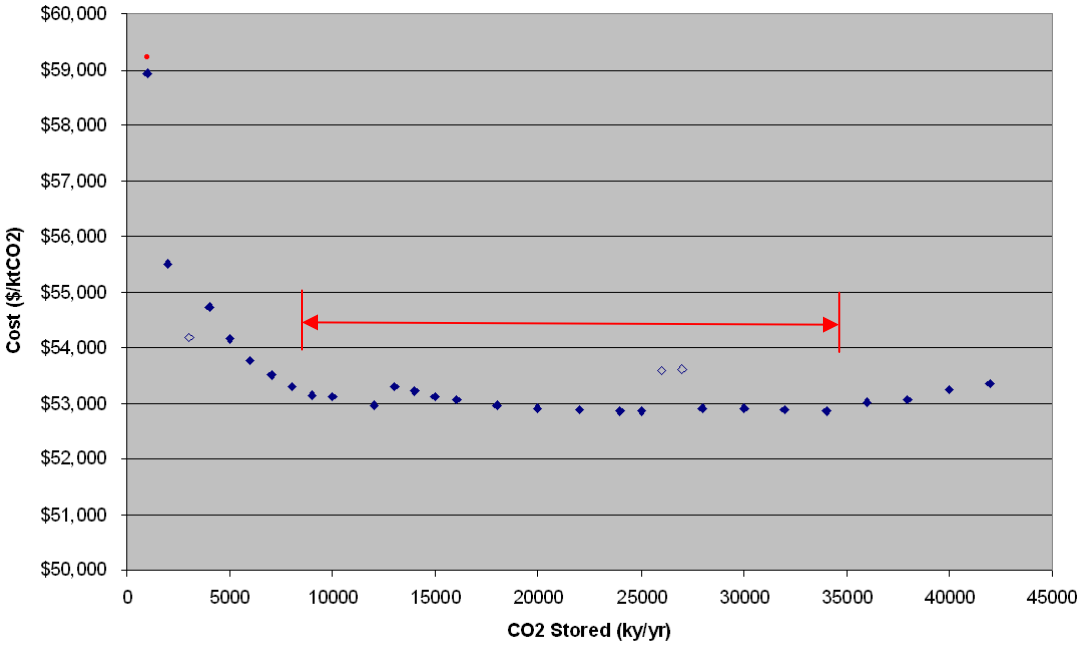
Technologically (legally, liability, economically, socially…)

- CCS
  - Capture equipment and processes
    - Natural gas, submarines, and space travel
  - Compression equipment and pipelines
    - Oil and gas exploration / markets
  - Injection equipment and processes
    - O&G – Enhanced oil recovery; municipal wastewater injection
  - Post-injection measuring, monitoring, verifying
- Facility equipment/processes
- Enhanced oil recovery
  - Security, technology, and field readiness

Spatially Optimized Deployment

- Build realistic pipeline networks
- Inform policy
  - CO_2 Tax and/or Permit pricing and quantities.
- Desirable network and injection site characteristics
  - Go big, but not too big; regional networks; dispersed sites





Legally (technologically, liability, economically, socially…)

- Examples
  - US Supreme Court Ruling: *Massachusetts et al. vs. Environmental Protection Agency et al.*, 549 U.S. ___ (2007).
    - Transport: “Commodity” vs. “Pollutant”
  - Geologic Storage
    - Underground Injection Control Program (UIC); Safe Drinking Water Act (USSDWA)
  - Ocean Storage
    - Exclusive economic zone
    - London protocol (and revisions) & OSPAR
- Inadequate but graftable?

Liability (technologically, legally, economically, socially…)

- Timeframe: 100's to multiple 1,000's of years
  - Measuring, monitoring, verifying
- Leakage/Seepage: Adverse impacts
  - Trespass, negligence, etc.
  - Credit-ability of storage?
- Who's responsible for what and when?

