Fall Term - 2013

Woodrow Wilson School 585b

Living in a Greenhouse: Technology and Policy

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Phil Hannam, AI

Week Nine: November 1, 2013

Low-carbon fossil-fuel-based electricity.
Natural Gas and Coal with CCS

Reminders:

Two Wednesday talks:

Nov 20, 4:30 pm, Bowl 1.
Michael Oppenheimer and Gabriel Vecchi: IPCC.

Dec 4, 4:30 pm, Aaron Burr, second floor.
Sam Scheffler, Philosophy, NYU: Our collective afterlife.

Course Deadlines:
Part Three: Technological options and related policy

Nov. 12 (last night): Second Interim paper
Nov. 19: Second short paper
Dec. 11: Third Prob set (to be assigned next week)
Jan. 14 (Dean's Date): Term Paper due.

Options for Reducing Electric Sector CO_2

- **Use less electricity** **WEEK 8**
  - Efficient appliances, motors; behavioral change.
- **Increase fossil fuel plant production efficiency** **THIS WEEK**
  - Two centuries of steady increase in efficiency, especially via higher pressures and temperatures. Pollution control has modest effect of opposite sign.
- **Switch to lower-carbon fuels (coal to gas)** **THIS WEEK**
  - A conventional coal plant emits 1 tCO_2 /MWh (1 $kgCO_2$ /kWh), while a natural gas combined cycle facility emits 0.5 tCO_2 /MWh.
  - Natural gas availability and price?
- **Carbon capture and sequestration** **THIS WEEK**
  - Treat CO2 emission as an industrial ecology problem: Where is the best place to put this byproduct?
- **Switch to non-fossil-fuel power** **WEEKS 10 AND 11**
  - Hydro, wind, solar, geothermal; biomass; nuclear fission.
- **Use offsets** **WEEK 8**
  - Domestic and international: waste-to-energy, methane & SF-6 capture, biofuel, tree planting.

Inputs to biomass calculations

Areas

World surface area:	5×10^{14} m^2 = 50,000 Mha
Land area:	1.5×10^{14} m^2 = 15,000 Mha
Cropland (≈ 10% of land area):	1500 Mha
U.S. land area (50 states)	1000 Mha

Yields (tons of dry biomass per hectare per year): hares and tortoises

Plantations for carbon storage: steady, slow growth, 50 years:
2 to 10 t/ha-yr (Steady state of 100 to 500 t/ha)

Plantations for biofuels: fast growth for short periods (1 - 5 years), frequent harvesting:
10 to 50 t/ha-yr. (Issues: fertilizer, irrigation)

Energy content: 15 GJ/t for grasses, 20 GJ/t for wood (lignin is like oil)

Carbon content: 0.5 tC/t biomass

Biomass as primary energy

Land for primary energy

Land in plantations to produce **100 EJ/yr** (≈ U.S. today, ≈ 25% of global primary energy today)

Inputs: 10 to 50 t/ha-yr @ 20 GJ/t: thus 0.2 to 1 TJ/ha-yr.

Result: **100 to 500 Mha**.

Note the inefficiency of photosynthesis. What is the **conversion efficiency** for solar energy to bioenergy for yields of 10 to 50 t/ha-yr?

Assume average flux of incident sunlight is 300 W/m^2 = 100 TJ/ha-yr.

Result: **0.2% to 1%** conversion efficiency.

Biomass supply complexities

"Dry" biomass

Drying can require significant energy inputs.

Residues

Residues of commercial forestry (slash) and agriculture (rice husks, corn stover), in principle, can become biomass feedstocks. The need to sustain soil nutrients (N, P, …) will limit residue use.

Unavailable land

Steep slopes
Stream banks
Urban areas
Wilderness (deliberately left unmanaged)

Net energy, net carbon

In the back-of-the envelope calculations of land requirements biomass "overheads" are often neglected.

In energy conversion, energy inputs are neglected.

In carbon conversion, carbon inputs are neglected.

Biomass as low-carbon energy

***If climate change is what matters*:**

Direct emissions of CO_2 in biomass system

Fertilizer, tractors, distillation

Indirect land use change (ILUC) -- requires planetary analysis

Conversion of forest managed for pulp and paper to forest for carbon storage may lead to forest conversion to pulp and paper elsewhere.

Conversion of land for fodder (for corn, soybeans) to land for bioenergy may lead to forest clearing elsewhere to produce equivalent fodder.

Conversion of pasture to bioenergy may elicit feedlot cattle-raising and land clearing for fodder.

Evapotranspiration change

Emissions of CH_4, N_2O

Albedo change

Biomass as fuel

Land for oil

If oil is what matters, everything that grows is a potential liquid-fuel feedstock.

Land in plantations to produce the feedstock for biomass synthetic fuels plants for **1 million barrels per day** (mbd) of fuels:

Examples: sugar cane to ethanol, palm oil to diesel

Assume 10,000 liters/ha-yr (above what can be done today)
(100 liters/t biomass * 100 t biomass/ha-yr)

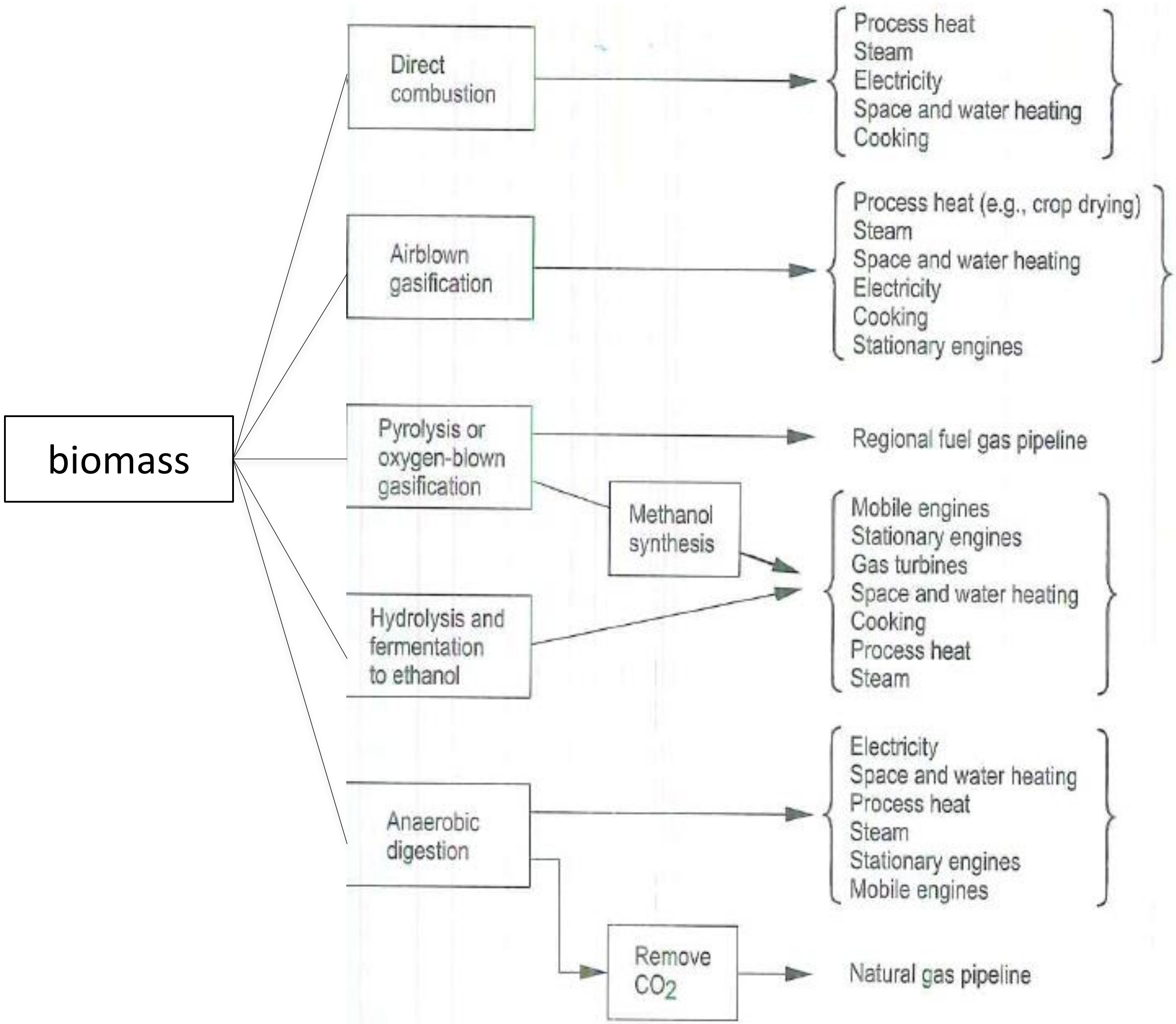
1 mbd = $365*10^6*150$ liters/yr = $50*10^9$ liters/yr.

So, **5 million hectares for 1 mbd**. A very different ballpark.

If liquid fuel is the objective, inputs of coal and natural gas do not need to be charged against the liquid-fuels balance. But these inputs could have become fuels by direct conversion (CTL, GTL).

Biomass to fuel

conversion processes and end use



Tester et al. "Sustainable Energy", p.425.

Biomass for CO_2 removal (CDR)

Two bio strategies for CDR

Biopower with CCS (BECCS)

Afforestation

Land for afforestation, removing 1 ppm/yr from the atmosphere

Inputs:

10 t biomass/ha-yr (for 50 years)

0.5 tC/t biomass.

1 ppm = 2 GtC

Result: **400 Mha**. (Recall: U.S. area is 1000 Mha.)

BECCS

- BECCS: Bioenergy Carbon Capture and Storage
- Produce energy from biomass and store the CO_2 emissions underground
- High uncertainty on costs and storage availability
- Same post-capture issues as fossil fuel CCS (coming soon)

Source: Felix Creutzig, Guest contribution, WWS 585b – Nov. 28, 2012

BECCS: Power and stored CO_2 from a large ethanol plant

1 Mt/yr dry cane- waste/yr, from 5 Mt/yr processed cane

O_2-gasification of cane waste*
Combined-cycle power
All internal power needs met
*Gasifier requires development.

or

2.0 TWh/yr (300 MW, 80% on)

CO_2 not captured

1.6 TWh/yr (220 MW, 80% on)

1.5 Mt CO_2 captured at power plant

+ 0.4 Mt CO_2 captured at distillery

Brazil today:

320 Mt cane/yr

360 TWh/yr all power

(300 TWh/yr is hydro)

320 $MtCO_2$/yr

fossil fuel emissions

Source of data and concept: Robert Williams

Conditionality for biocarbon

What will go wrong if we move headlong to maximize either global biostocks or global biofuels without conditionalities?

Suppose you were a forester or an agronomist in a world where the carbon price was very high. You were told that storing carbon was your only objective. What would you do? Establish a monocrop? Pour on fertilizer? Be inventive….

Conditionality for biocarbon

What will go wrong if we move headlong to maximize either global biostocks or global biofuels without conditionalities?

Suppose you were a forester or an agronomist in a world where the carbon price was very high. You were told that storing carbon was your only objective. What would you do? Establish a monocrop? Pour on fertilizer? Be inventive.…

Now, change roles. You are the policy maker in the same world. What conditionalities would you place on the carbon market for biostocks in the interest of eliciting actions you would welcome and deterring out comes you would decry?

Weeks 9-11: Low-carbon Electricity

Structure and local case studies:

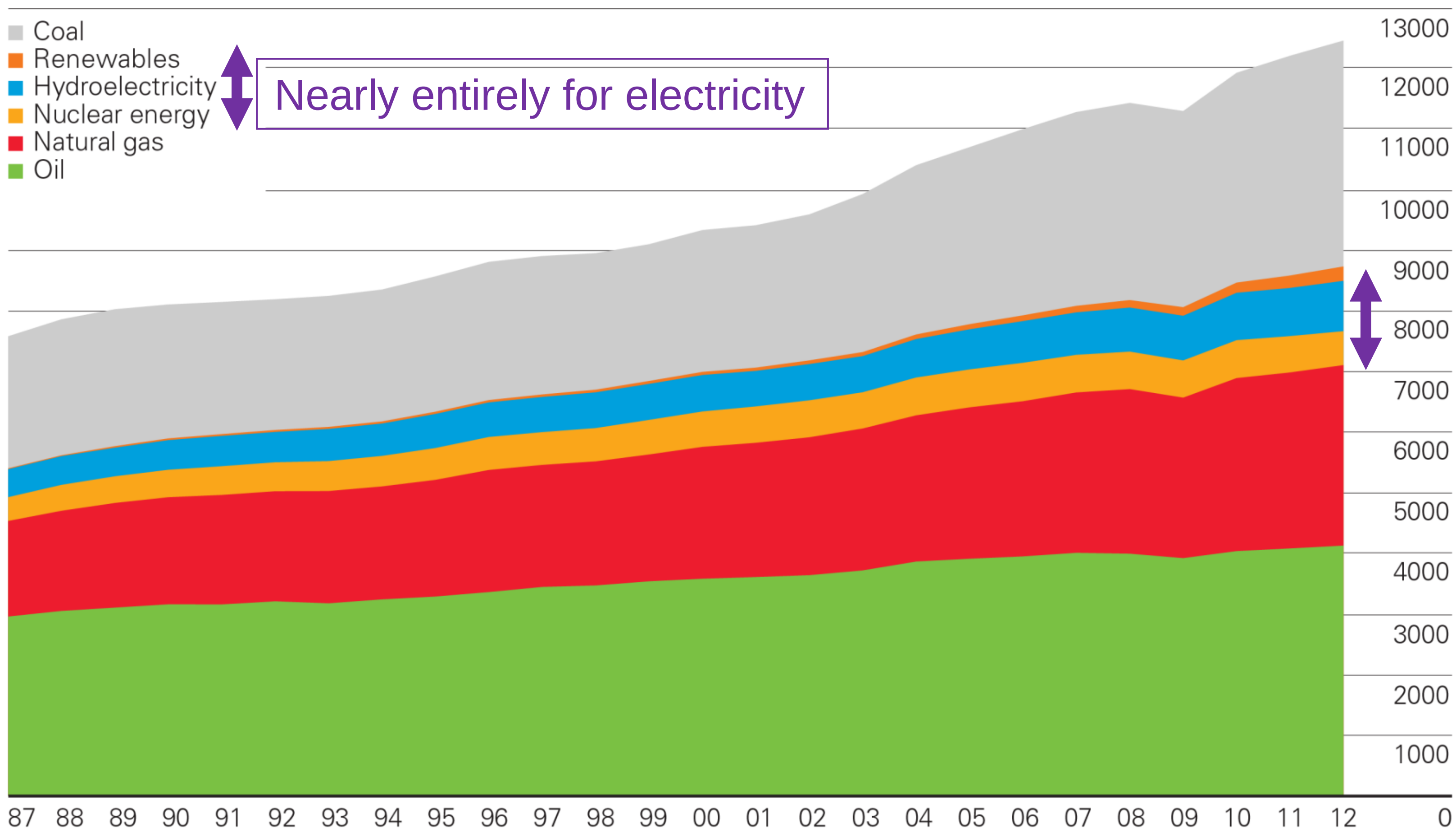
Week 9: Low-carbon fossil-fuel energy via more efficient power plants, gas instead of coal, CCS
Mercer County Generating Station (1950s coal plant)

Week 10: Renewable electricity
NJ offshore wind
Princeton University's 5 MW photovoltaic system

Week 11: Nuclear power
Oyster Creek, NJ

Primary energy world consumption

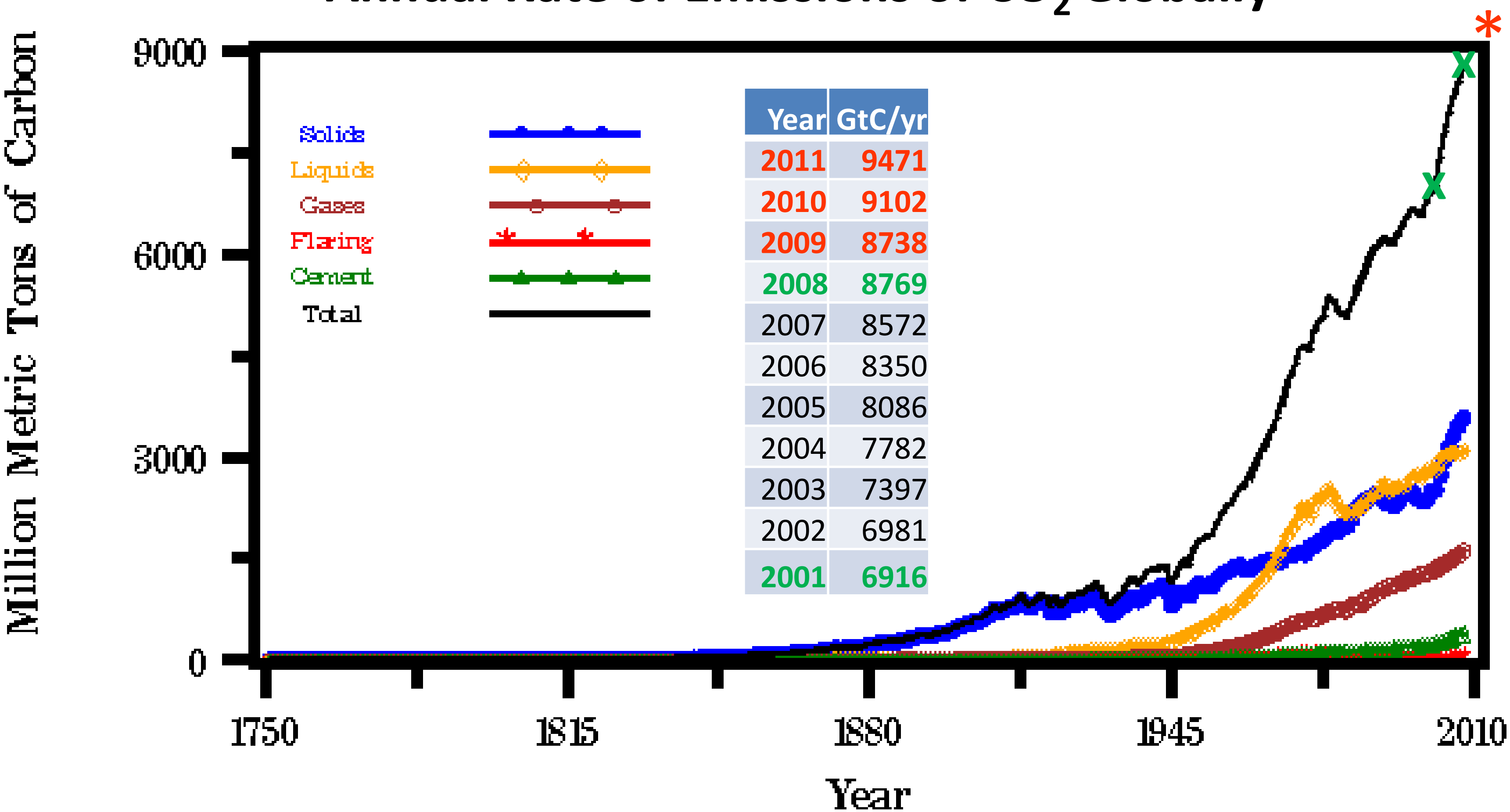
Million tonnes oil equivalent



BP Statistical Review of World Energy 2012 © BP 2012

Emissions keep rising

Annual Rate of Emissions of CO_2 Globally

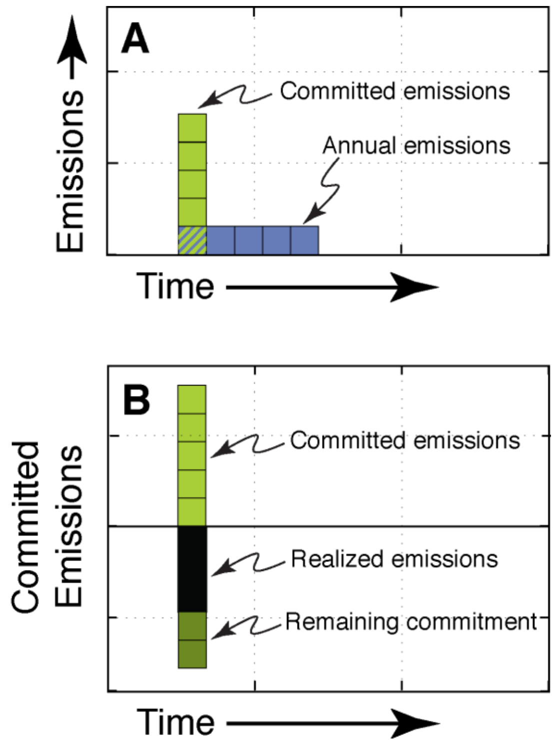


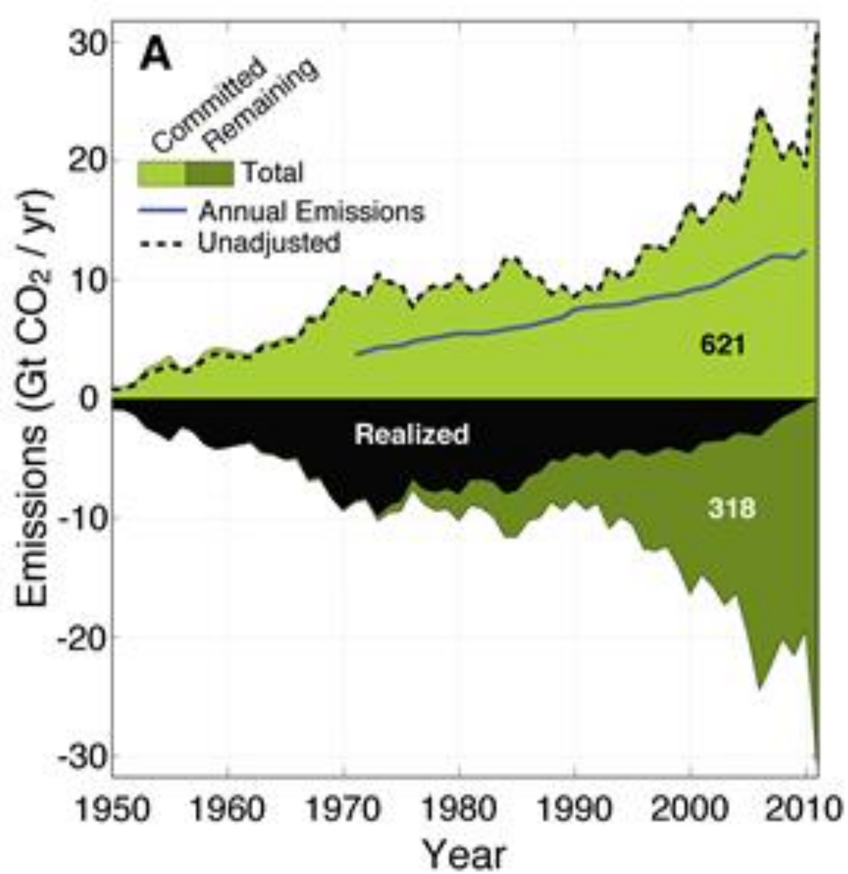
Year	GtC/yr
2011	9471
2010	9102
2009	8738
2008	8769
2007	8572
2006	8350
2005	8086
2004	7782
2003	7397
2002	6981
2001	6916

Source (accessed 10/1/11): http://cdiac.ornl.gov/trends/emis/glo.html.

Updated 1/5/13

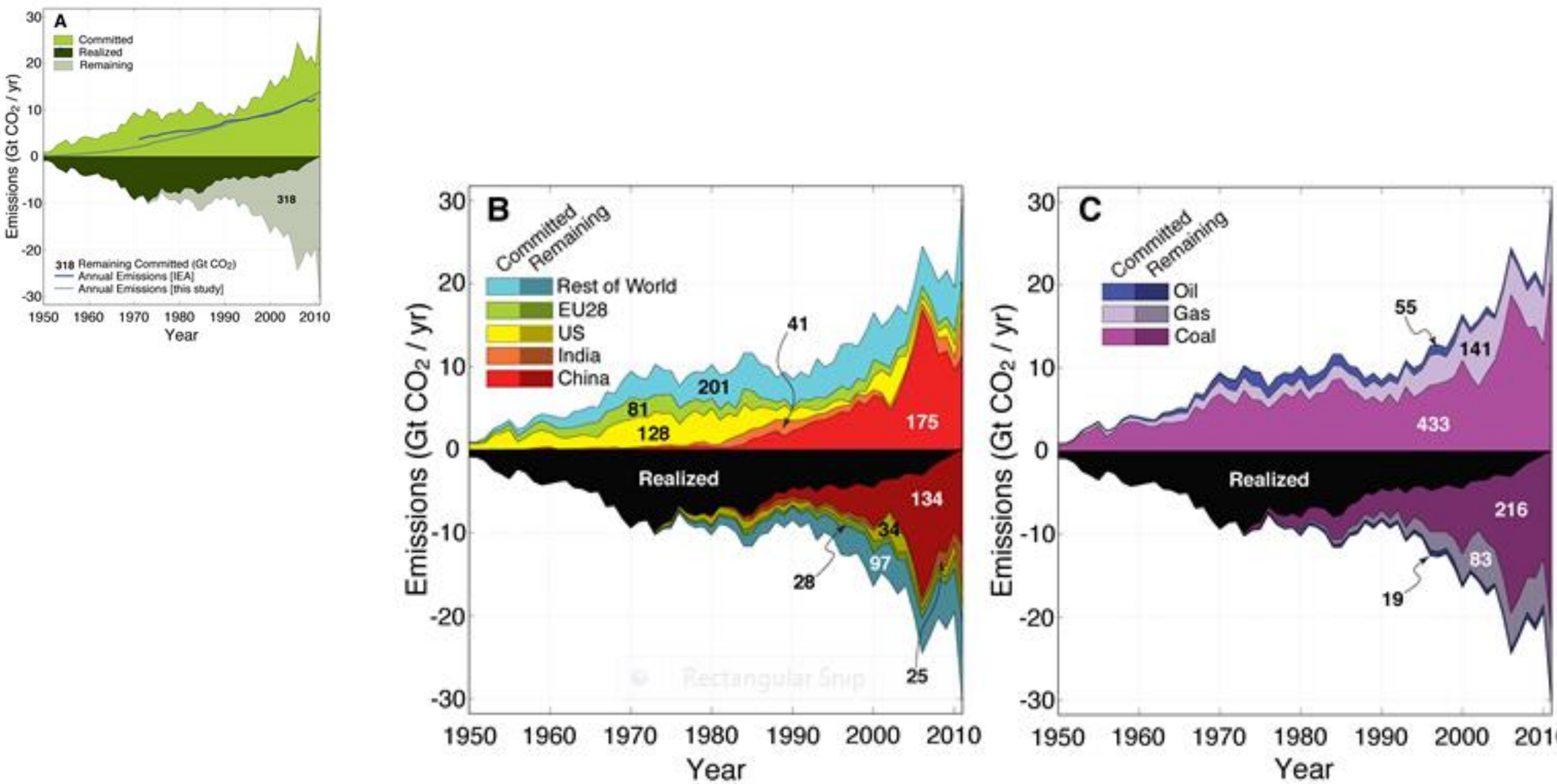
Committed CO_2 emissions from global power plants



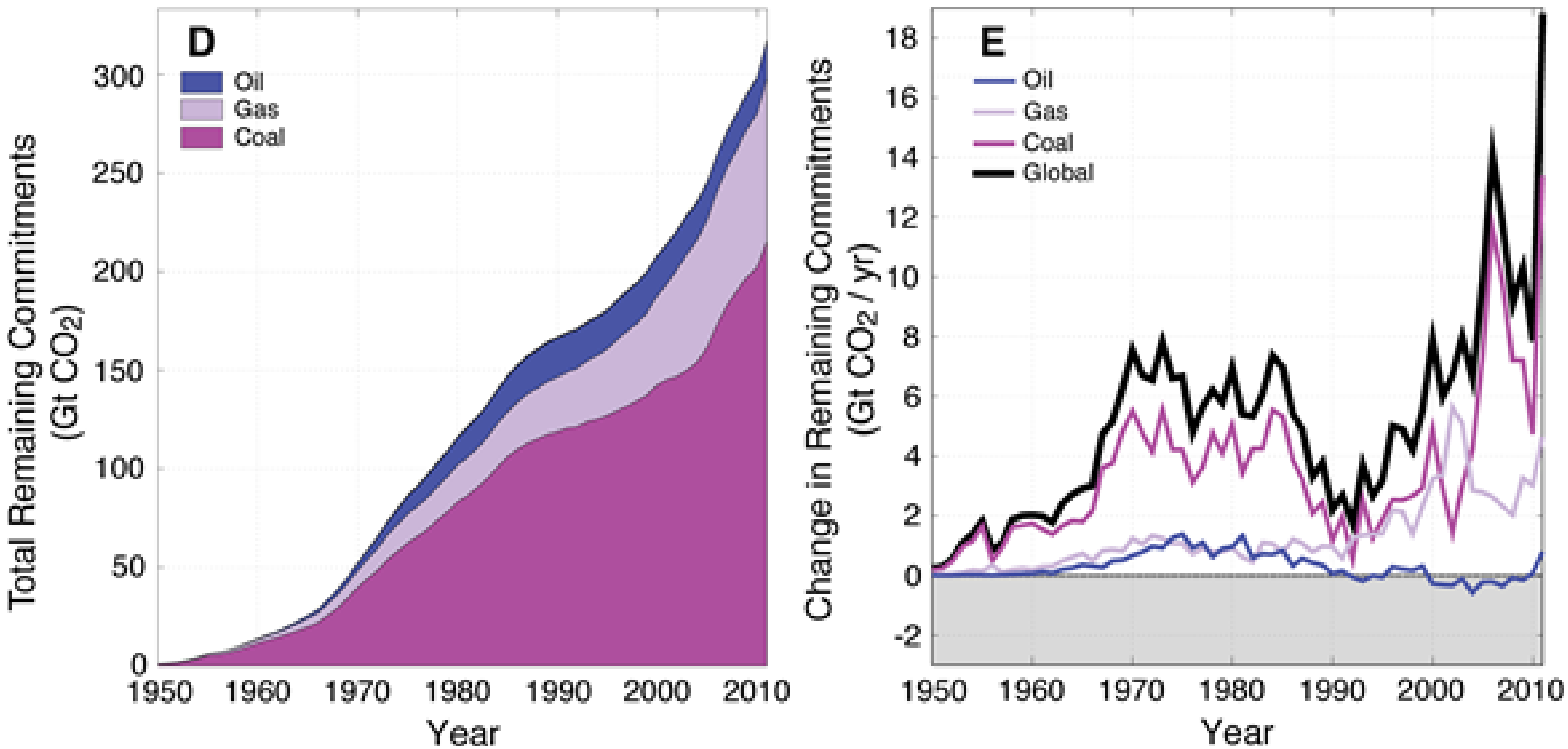


Assume 40-year life for power plants. Update for retirements and plant-life extensions. Figure shows 2009 view: remaining emissions are 318 $GtCO_2$.

Committed emissions, 2009, by fuel and region

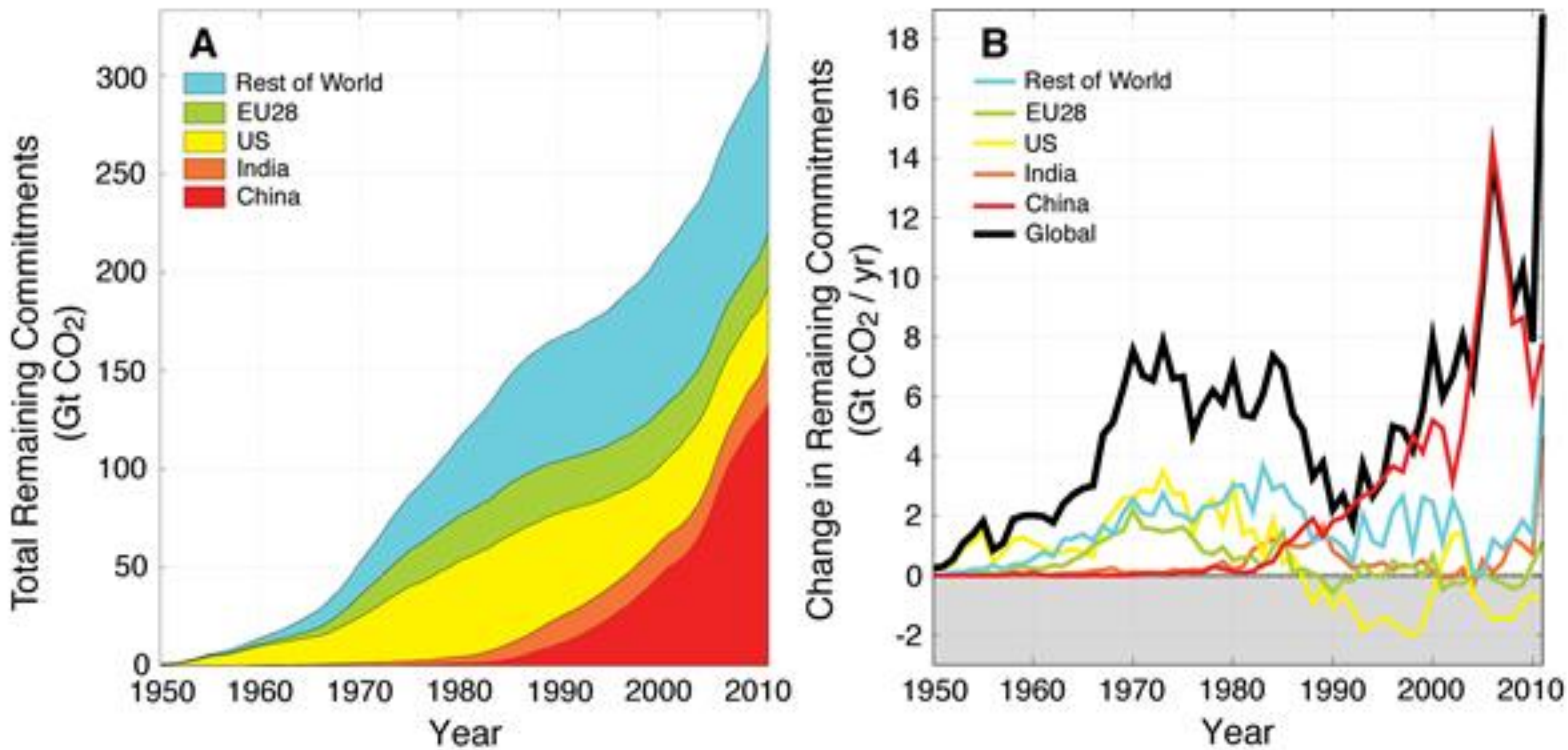


Committed emissions keep rising: coal and gas for power (fuels view)



No sign of saturation. Rather, an acceleration in commitments to future emissions.