Economically (technologically, legally, liability, socially…)

- "Price on carbon"…
  - Tax or Cap-and-Trade and Politicality
- Co-benefits
  - Enhanced recovery
- Price on something else
  - Security and EOR
- Insurance industry
  - Liability and Price-Anderson Act?

Enhanced Recovery

- Enhanced Oil Recovery
  - ~2.5 bbl oil per ton CO_2 injected; Put away ≈ 13 t_C and get ≈ 29 t_C
  - But wouldn't have put away that 13 t_c.
    - Depending on marginal hydrocarbon / marginal technology that is replaced
  - BUT CO_2 MUST COME FROM INDUSTRIAL SOURCES
    - Currently only about ¼ does
- Enhanced Hydrate Recovery
  - One gas (CH_4) hydrate per CO_2 hydrate
  - But GWP of CH_4 = 23x that of CO_2.
  - Need < 4.3% pore space occupied

Oil is C_nH_{2n+2}, assume C_5H_{12} and 50% recycle rate: $^{2.5bbloil}/_{tonCO2} * ^{0.159m3}/_{bbl} * ^{0.87tCH2}/_{m3} * ^{60tC}/_{72toil} * ^{0.9ton}/_{tonne}$ * 0.50 ≈ put away 13tC, get 29tC

Socially (technologically, legally, liability, economically…)

- Public perception, reaction, etc.
  - Why?
    - Is climate really a problem?
    - Is CCS really a solution?
  - Where?
    - NUMBY, BANANA, NIMO…
  - Greenness of Attitudes

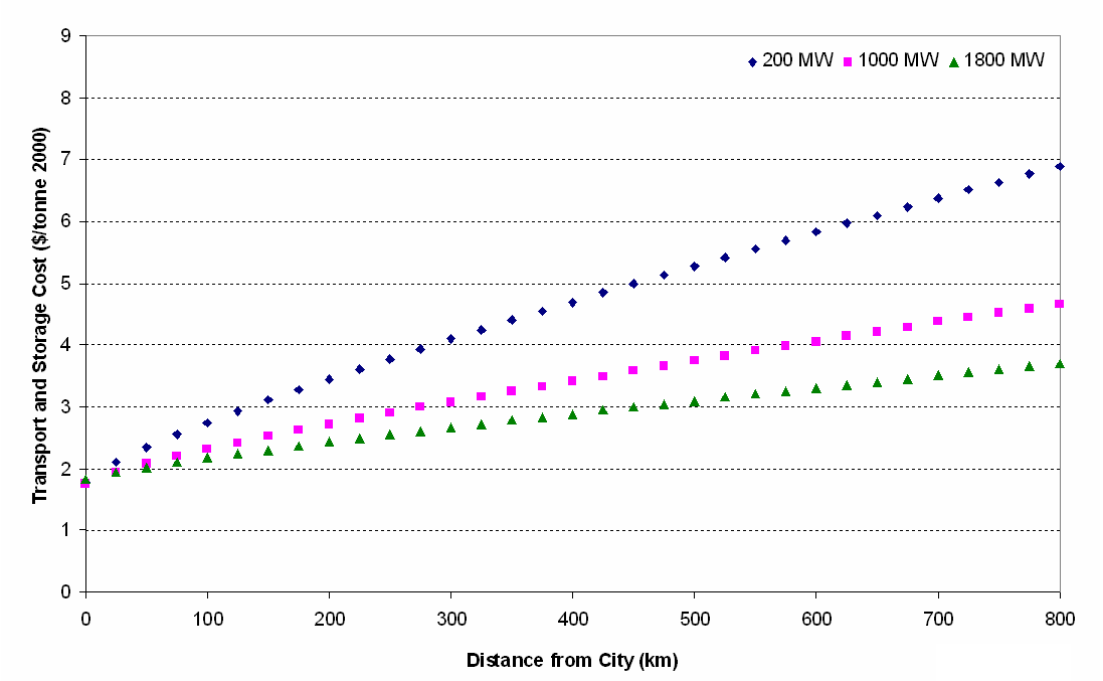
- Stakeholder drivers, impeders, etc.
  - Governments (local to national)
  - Businesses
  - Academics
  - NGOs