Committed emissions keep rising: coal and gas for power (regional view)



Note: The U.S. reduces its remaining commitments (negative values in panel B) when, as a "post-industrial" country, it runs on already-built plants. *Note also*: U.S. "rush to gas," 2000-2005.

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO	A nuclear or renewables world unmotivated by climate.	Most people in the fuel industries and most of the public are here. **5^{o}C.**
	YES	Environmentalists, nuclear advocates are often here. **2^{o}C.**	OUR WORKING ASSUMPTIONS. **3^{o}C, tough job.**

“Low-carbon” fossil-fuel power

“The Warsaw Communiqué”

The World Coal Association and the Polish Ministry of Economy are advocating a future for coal in the lead up to the UNFCCC negotiations happening in Warsaw this week.

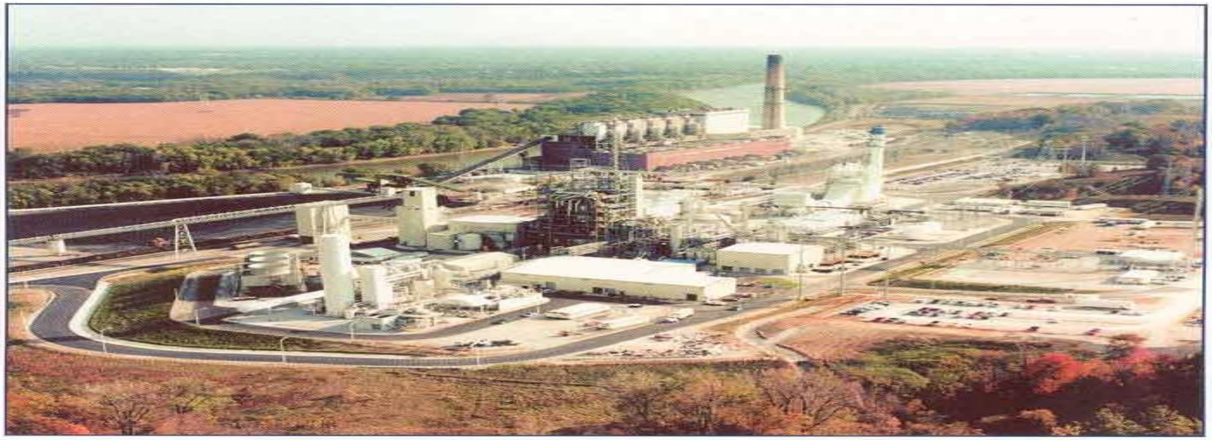
1)Call for “immediate use of high-efficiency low-emissions coal combustion technologies” and “carbon capture utilisation and storage technologies once demonstrated and commercialised”

2)Support R&D and set goals to move “global average efficiency of coal-fired power generation plants to current state of the art levels”

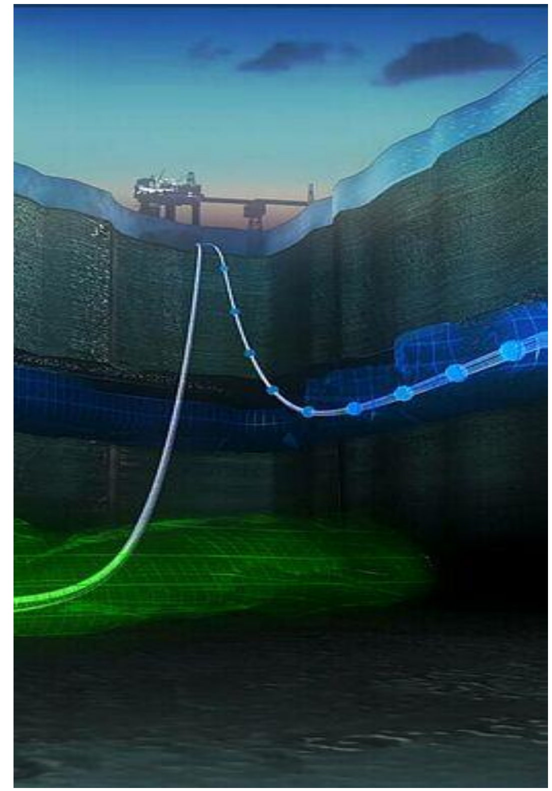
3)Call on “development banks to support developing countries in accessing clean coal technologies”

Source: http://www.worldcoal.org/extract/the-

Coal with Carbon Capture and Storage



The Wabash coal gasification reprocessing project



Sleipner field, Norway

1 wedge: By 2062, 800 GW, if 90% capture.

Graphics courtesy of DOE Office of Fossil Energy and *Statoil ASA*

CO_2 Capture and Storage

Capture

Pipeline transport

Storage

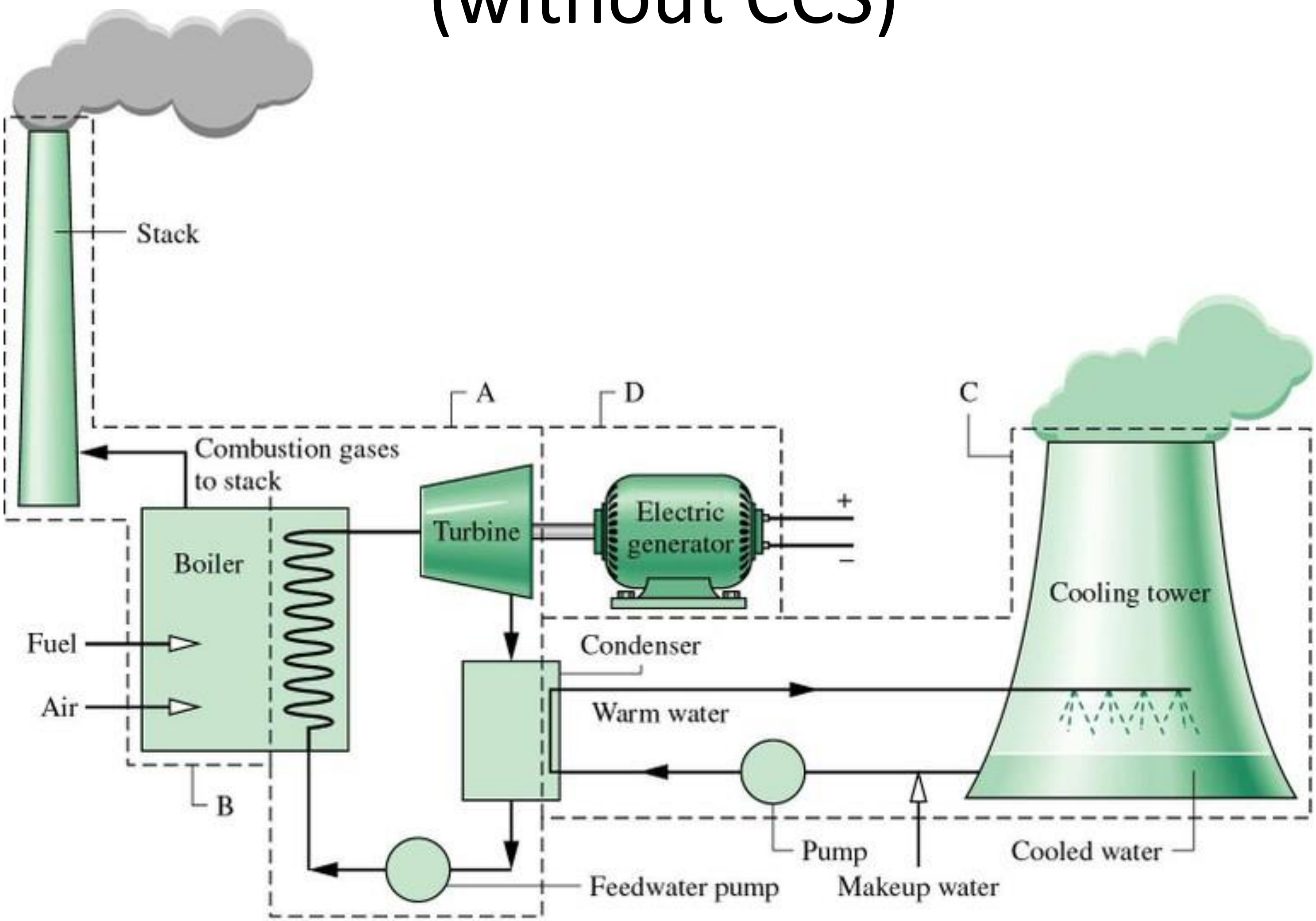
CO_2 Capture

1. Post-combustion capture, combustion in air

2. Post-combustion capture, combustion in oxygen ("oxyfuel combustion")

3. Pre-combustion capture

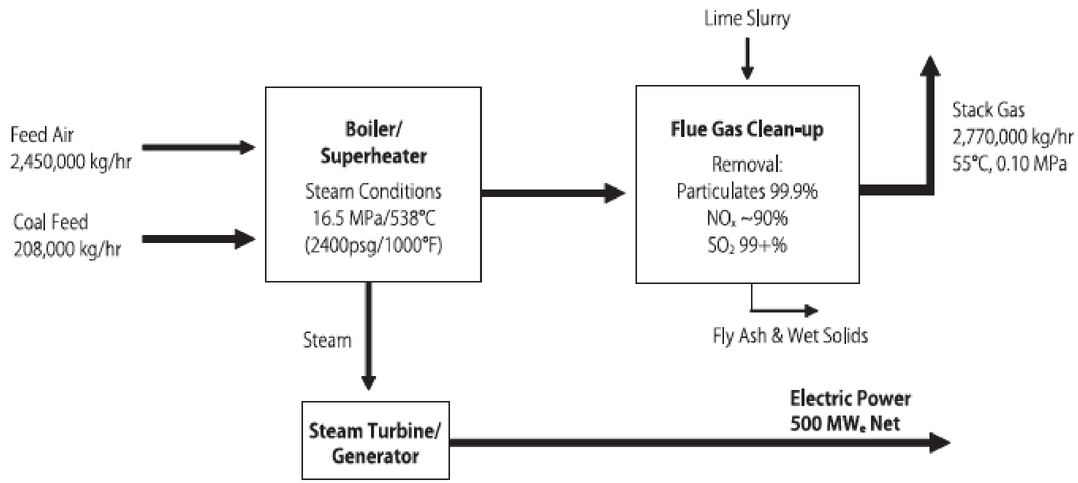
A typical Coal burning powerplant (without CCS)

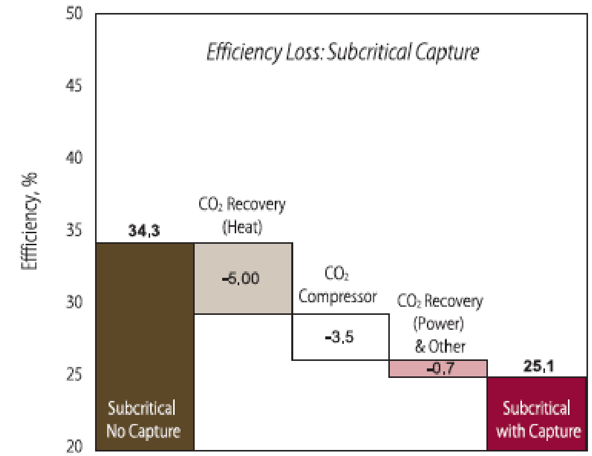


http://www.leam.illinois.edu/up466/transportation/lab-3-demo/making-electricity/03-making-electricity.html

SubCritical Coal
with and without CCS

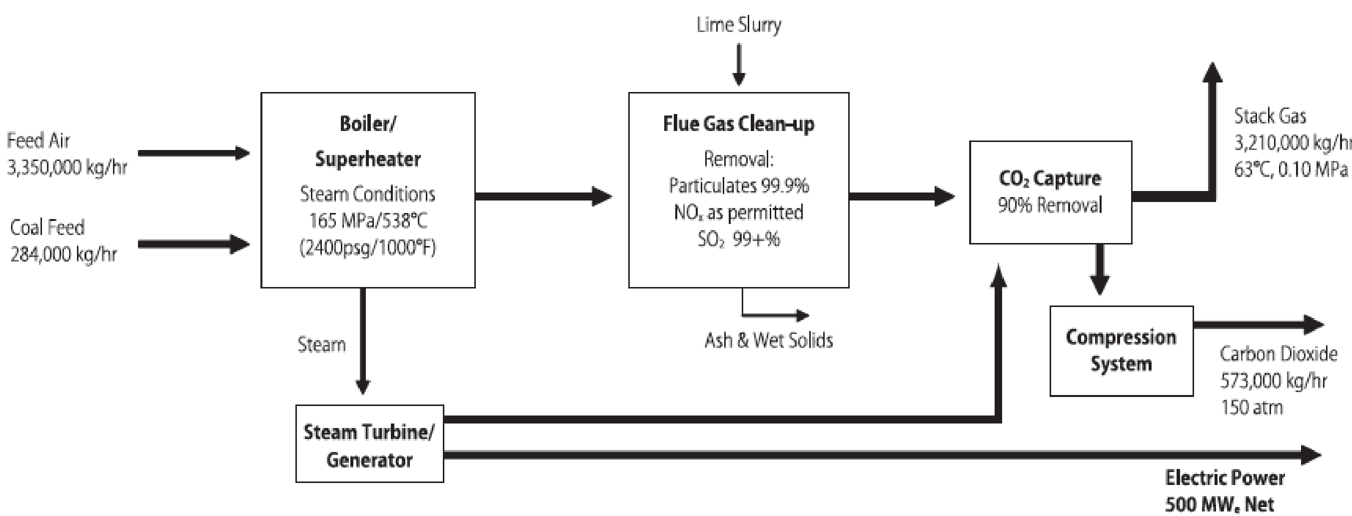
Without CO2 capture





Parasitic losses

With CO2 capture

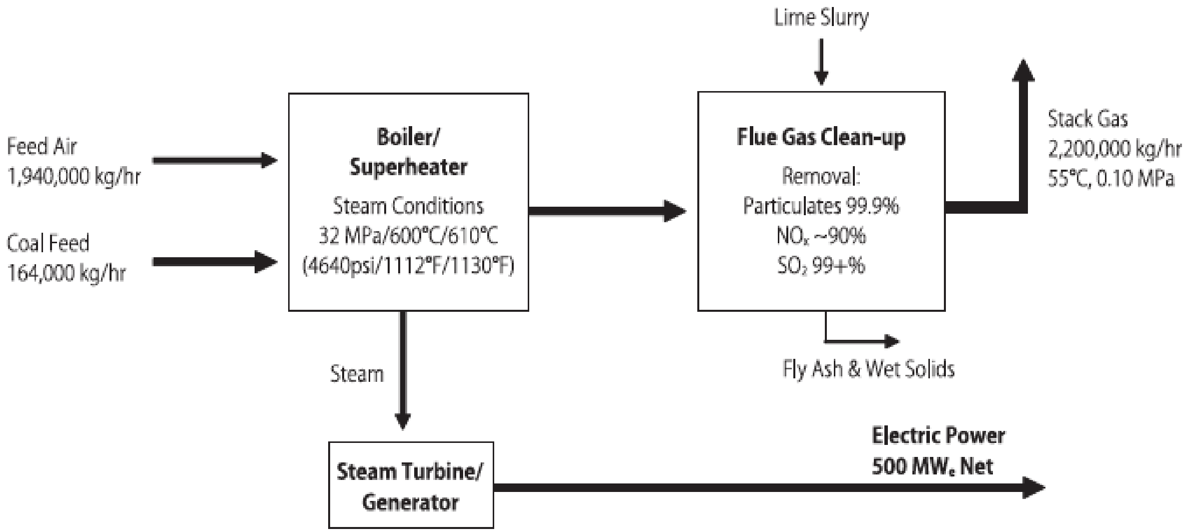


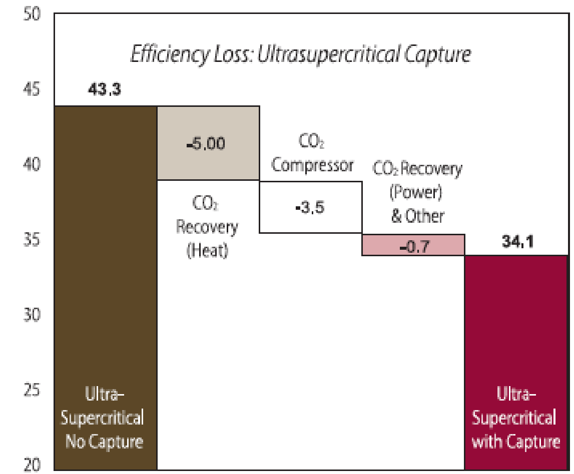
[MIT (2007) Future of Coal]