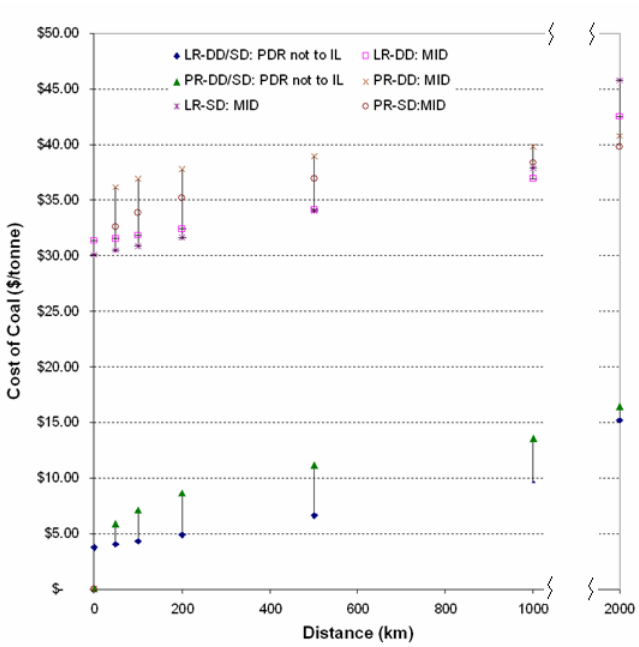
Impact on Facility Locations

- Facilities are, and will continue to be, sited without concern for CCS
  - Need to resolve a lot of issues to know where CO_2 will go and who is responsible and how it's governed and what is acceptable and …
- But CCS will be a concern…
  - Case Study: Coal-to-Liquid Plant
  - Case Study: Coal-fired Power Plant

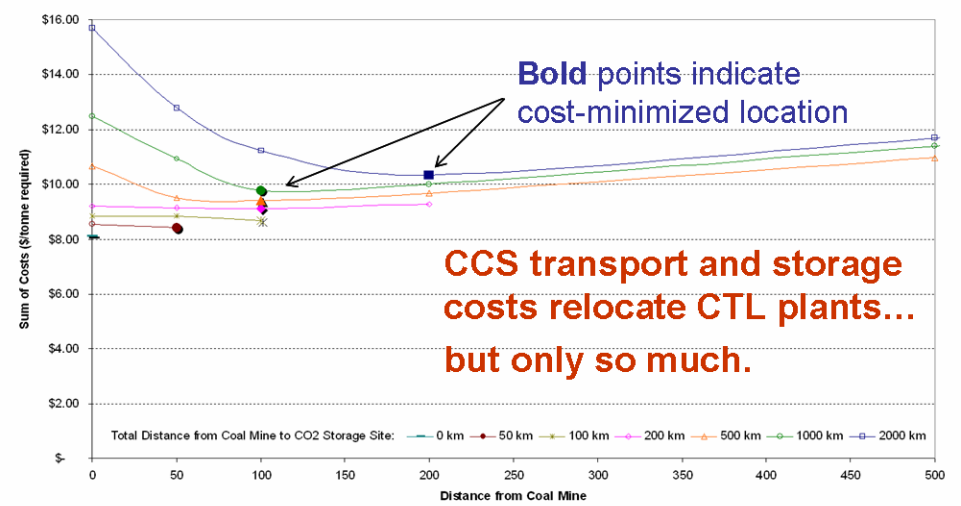
Cost Balance over Distance

Transporting and Storing CO_2 vs. Shipping Coal





Case Study: Coal to Liquids Plant



Coal mine on left vs. CO_2 storage site on right[4]

- Coal gasification for synthesis gas: CO_2+H_2
- Fischer-Tropsch:

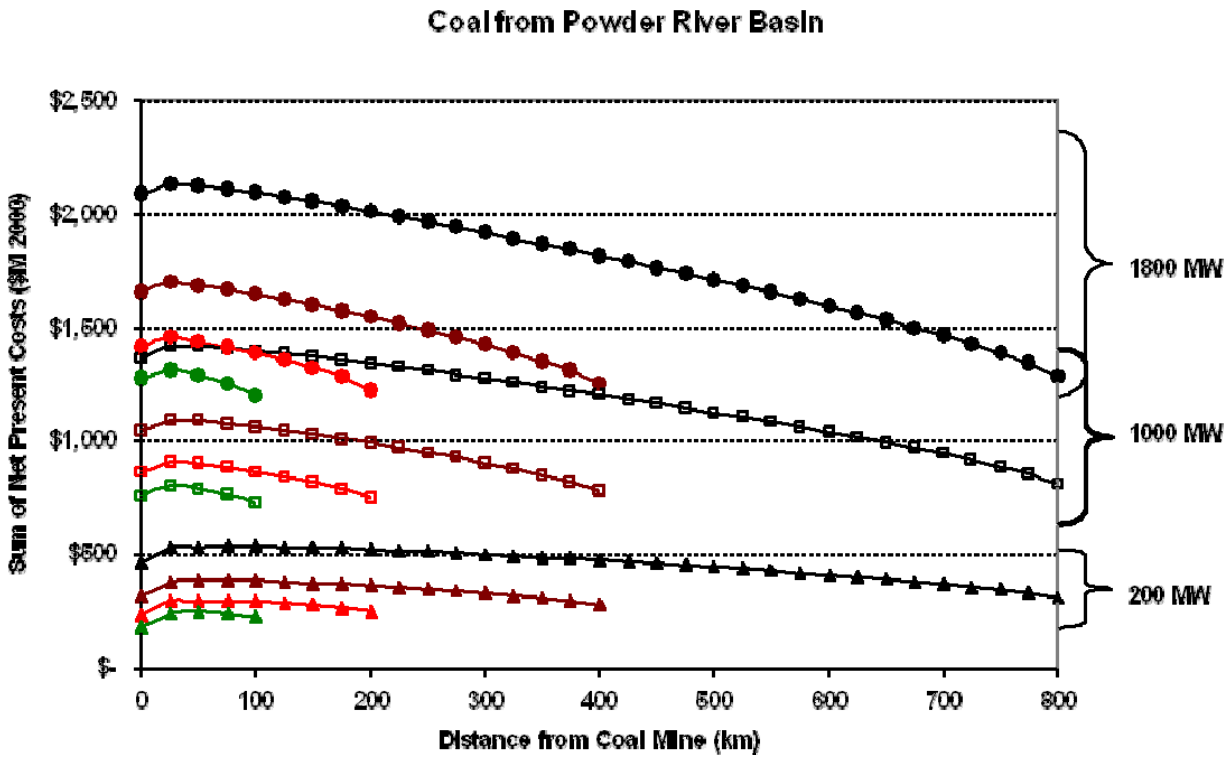
$$2CO_{2(g)} + H_{2(g)} \rightarrow CH_{2(l)} + CO_{2(g)}$$

- 2.5 bbl oil and 1.7 tonnes CO_2 from 1 tonne coal.[1]
- Assume SASOL production[2]
- Assume Powder River Basin coal[3]

[1]Assuming 75% efficient gasifier (Argrawal et al, 2007); [2]150,000 bbl/d; [3]Power model for shipping distance with same cost structure as non-PRB coal; [4]5%, 50 years.

Power Plant: CO_2 or Coal?