Ultra-Supercritical Coal

with and without CCS

Without CO2 capture





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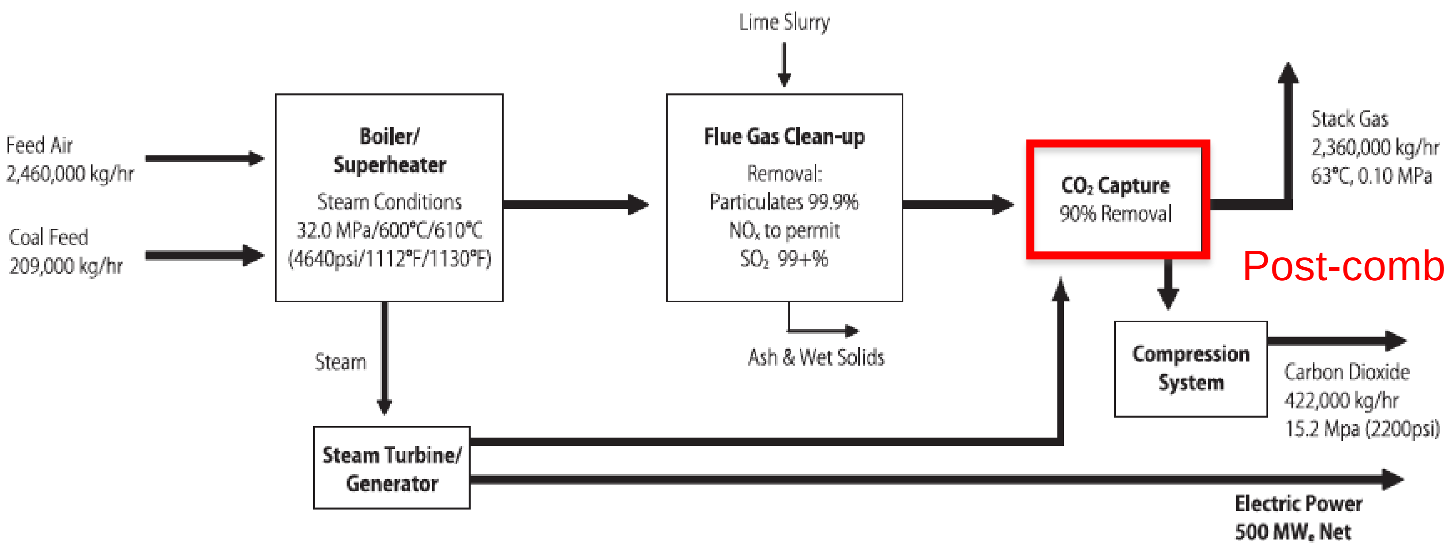
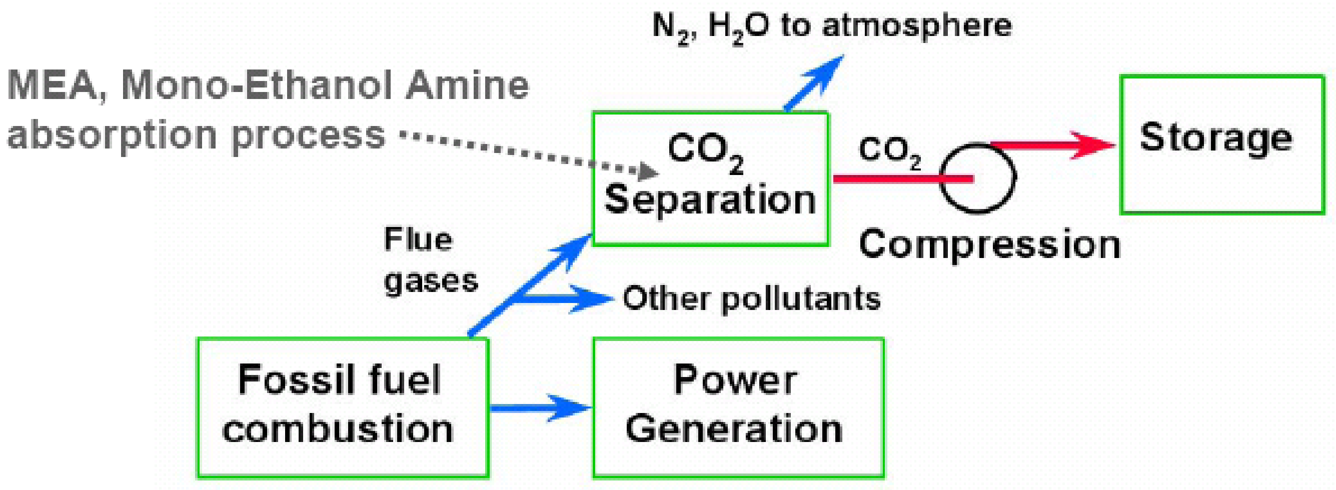


Post-combustion capture

[MIT (2007) Future of Coal]

POST-COMBUSTION CO_2 CAPTURE



Amines - Any of a class of nitrogen- containing organic compounds derived from ammonia NH_3

- Capture in chemical solvent (*40-60 °C*) from flue gas (*6-15% CO_2*)
- High energy penalty for solvent regeneration (*100-140 °C*)
- SO_x/NO_x removal to low levels before CO_2 capture to protect solvent
- Commercially available: 10 MW_t coal-to-urea plant in Malaysia

Source: Robert H. Williams, "Coal Power In A Climate-constrained World," Lecture in MAE 328, 27 February 2007.

The 2009 AEP Mountaineer Plant, West Virginia

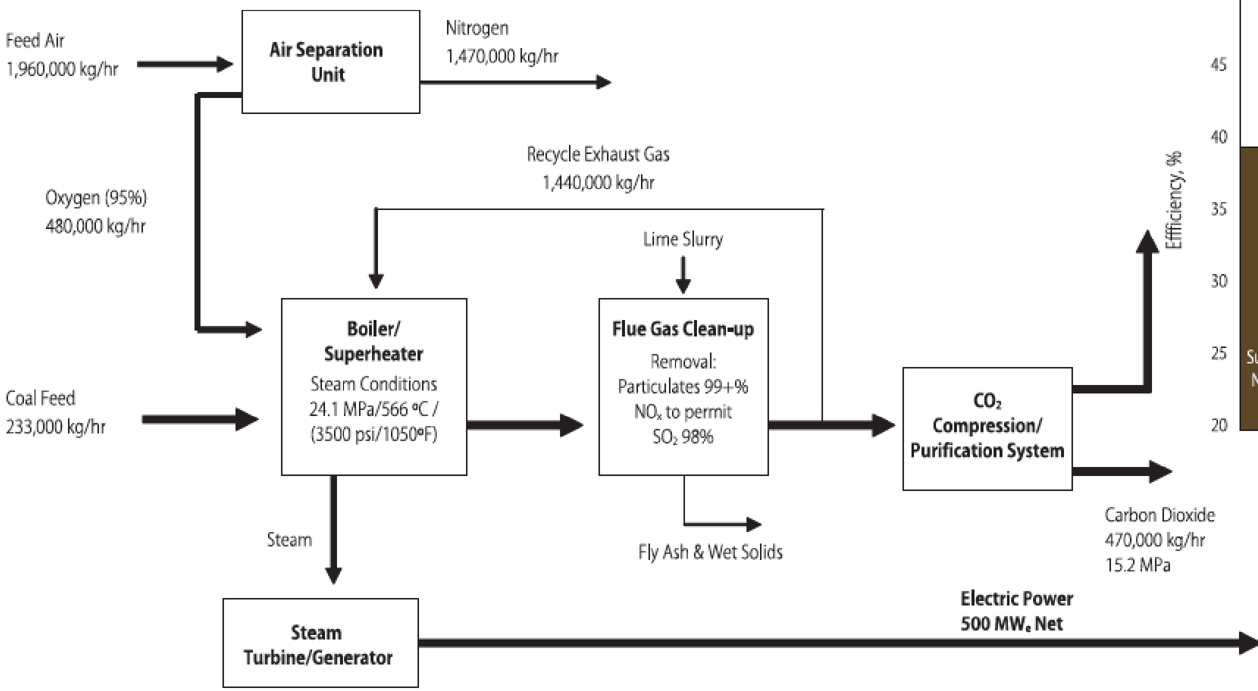
Na_2CO_3 sorbent: "chilled ammonia" process

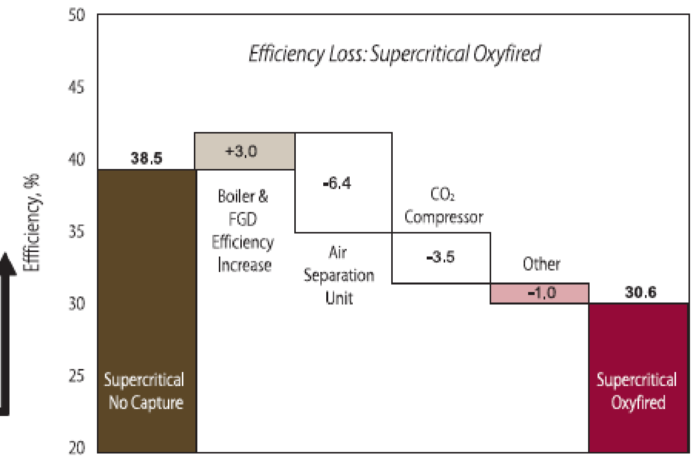
**Mountaineer is the first power plant in the world to capture and store carbon dioxide. First stage, shown here, captures 100,000 tCO_2/yr, less than 2% of ≈6 $MtCO_2$/yr emitted.
In 2011, scale-up was canceled.**

Source: Alstom via *Yale 360*, February 18, 2010

Oxy-Fuel Coal

With CO2 capture





Parasitic losses

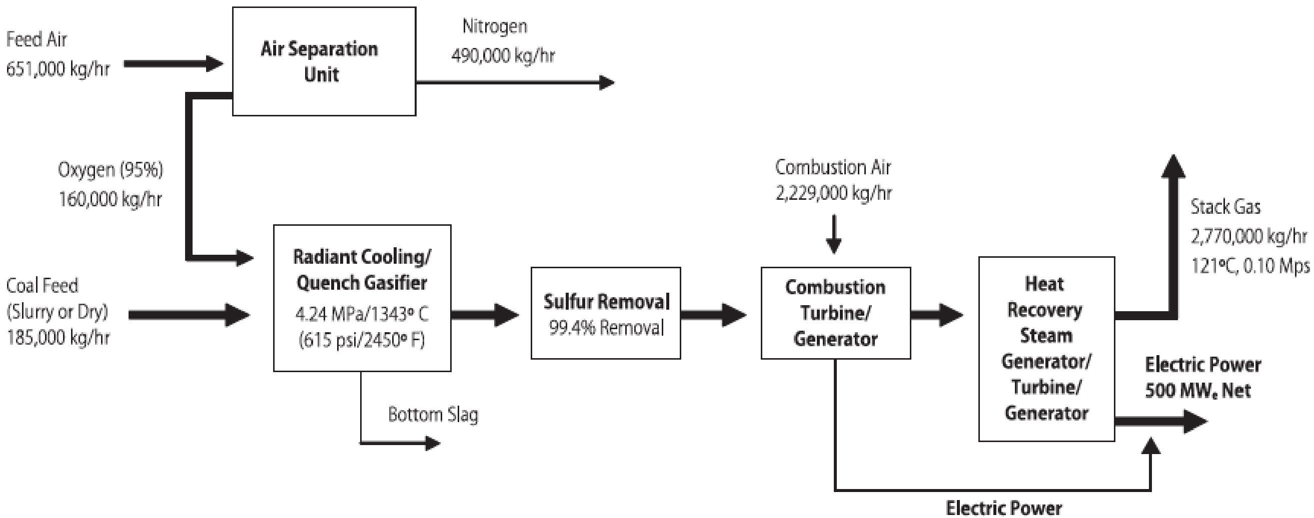
- Fuel is burned in O_2 + CO_2 instead of air so that main combustion products are CO_2 & H_2O
- H_2O condensed from stack gases leaving nearly pure CO_2 stream
- Requires ~ 3 X as much O_2 as IGCC per MWh generated
- Technology not yet commercial

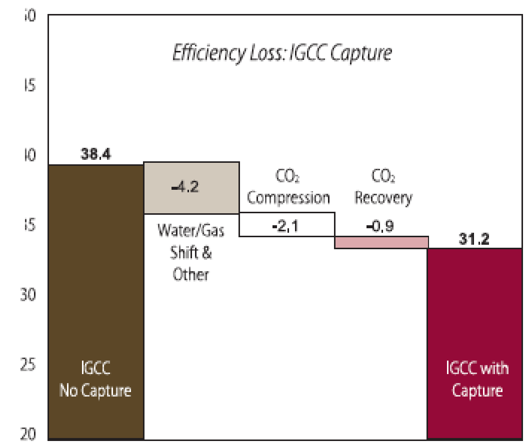
[MIT (2007) Future of Coal, and Bob Williams]

Integrated Gasification Combined Cycle

with and without CCS

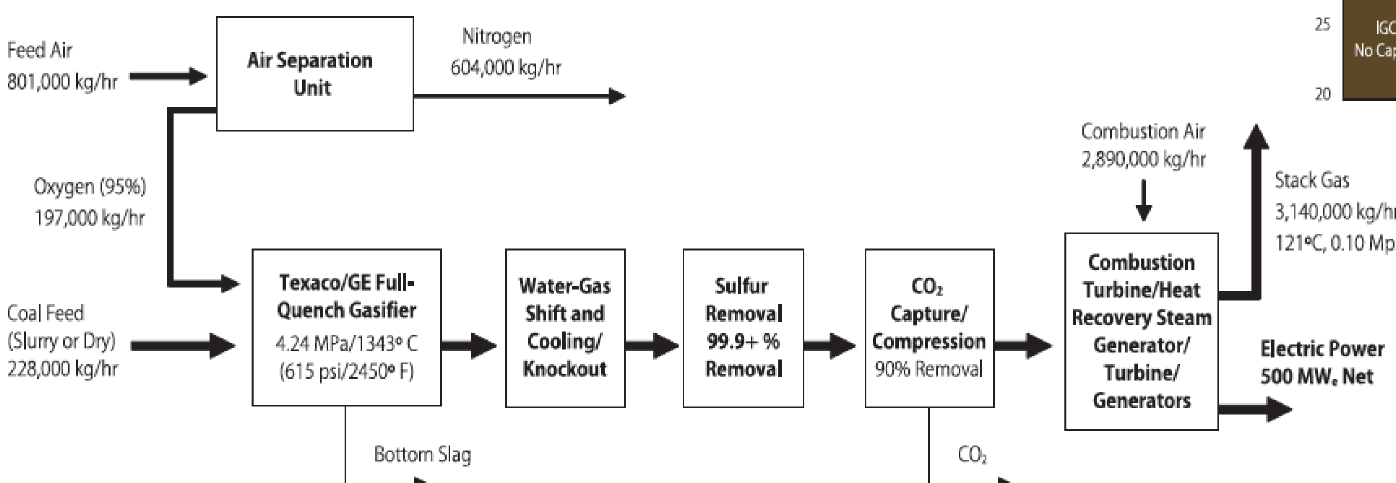
Without CO2 capture





Parasitic losses

With CO2 capture



[MIT (2007) Future of Coal]

Current IGCC plants are almost pre-combustion CO_2 capture plants

For CO2 capture, add: 1) "Shift reactor" [$CO + H_2O \rightarrow CO_2 + H_2$]; 2) CO_2 - H_2 separation; 3) H_2 to turbine for power; 4) CO_2 pressurization, export off site.

Graphics courtesy of DOE Office of Fossil Energy

An IGCC Under Construction, Edwardsport, Indiana

Edwardsport will not be in the top 10 in size in Indiana when completed. It may capture some CO_2.

Source; Marty Irwin, Purdue, Sept 27, 2010

Planned CCS demonstrations

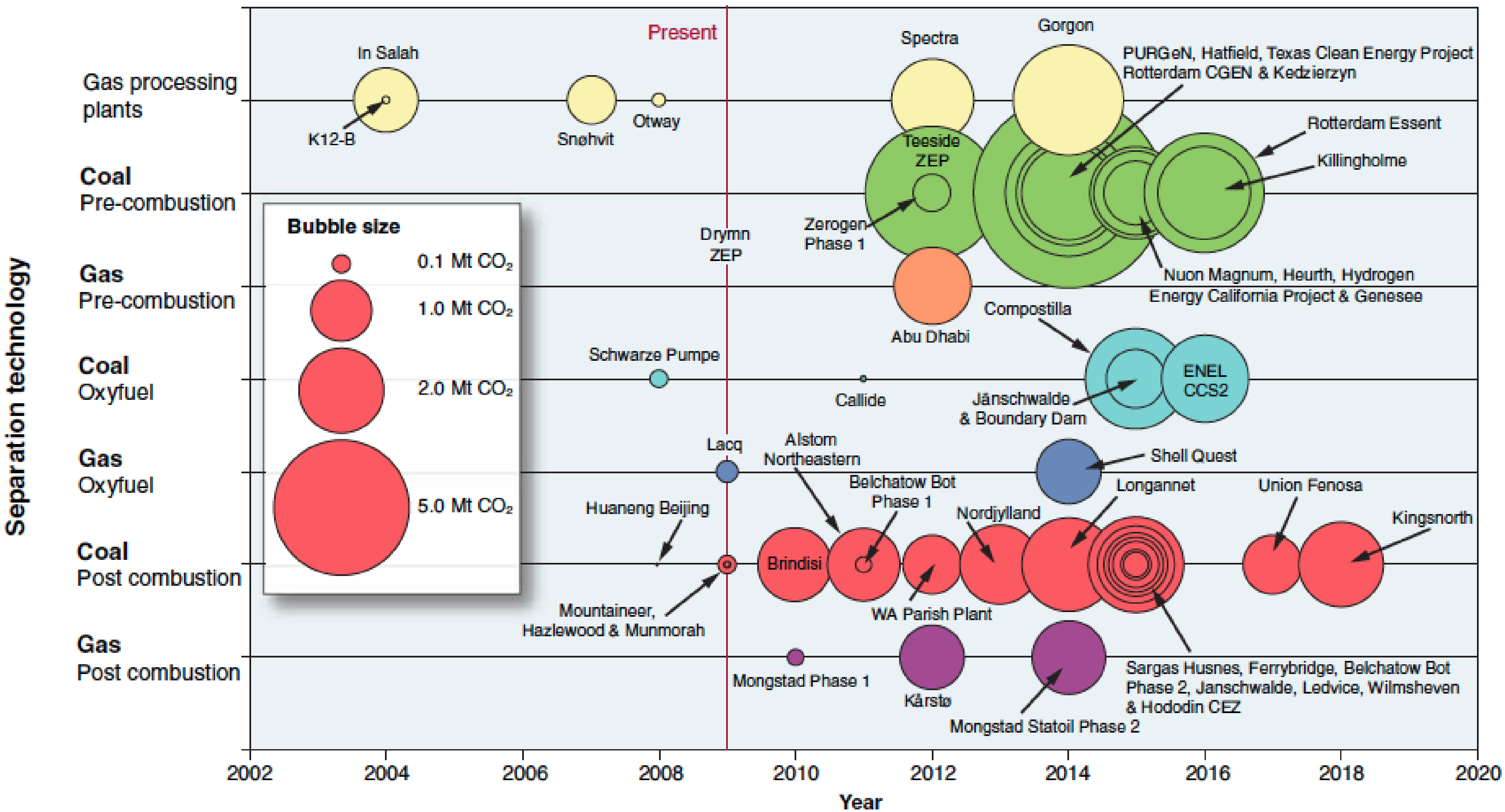


Fig. 4. Chart of large CCS demonstration projects planned worldwide, plotting calendar year against capture type and fuel. Coal and postcombustion power plants dominate. There is typically a 5-year lead time on design and construction (Fig. 2), so to operate these plants on schedule requires that projects commence spending on design now. Few of these projects have certain funding to assist construction, and even fewer have systems to enable commercial operation. National CCS targets with worldwide coordination and exchanges of learning are needed. [Compiled by Y. Bushby (15)]

[Haszeldine 2009 *Science*]

Costs and efficiencies of powerplant technologies

Table 3.5 Representative Performance and Economics for Oxy-Fuel Pulverized Coal and IGCC Power Generation Technologies, Compared with Supercritical Pulverized Coal

	SUPERCRITICAL PC		SC PC-OXY	IGCC	
	W/O CAPTURE	W/ CAPTURE	W/CAPTURE	W/O CAPTUREQ	W/CAPTURE
PERFORMANCE					
Heat rate (1), Btu/kW_e-h	8,868	11,652	11,157	8,891	10,942
Generating efficiency (HHV)	38.5%	29.3%	30.6%	38.4%	31.2%
Coal feed, kg/h	184,894	242,950	232,628	185,376	28,155
CO_2 emitted, kg/h	414,903	54,518	52,202	415,983	51,198
CO_2 captured at 90%, kg/h (2)	0	490,662	469,817	0	460,782
CO_2 emitted, g/kW_e-h (2)	830	109	104	832	102
COSTS					
Total Plant Cost (3), \$/kW_e	1,330	2,140	1,900	1,430	1,890
Inv. Charge, ¢/kW_e-h @ 15.1% (4)	2.70	4.34	3.85	2.90	3.83
Fuel, ¢/kW_e-h @ \$1.50/MMBtu	1.33	1.75	1.67	1.33	1.64
O&M, ¢/kW_e-h	0.75	1.60	1.45	0.90	1.05
COE, ¢/kW_e-h	**4.78**	**7.69**	**6.98**	**5.13**	**6.52**
Cost of CO_2 avoided vs. same technology w/o capture (5), \$/tonne		**40.4**	**30.3**		**19.3**
Cost of CO_2 avoided vs. supercritical technology w/o capture (5), \$/tonne		**40.4**	**30.3**		**24.0**

Basis: *500 MW_e plant net output, Illinois # 6 coal (61.2 wt % C, HHV = 25,350 kJ/kg), & 85% capacity factor; for oxy-fuel SC PC CO_2 for sequestration is high purity; for IGCC, GE radiant cooled gasifier for no-capture case and GE full-quench gasifier for capture case.*

(1) efficiency = (3414 Btu/kW_e-h)/(heat rate)

(2) 90% removal used for all capture cases

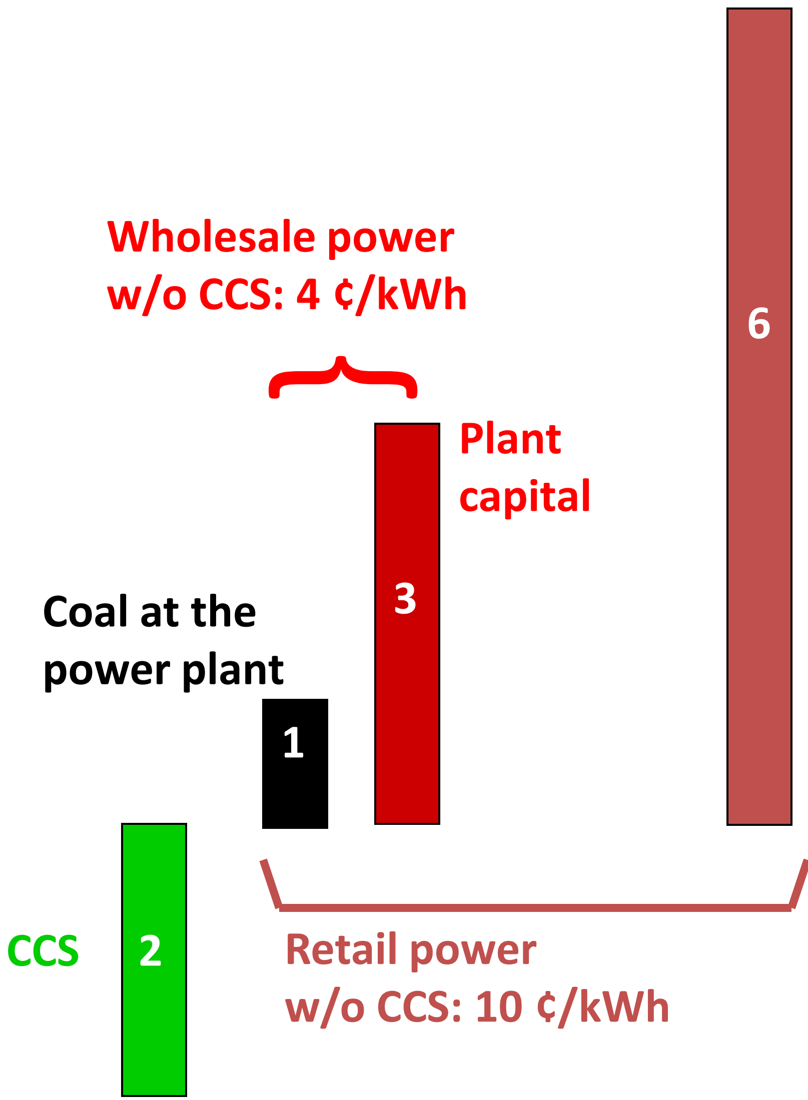
(3) Based on design studies done between 2000 & 2004, a period of cost stability, updated to 2005\$ using CPI inflation rate. Refers to the N[th] plant where N is less than 10. 2007 cost would be higher because of recent rapid increases of engineering and construction costs, up to 30% since 2004.

(4) Annual carrying charge of 15.1% from EPRI-TAG methodology, based on 55% debt @ 6.5%, 45% equity @ 11.5%, 39.2% tax rate, 2% inflation rate, 3 year construction period, 20 year book life, applied to total plant cost to calculate investment charge

(5) Does not include costs associated with transportation and injection/storage

[MIT (2007) Future of Coal]

$\$30/tCO_2 \approx 2¢/kWh$ induces CCS. Three views.



A coal-gasification power plant can capture CO_2 for an added 2¢/kWh ($100/tC). This:

- triples the price of delivered coal;
- adds 50% to the busbar price (price for generation only) of electricity from coal;
- adds 20% to the household price of electricity from coal.

Benchmark: $60/tCO$_2$

Carbon emission charges in the neighborhood of $60/tCO$_2$ can enable scale-up of most low-carbon technology, if supplemented with sectoral policy to facilitate transition.

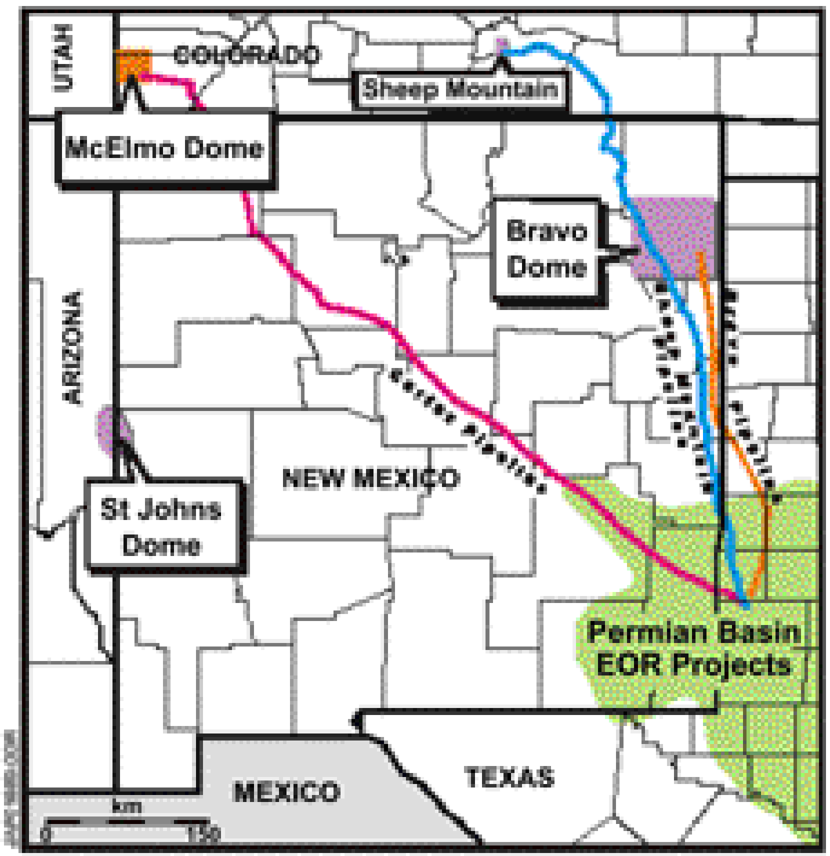
Form of Energy	Equivalent to $60/tCO$_2$ (≈ $200/tC)
Natural gas	**$3.20/1000 scf**
Crude oil	**$26/barrel**
Coal	**$140/U.S. ton**
Gasoline	50¢/gallon (ethanol subsidy: 50¢/gallon)
Electricity from coal	4.8¢/kWh (wind and nuclear subsidies: 1.8 ¢/kWh)
Electricity from natural gas	2.2¢/kWh

$60/tCO$_2$ values current global emissions (30 GtCO$_2$/yr) at $1.8 trillion/yr, 3% of GWP (PPP).
$60/tCO$_2$ values current U.S. emissions (6 GtCO$_2$/yr) at $360 billion/yr, 3% of GDP.
$40/tCO$_2$ was the peak 2008 EU Trading System price (yesterday's price was only ~$6/tCO$_2$!).

CO_2 Pipelines

Natural CO_2 fields in southwest U.S.

- McElmo Dome, Colorado: 0.4Gt(C) in place
- 800 km pipeline from McElmo Dome to Permian Basin, west Texas, built in the 1980s

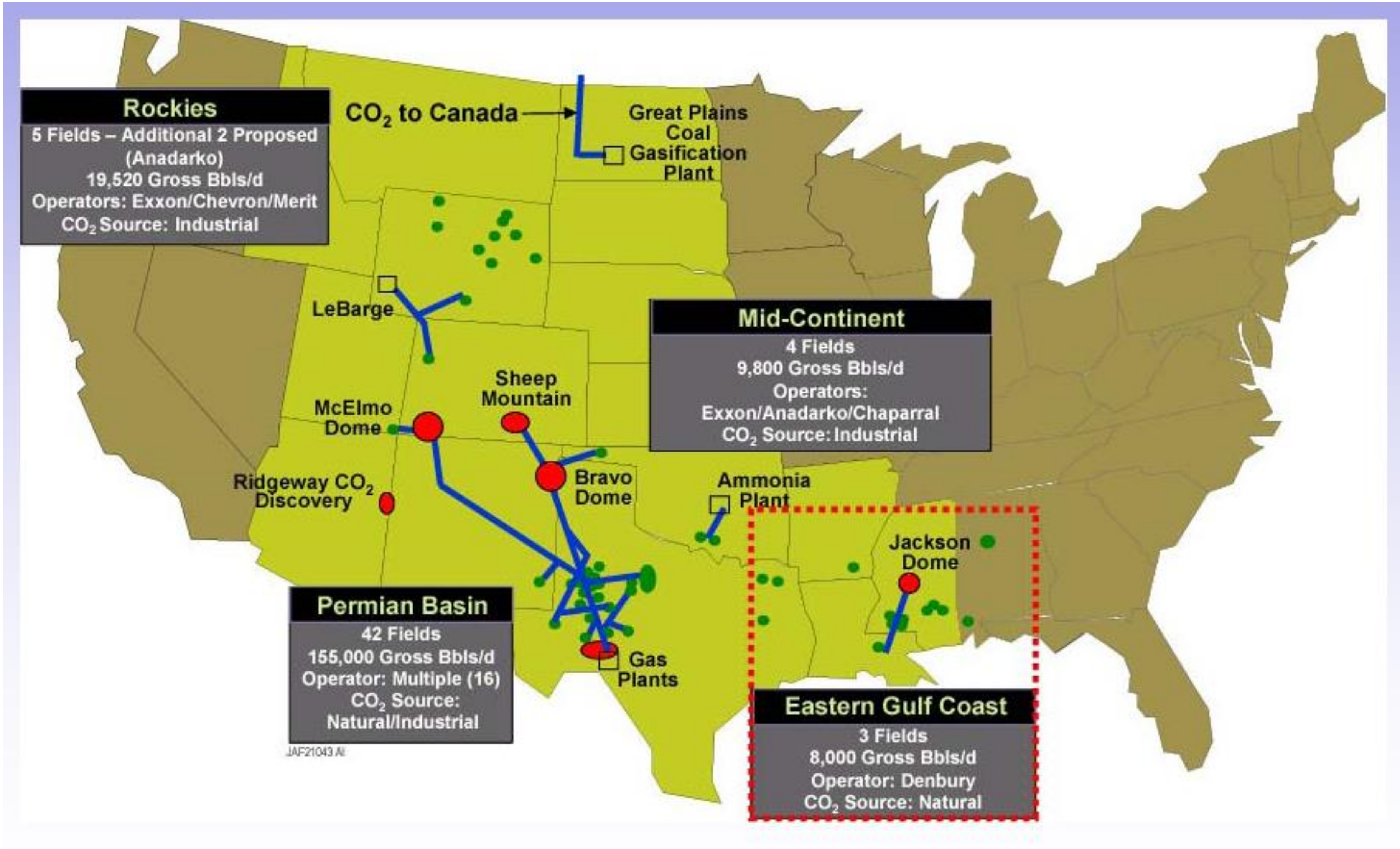


Two conclusions:

1. CO_2 in the right place is valuable.

2. CO_2 from McElmo was a better bet than CO_2 from any nearby site of fossil fuel burning.

U.S. CO_2 pipelines: Another infrastructure



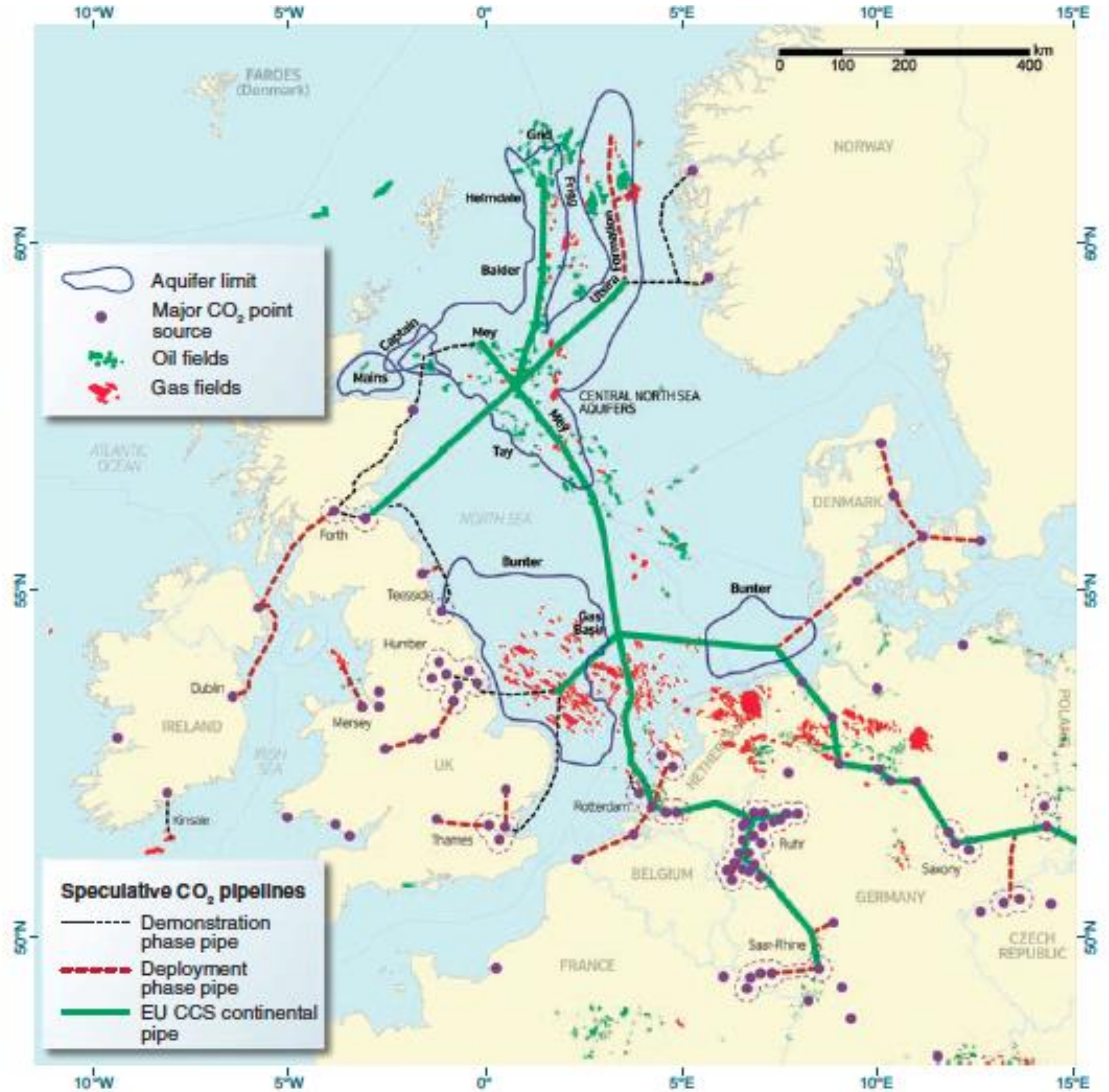


Fig. 3. Map of northwest Europe, showing sites of emissions, saline formations, gas fields, and oil fields. CO_2 can be collected from clusters of large power plants and transported to storage. This transport scenario visualizes pipelines built to offshore hubs accessing large-scale storage beneath the North Sea. Such sites can be evaluated with the use of legacy hydrocarbon data and may prove to be more reliable to develop and monitor than onshore storage. [Basemap of hydrocarbon fields supplied by M. Ricketts, Wood Mackenzie]

Potential CO2 transport network to the North Sea

[Haszeldine 2009 *Science*]

BREAK

Readings for Week 10

Required: Renewable energy and energy storage

Richter, B. (2011). Beyond Smoke and Mirrors: Climate Change and Energy in the 21st Century. Cambridge University Press. *Read Chapter on Renewable Energy. A mostly non-quantitative examination.*

National Academies of Science (2009). America's Energy Future. *Section on Renewable Energy: P. 271-323.*

MacKay, D. (2008). *Sustainable Energy-without the hot air*. UIT Cambridge. *Read each of the following short sections: Chapters 4 (Wind), Chapter 6 (Solar), Chapter 8 (Hydroelectricity), Chapter 10 (Offshore wind), Chapter 12 (Wave), Chapter 14 (Tide), and Chapter 16 (Geothermal). A more quantitative analysis.*

REN21. 2013. Renewables 2013 Global Status Report (Paris: REN21 Secretariat). *Beautiful report on national/sub-national action on renewable energy.*

Martinot, E. (2010). Renewable power for China: Past, present, and future. *Frontiers of Energy and Power Engineering in China*, *4*(3), 287-294.

Readings for Week 10

Recommended: Renewable energy and energy storage

IPCC, 2011: Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Also read a critique by Dr. Ted Trainer (Univ. New South Wales).

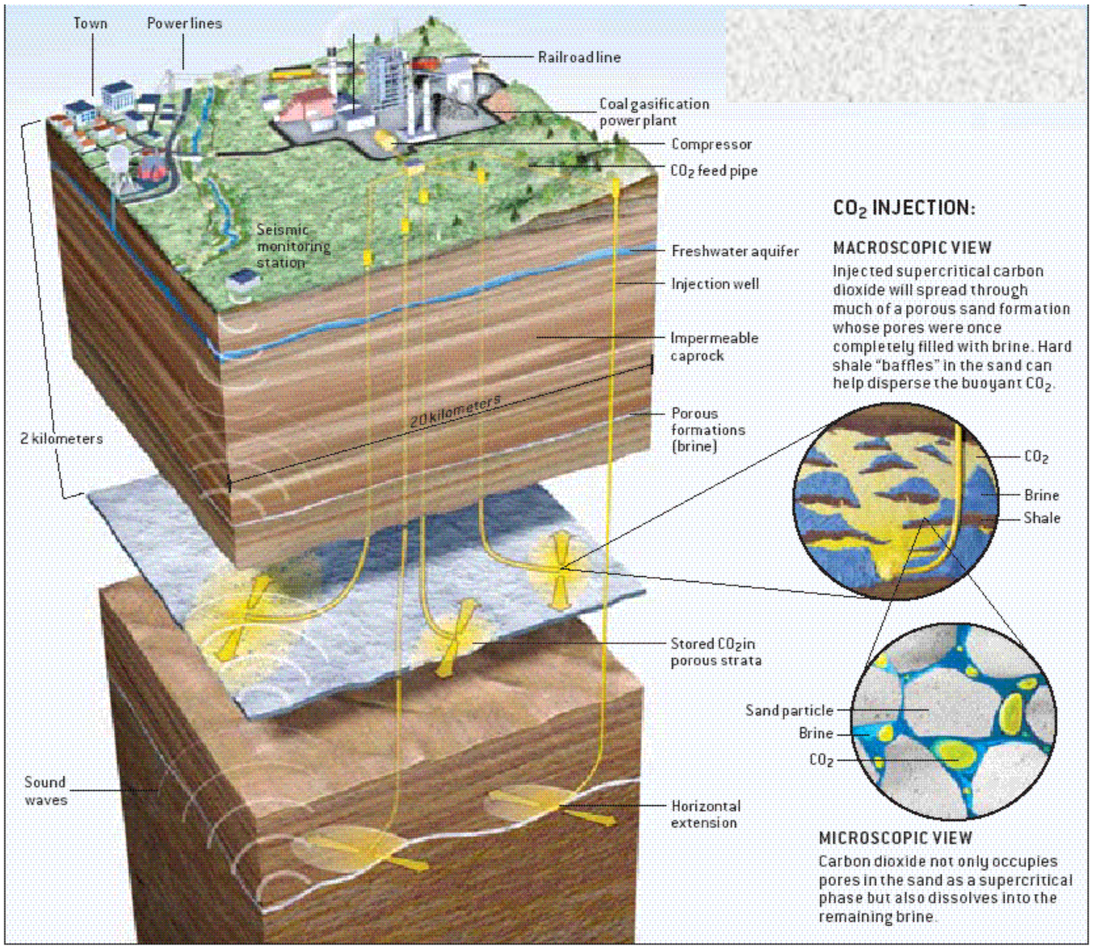
Budischak, C., Sewell, D., Thomson, H., Mach, L., Veron, D. E., & Kempton, W. (2012). Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. *Journal of Power Sources. [There was an Andlinger Center talk on this paper on Monday]*

Ruttan, V. (2002). “Sources of Technical Change: Induced Innovation, Evolutionary Theory, and Path Dependence.” *In* Grübler, A., Nakićenović, N., & Nordhaus, W. D. (Eds.). *Technological change and the environment*. RFF Press.

CO_2 Storage

The future coal power plant

ILLUSTRATION BY DAVID FIERSTEIN; CONCEPT BY JULIO FRIEDMANN *Lawrence Livermore National Laboratories*



www.sciam.com SCIENTIFIC AMERICAN 51

Shown here: After 10 years of operation of a 1000 MW coal plant, 60 Mt (90 Mm^3) of CO_2 have been injected, filling a horizontal area of 40 km^2 in each of two formations.

Assumptions:

- 10% porosity
- **1/3 of pore space accessed**
- 60 m total vertical height for the two formations.

- *Note:* Plant is still young.

Injection rate is 150,000 bbl(CO_2)/day, or 300 million standard cubic feet/day (scfd).
Lifetime injection: 3 billion barrels, or 6 trillion standard cubic feet, over 60 years.

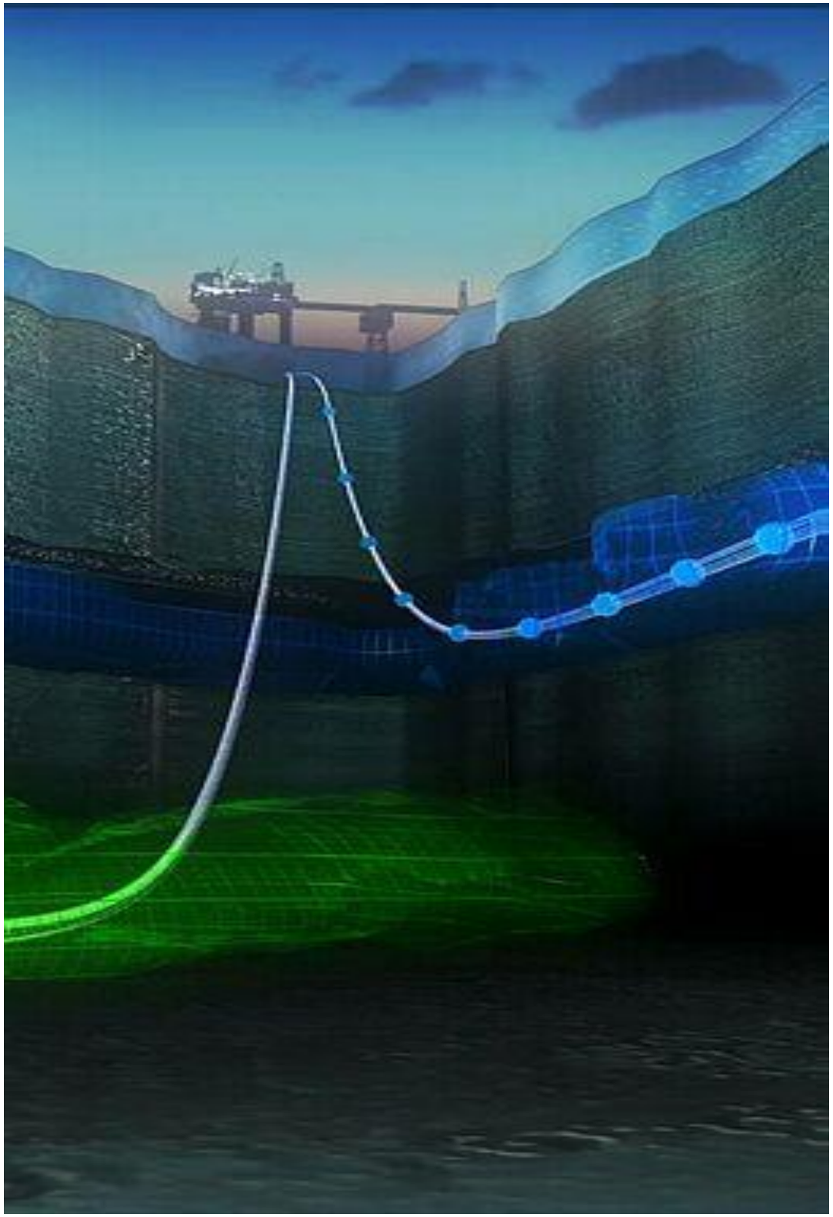
Carbon Storage

Effort needed by 2055 for 1 wedge:

3500 Sleipners @1 $MtCO_2$/yr

100 x U.S. CO_2 current injection rate for EOR

A flow of CO_2 into the Earth equal to the flow of oil out of the Earth today

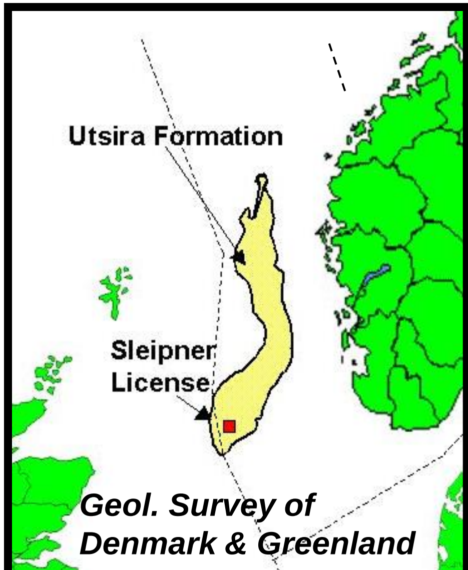


Sleipner project, offshore Norway

Graphic courtesy of Statoil ASA

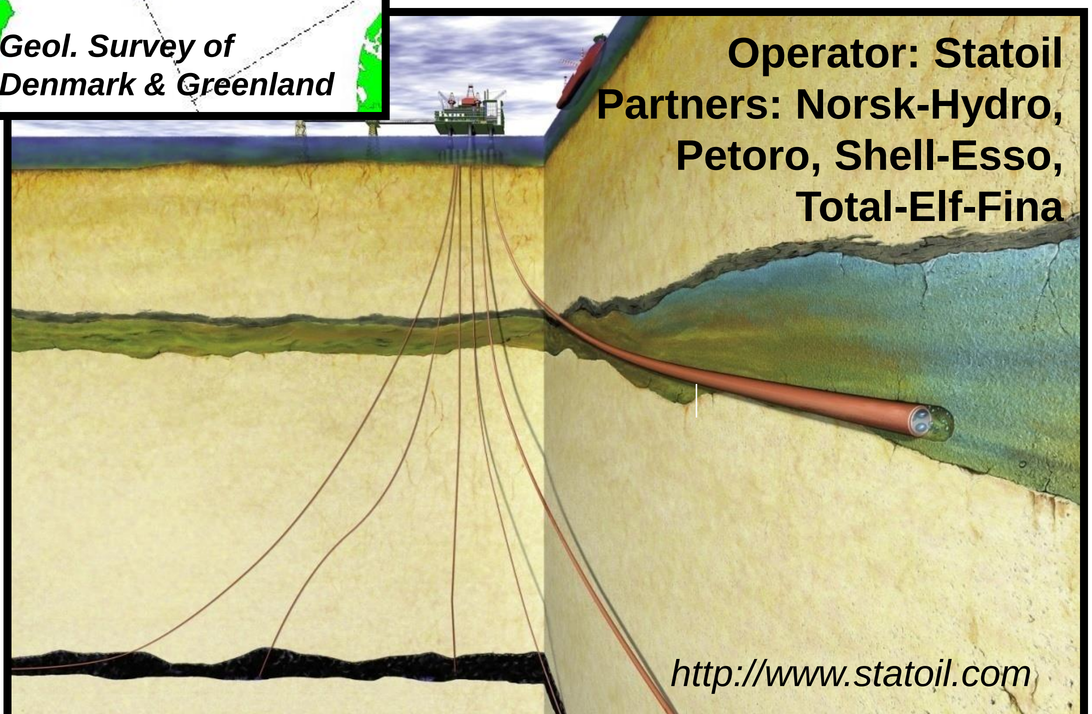
Graphic courtesy of David Hawkins

Sleipner Vest: Utsira Formation



First attempt at large-volume CO_2 sequestration, Monoethanolamine (MEA) capture from offshore Norway gas. Active since 1996.