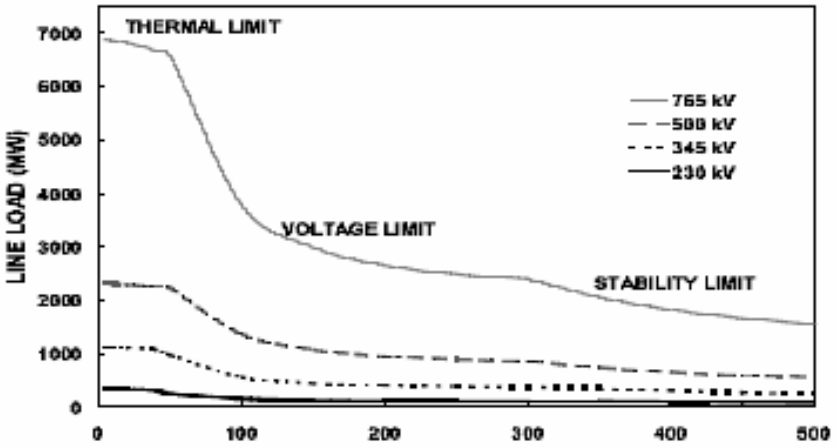
- Should we transport CO_2 or ship coal?



- **CCS pulls power plants away from coal mines and towards storage sites.**
- **The tug weakens as the distance between the coal mine and the storage site decreases.**

Transmitting Electricity

- Transmission lines:
  - Discrete voltage ratings.
  - Capacity degrades over distance.
  - Losses depend on distance, diameter, material, impedence…



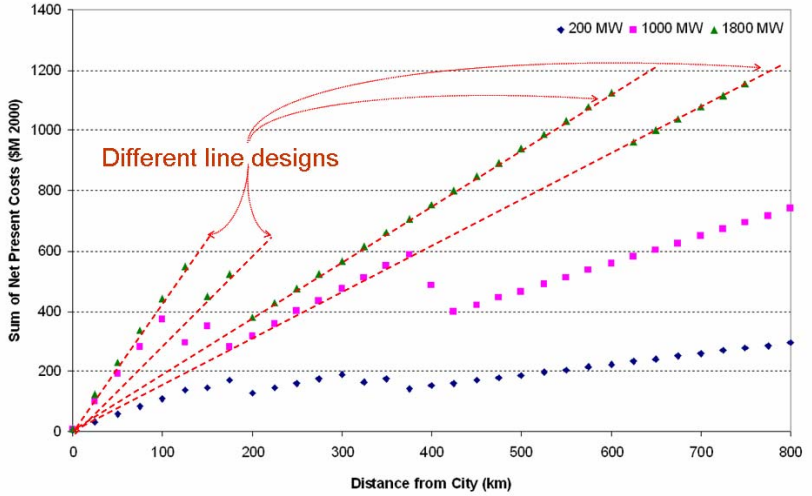
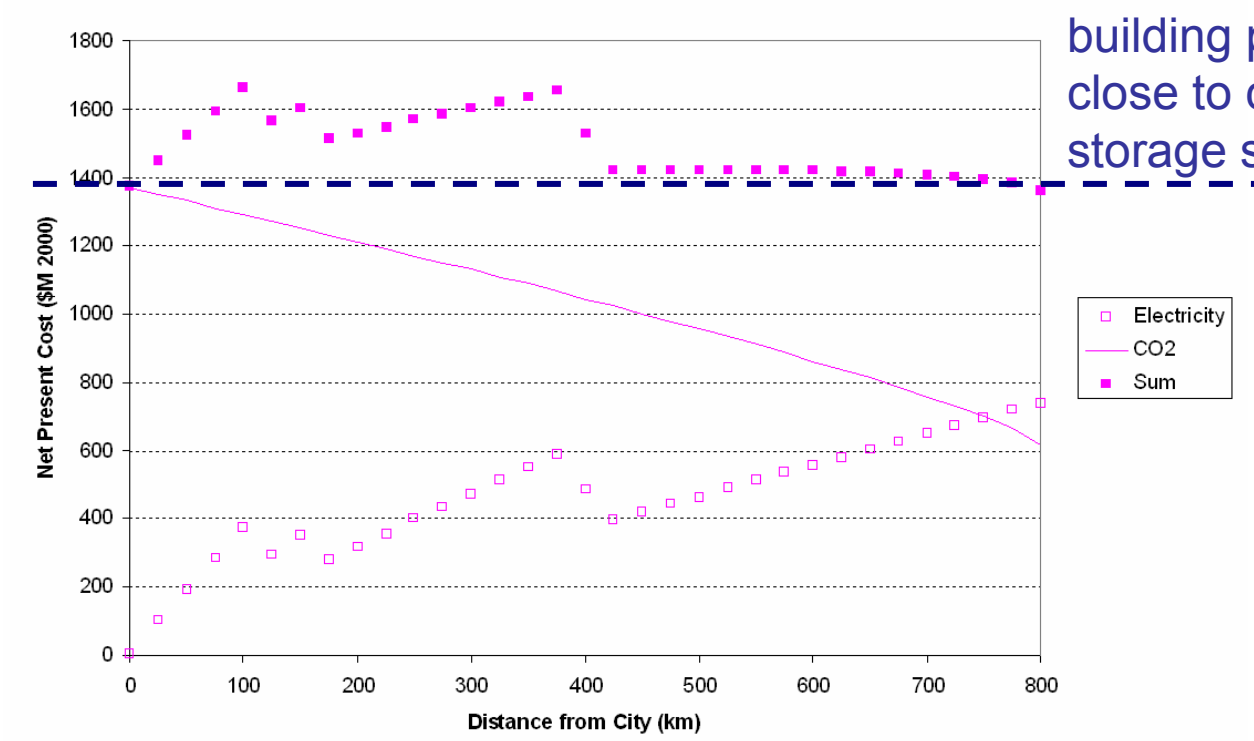