Economic driver is Norwegian carbon tax on industry: $50/t$CO_2$
Cost of storage: $15/t$CO_2$



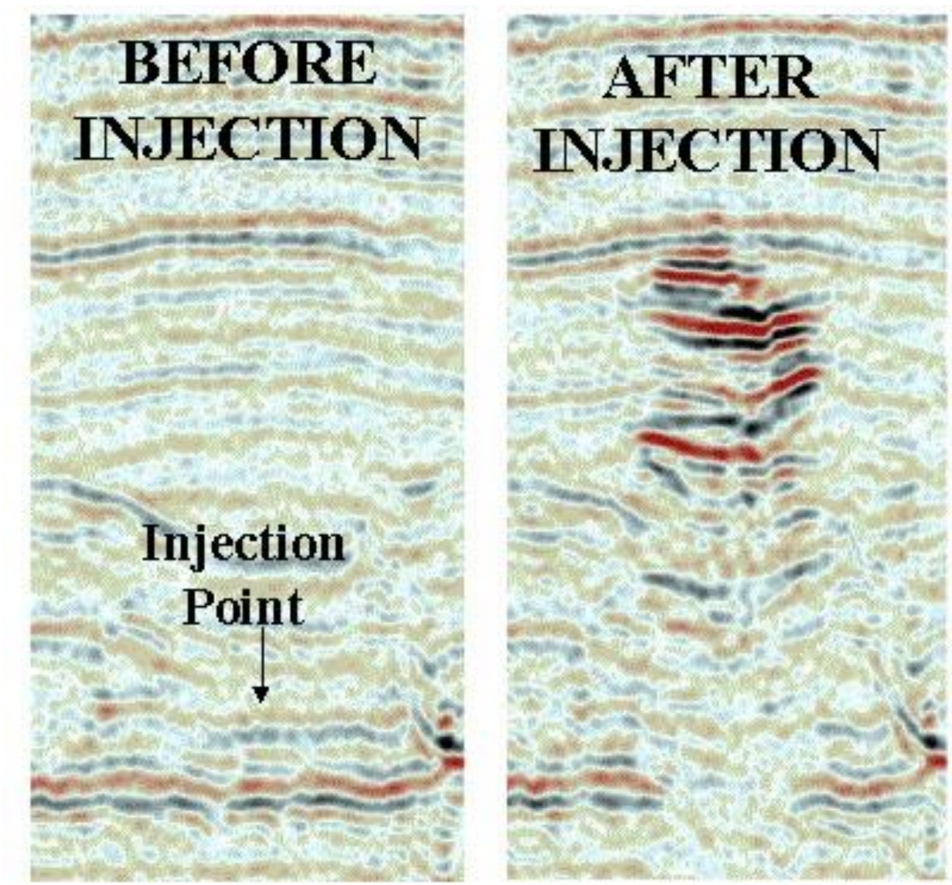
Target: 1 MtCO_2/yr.

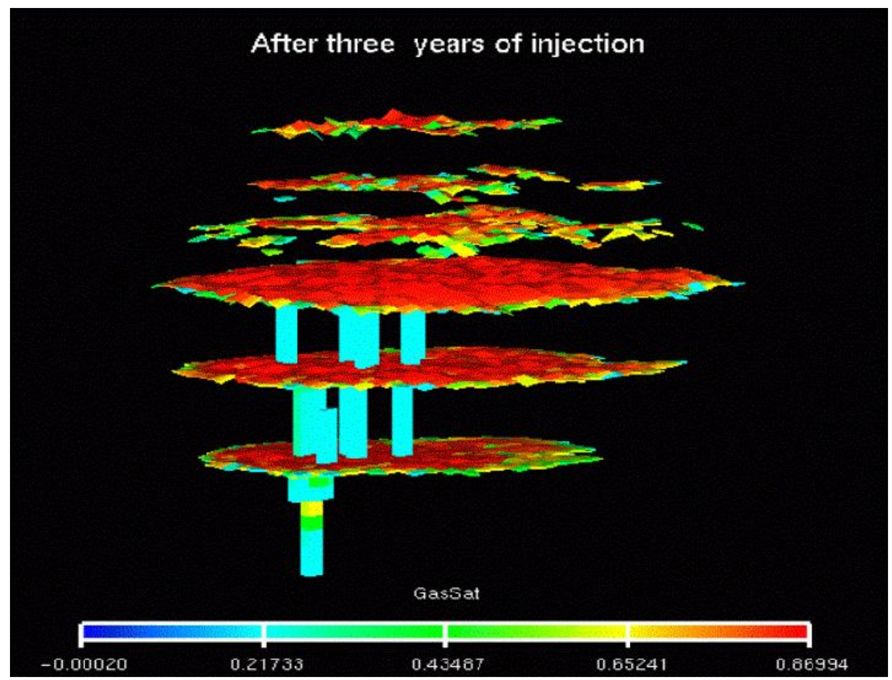
Miocene Aquifer: DW fan complex

- **30-40% porosity, 200 m thick**
- **high permeability**
- **between 15-36 °C, so CO_2 density is high.**

4D seismic monitoring and visualization

Seismic Survey of Utsira Formation.



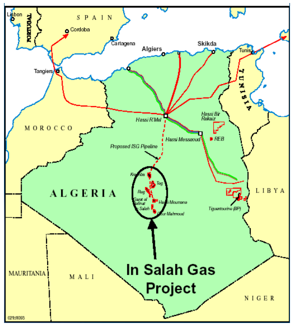


Courtesy of Statoil and IEA

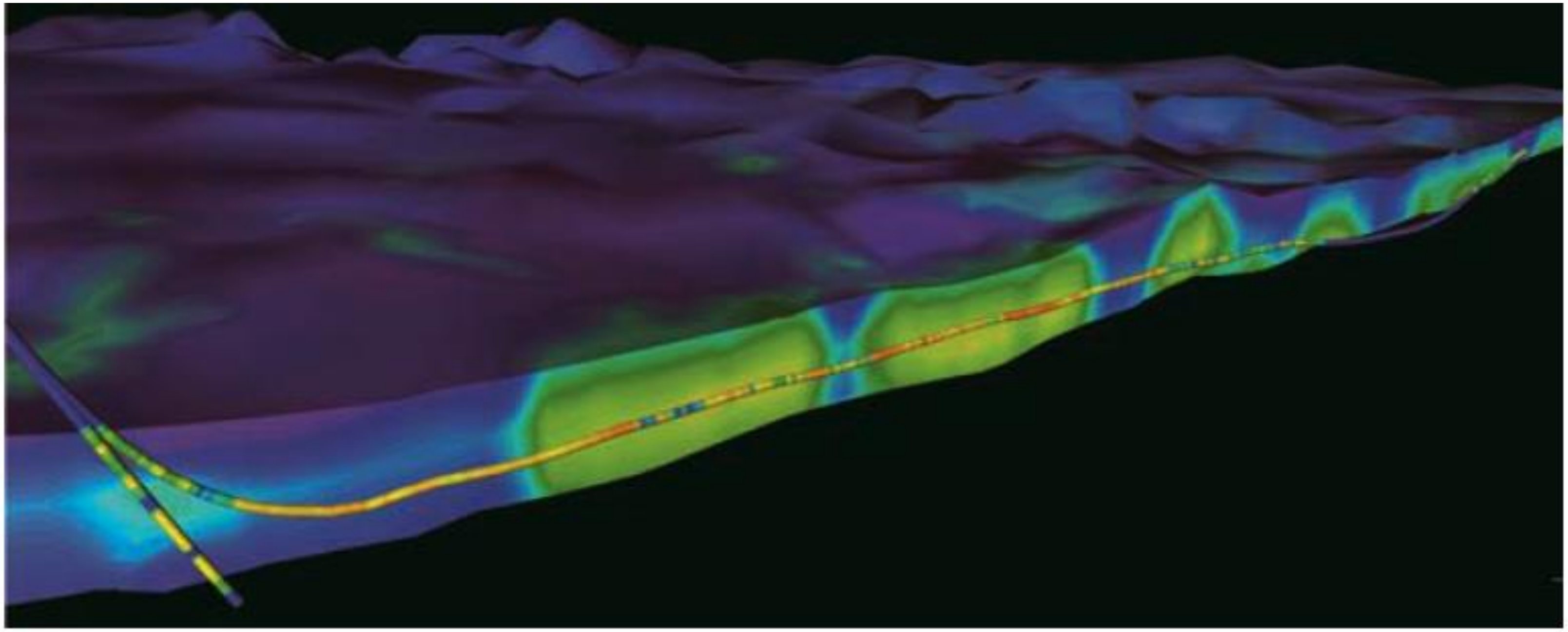
For a while, in the middle of the Sahara

Separation at amine contactor towers

At In Salah, Algeria, natural gas purification by CO_2 removal plus CO_2 pressurization for nearby injection



Smart CO_2 injection



Two sets of measurements of the porosity at the 20-m-thick Krechba field in the Algerian desert, near a CO_2 injection well (*thin tubing*):

Coarse mapping by seismic echolocation soundings. Red and yellow represent high porosity regions; blue indicates low porosity areas.

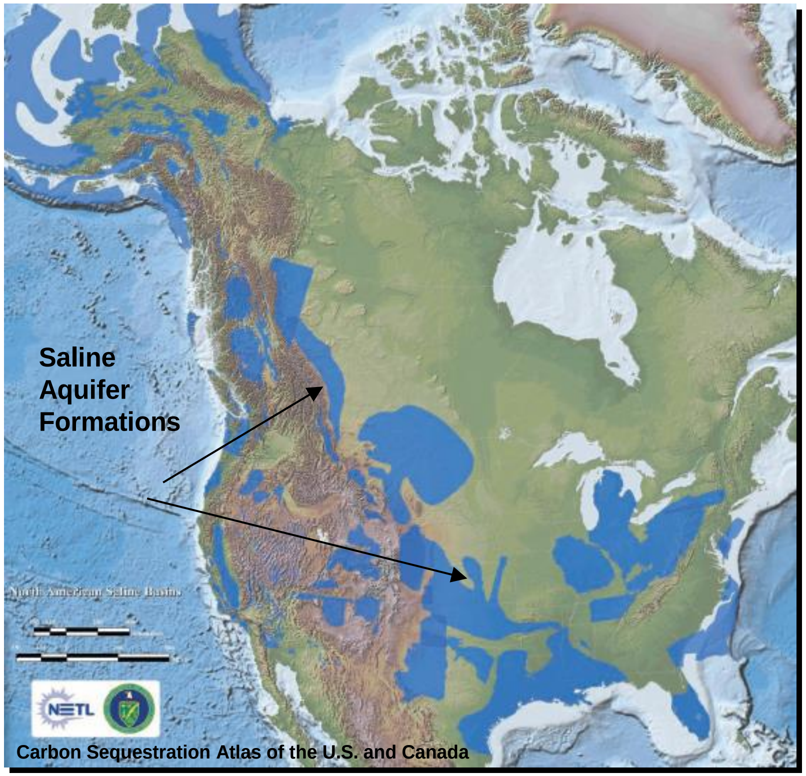
Finer depiction of porosity (looking like colored beads), within a few centimeters of the well, by a down-hole electric sensor probe. Fine-scale is used for steering the drilling apparatus toward regions of high porosity.

OPTIONS FOR CO_2 STORAGE

- Goal: Store 100s to 1000s of Gt CO_2 for 100s to 1000s of years.
- Major options for disposal location:
  – Deep ocean (*concerns about storage effectiveness, environmental impacts, legal issues, difficult access*)
  – Carbonate rocks (*permanent, but requires huge rock volumes)*
  – Geological media (*focus of current interest*)
    - Enhanced oil recovery (*30 million tonnes CO_2/yr used in U.S. today, contributing 4% to US oil production – with no CO_2 storage goal*)
    - Depleted oil and gas fields (*geographically limited*)
    - Beds of unminable coal (*CO_2 adsorbed in pore spaces of coal*)
    - Deep saline aquifers (huge potential, ubiquitous)
      – Must be at least 800 m down, so that CO_2 pressure is supercritical
      – Such aquifers underlie half of inhabited continents

***Source*:** adapted from Robert H. Williams, "Coal Power In A Climate-constrained World," Lecture in MAE 328, 27 February 2007.

Geologic Sequestration Options



Source: NETL

Oil and gas formations—inject into depleted or mature oil and gas fields (can provide enhanced oil recovery in mature fields)

Unminable coal seams—Inject into coal seams that absorb CO_2 and desorb methane for recovery

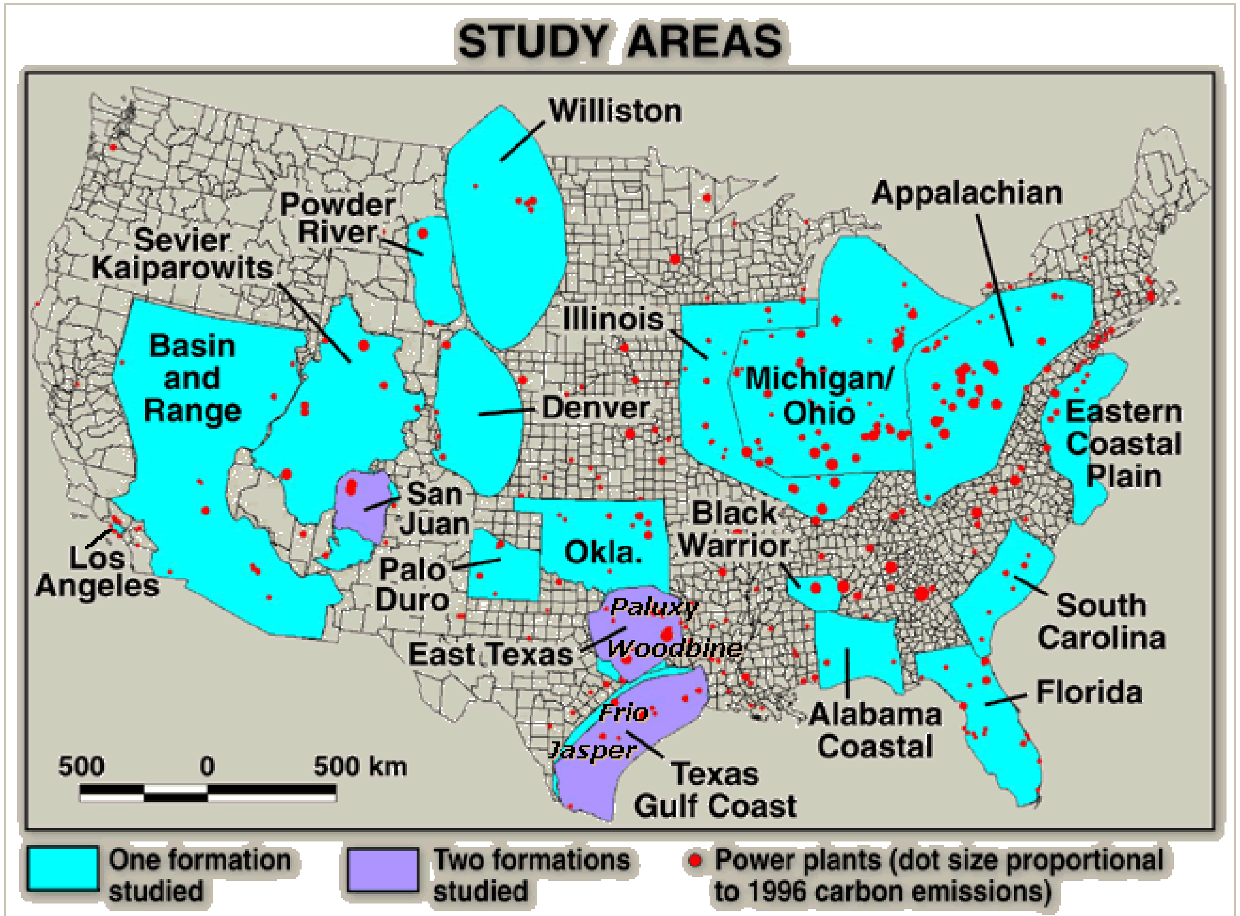
Shale formations—inject into shale formation that absorb CO_2 and desorb methane for recovery

Saline aquifers—inject into deep saline formations that may be able to store hundreds of billions of tons of CO_2.

Deep saline aquifers are considered important potential CO_2 sinks because many are large, generally contiguous reservoirs and may be capable of storing large volumes of carbon dioxide.

Source: D. Cunningham (PSE&G), MAE 328 lecture, March 6, 2008

U.S. Saline Reservoirs



Test sequestration projects 2002-2004

Mountaineer Project

- **AEP/Battelle**
- **Mt Simon Fm.**
- **Sequestration**

S. Texas:

- **DOE/U. Texas**
- **Frio Trend**
- **Small (2000 tons)**

US saline reservoirs have a potential of up to 130 G tCO_2 sequestration

DOE, 1999

A 1000 MW coal plant with CCS requires lifetime storage of 3×10^9 barrels of CO_2

CO_2 emissions rate: **6 MtCO_2/yr = 150,000 bbl/day.**

Assume: 1) 9 barrels CO_2/t, and 2) extra coal for CCS balances less than 100% CO_2 capture.

For 60-year plant lifetime*:* **3 billion barrels.**

World's oil fields larger than 3 billion barrels*: **80.**

Percent of total production from these 80 fields: **40%.**

This is familiar territory!

*** Including *water reinjection,* fluid flow in and out of a 500 million barrels (Mbbl) field may be 3000 Mbbl. 500 fields are > 500 (Mbbl) and account for 2/3 of global production.**

The carbon doesn't fit when you put it back

One needs to Inject *4* km^3 of supercritical CO_2 below ground to put back as much carbon as was in 1 km^3 of extracted oil.

Calculation:

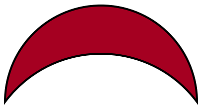
Supercritical CO_2: $1\ km^3 \approx 2/3\ GtCO_2 = 2/11\ GtC = 0.18\ GtC$

Reference crude oil: $1\ km^3 \approx 0.73\ GtC$

Then $x \approx 0.73/0.18 \approx 4.0$.

One wedge: inject 5.5 km^3 CO_2/yr in 2062.

How long will CO_2 stay underground and how long is long enough?