Image from Hirst and Kirby (2001).

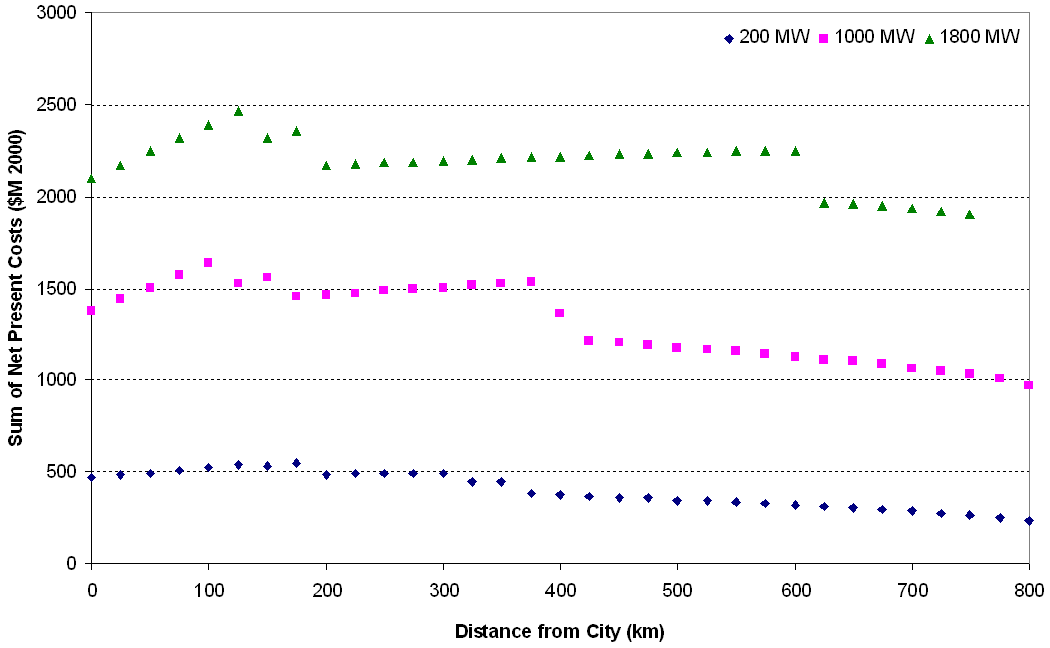
CO_2 or Electricity?

- EX: 1000 MW Power Plant, 800 km between 'city' and storage site.



Indifferent between building power plant close to city or close to storage site.

But… Part of the Grid Exists



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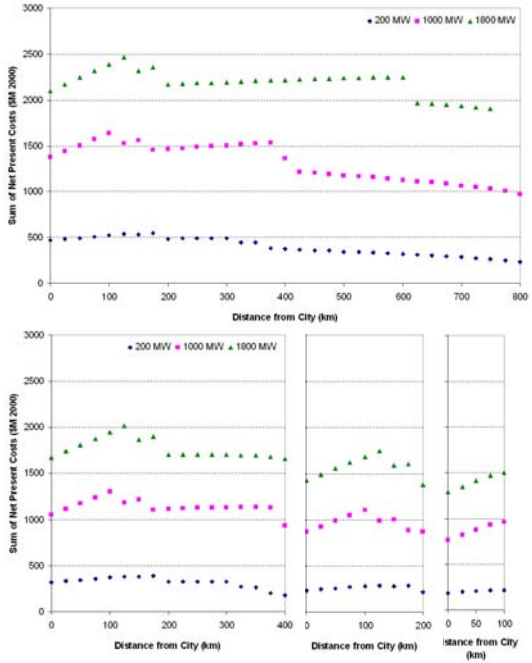
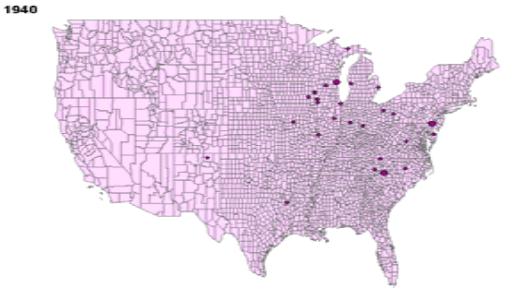
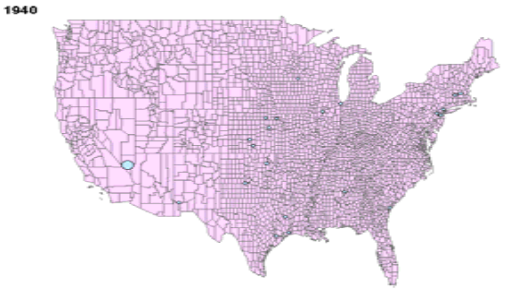


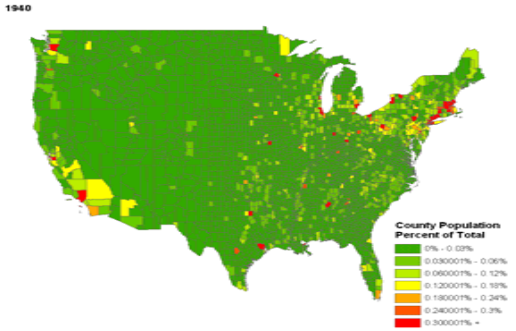
- The ‘tug’ of CCS transportation and storage depends on:
  - Plant size/output.
  - Distance between demand and storage.
  - Amount of transmission infrastructure to be built.

Power Plant Pulls

- CCS has a centralizing effect on siting locations…
  - But not necessarily on size of power plant[1]
  - And price-discriminatory behavior from transporters/storers[1]
- Will CCS centralize electricity production?
  - Where/when will CO_2 be stored?
  - Interaction between technological advance/change/stasis
    - Generation, Transmission
  - Population migration
    - Natural
    - Mortgage guarantees, interstate highway system







[1]Lessons from Clean Air Act and SO2 controls.

CCS is an 'Engineering System'

- Characteristics of an Engineering System
  - Technologically enabled with many interconnections and components.
  - Influence/influenced by social, political, economic considerations.
  - Nested complexity within both technical and social/political/economic systems
  - Dynamic and emergent with uncertainty and multiple time scales.

A history of doing big things

- Bulletin of the Atomic Scientists: 1946, 1951
  - Program for Urban Dispersal
  - Set out to disperse populations to minimize vulnerability to nuclear attack
  - Interstate highway system
  - Mortgage guarantees