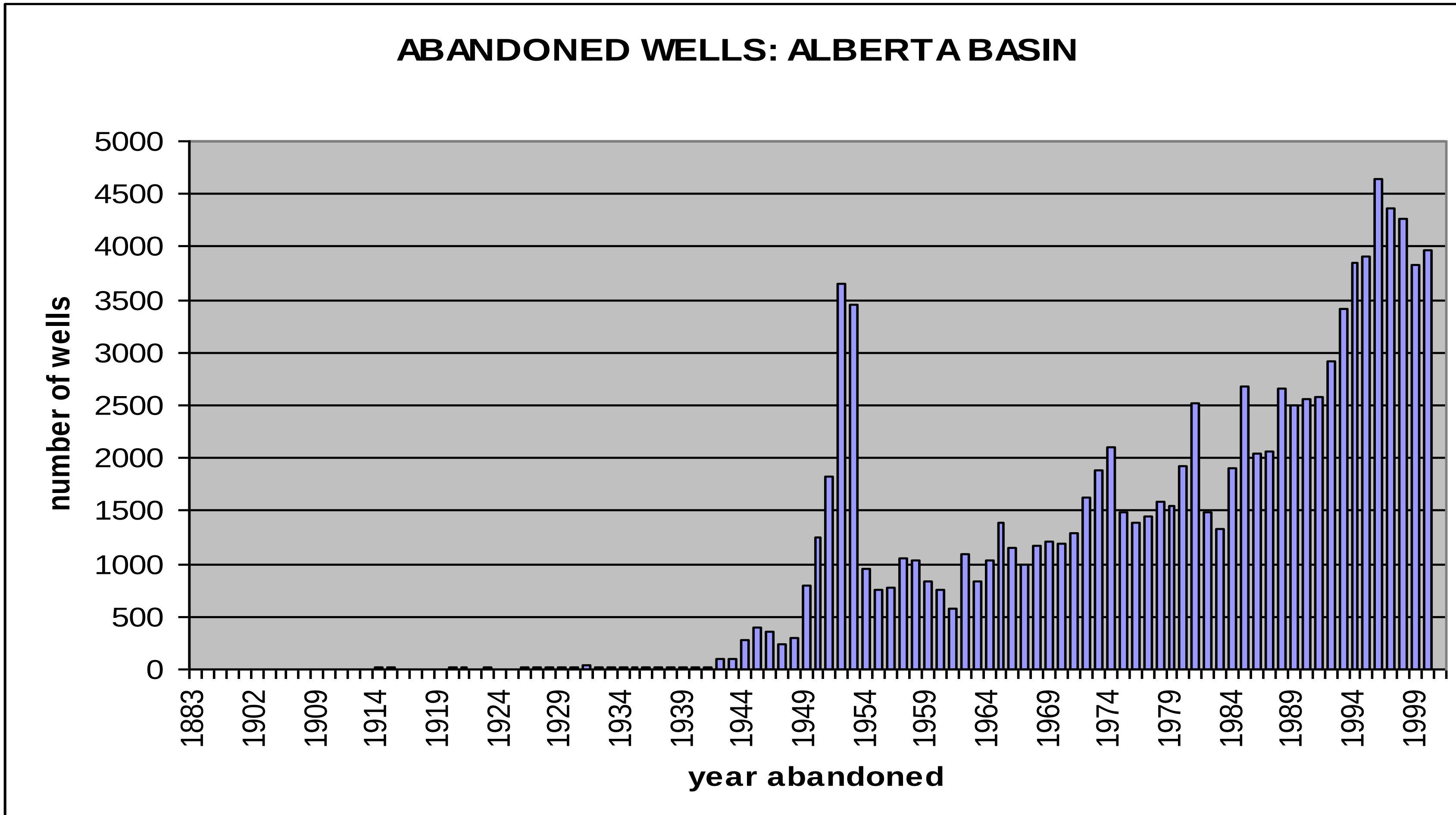


Oil/gas reservoirs: rare,
1,000,000 year retention.

Large unconfined aquifers: abundant, 1000 year retention.
This realization, reported in 1996 by Sam Holloway, British Geological Survey for Joule II, revolutionized the world's perspective on CCS.

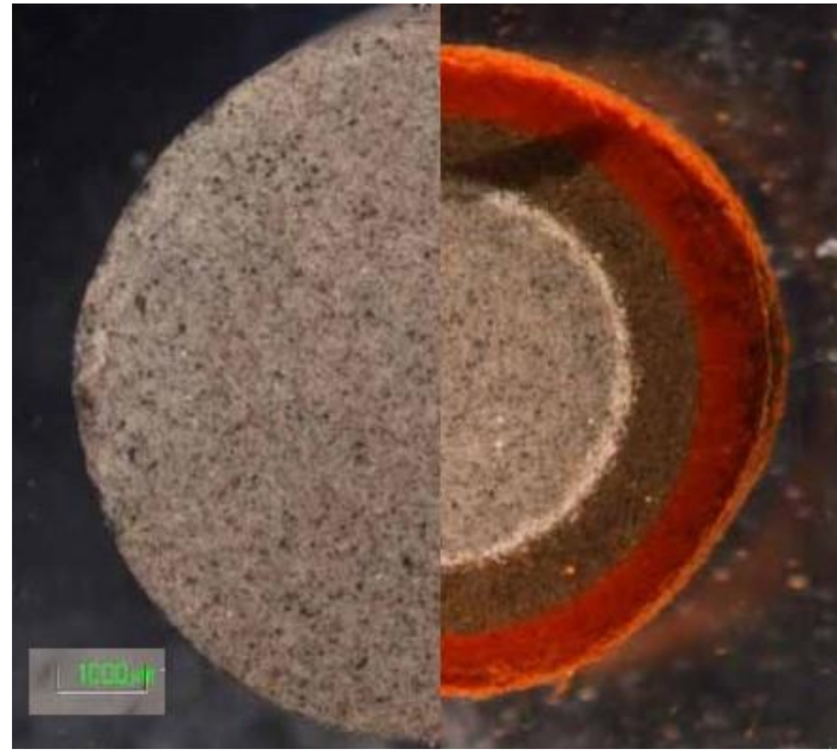
How nearly permanent should storage be? "Environmental ethics and traditional economics give different answers. Following a strict environmental ethic that seeks to minimize the impact of today's activities on future generations, authorities might, for instance, refuse to certify a storage project estimated to retain CO_2 for only 200 years. Guided instead by traditional economics, they might approve the same project on the grounds that two centuries from now a smarter world will have invented superior carbon disposal technology." RHS, *Scientific American*, July 2005, p. 55.

Existing Wells (“Artificial Penetrations”) are Critical Leakage Pathways



Field and Lab Studies of CO_2 Effects on Cement

Cement recovered with sidewall corer from a 19 year-old oil well at RMOTC in Wyoming. Cement adhered to outside casing at 933.3 m at a band of dense limestone. Scanning electron microscopy on sample and original cement materials reveal post-injection calcium leaching.



Samples of unreacted H-type cement (left) and cement after 3 weeks in flow-through reactor at 50ºC and pH 2.4 (right). Color variation is due to changes in oxidation in iron impurities.

Estimates in the IPCC's SRCCS*

The 2005 IPCC Special Report on CO_2 Capture and Storage provides four consensus estimates:

1. The contribution of CCS to total CO_2 emission reductions in a portfolio of climate mitigation technologies might be 15 - 55%.

2. Including CCS in a portfolio of mitigation technologies might reduce the cost of mitigating climate change by 30% or more.

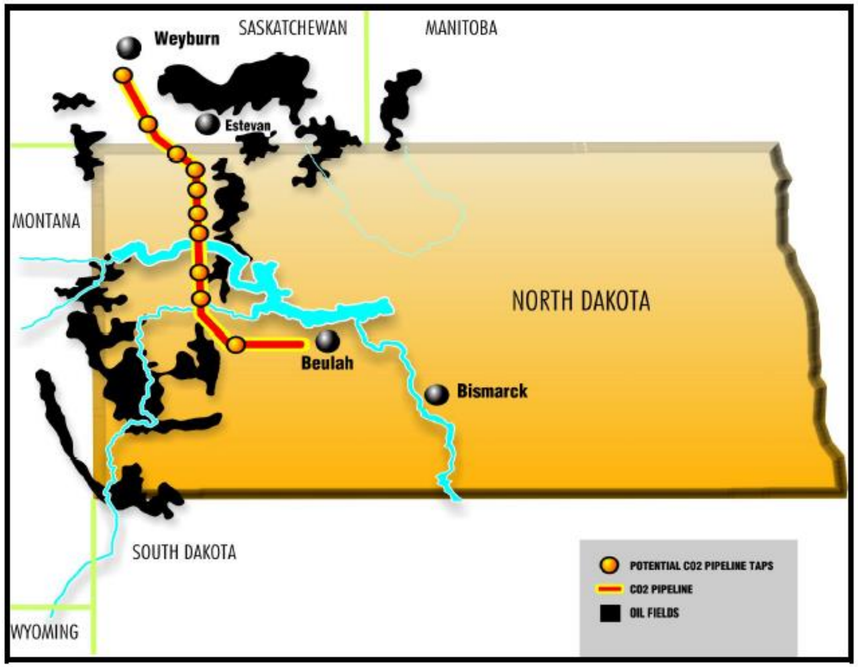
3. The fraction of stored CO_2 that will be retained in a typical geological storage reservoir is:

   -- very likely to exceed 99% over 100 years (“very likely”: 90 - 99%).
   -- likely to exceed 99% over 1000 years (“likely”: 66 - 90%)

4. World-wide geological storage capacity is “likely” to exceed 2000 $GtCO_2$. (70 times current annual fossil fuel emissions).

*SRCCS: *Special Report on Carbon Dioxide Capture and Storage*, 2005.

Weyburn Project uses CO_2 co-product of coal gasification for Enhanced Oil Recovery (EOR)



The $2.1 billion Great Plains Synfuels Plant (GPSP) at Beulah, ND, with capacity to produce up to 170 million cubic feet of methane daily from 18,500 tons of lignite, went on line in 1984.

The GPSP generates as coproduct up to 200 million cubic feet per day of nearly pure CO_2.

Since 2000 the GPSP has sold 95 million cubic feet of CO_2 per day to Encana Corporation for CO_2-EOR at the Weyburn oil field in Saskatchewan, Canada.

The CO_2 is transported 205 miles to the CO_2-EOR site via pipeline.

The incremental costs of CO_2 capture are less at synfuels plants than at power plants.

***Source*:** Robert H. Williams, "Coal Power In A Climate-constrained World," Lecture in MAE 328, 27 February 2007.

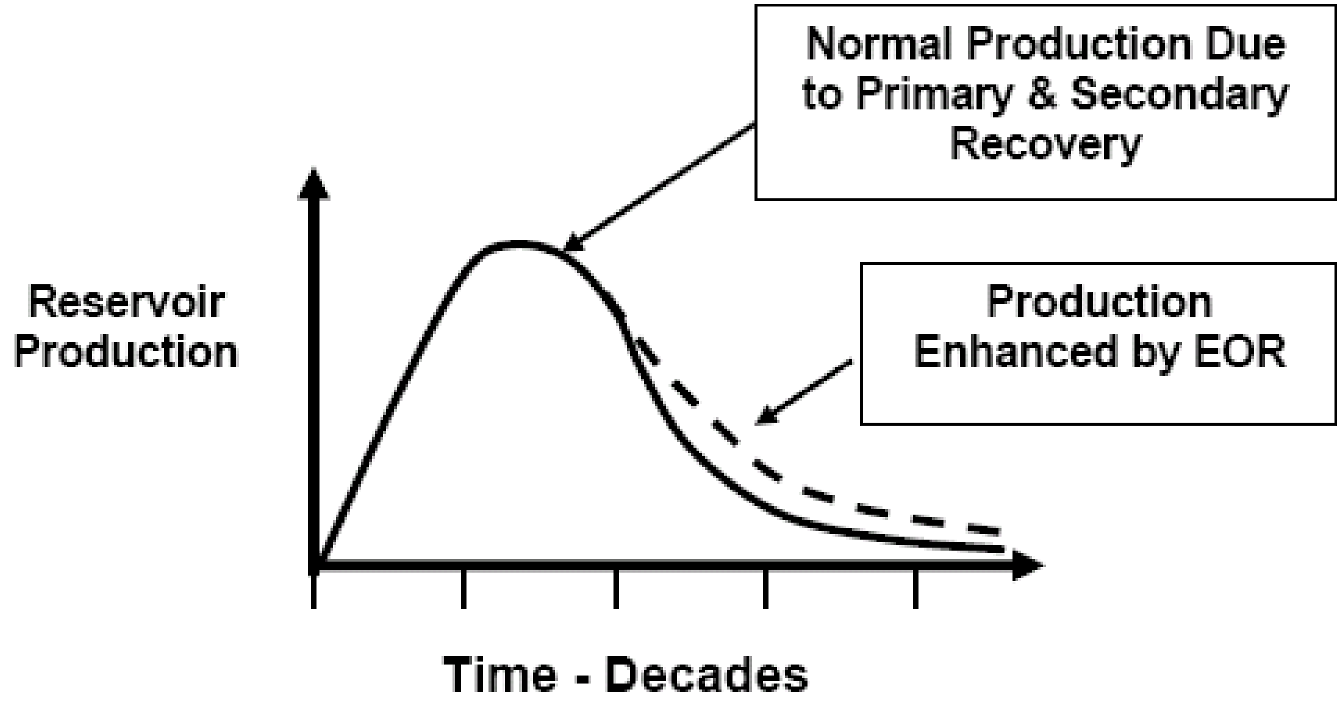
Synfuel-with-CCS wedges

Coal plants producing 24 million barrels of synthetic fuels per day without capture and storage of CO_2, will emit 8 $GtCO_2$/yr to the atmosphere.

4 $GtCO_2$/yr will be emitted at the coal-to-liquids plants and 4 $GtCO_2$/yr in fuel exhaust from the vehicles.

Fuel-carbon wedges result from capturing the CO_2 at 24 mbd of coal-to-liquids plants.

Enhanced Oil Recovery



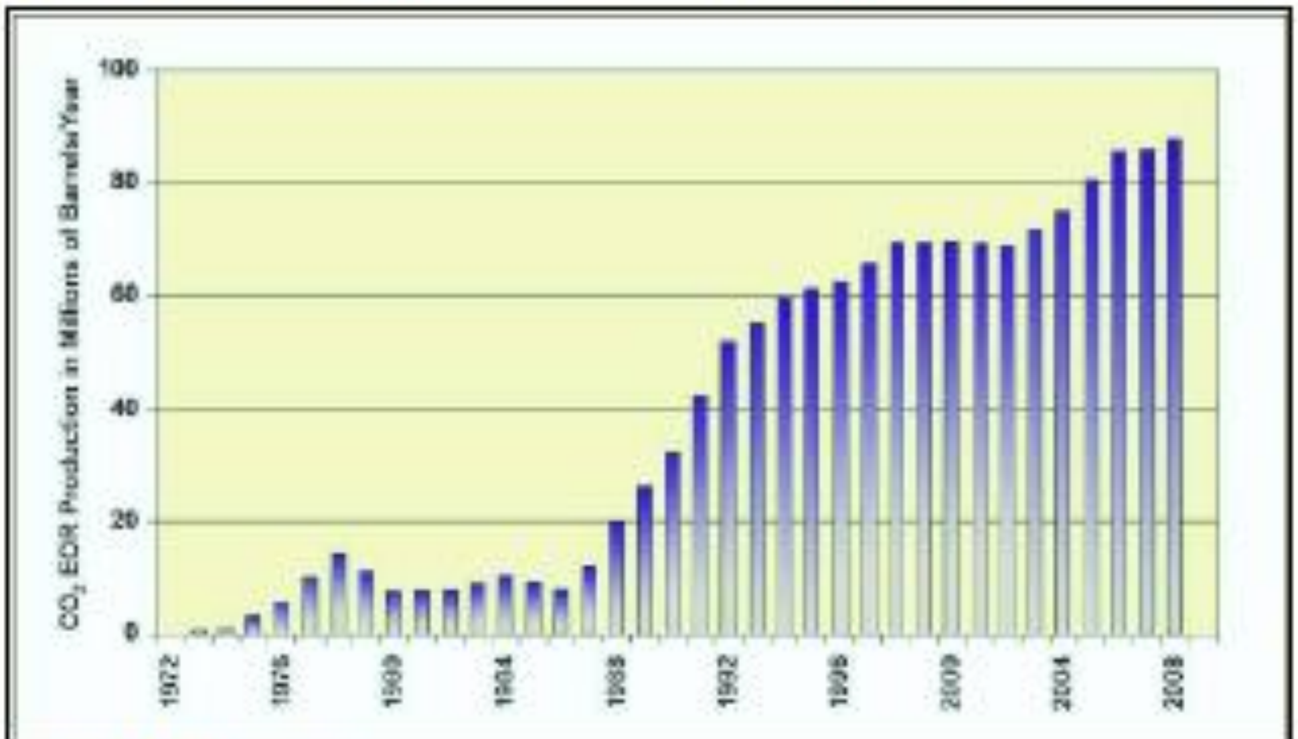
A 1000 MW coal plant will emit 6 Million tons of CO_2/yr per year. If captured and directed to EOR, at 2 to 5 bbl/tCO_2, the oil field will produce an extra 30,000 to 80,000 b/d.

With a high price on CO_2 emissions, how different will EOR be? Store as much CO_2 as possible.

Source of Figure: Hirsch, et. al, 2006. *Peaking of World Oil Production*, Fig VI-1

How important can EOR become?

Figure D-1. Growth of U.S. Oil Production from CO_2-based EOR



Source: (NETL 2010)

Source: Report of the Interagency Task Force on Carbon Capture and Storage, August 2010

ARI (2005) ASSESSMENT OF CO_2-EOR POTENTIAL

Basin/Area	# of Large Reservoirs		30-y Levelized Economic CO_2-EOR Potential (10^3 barrels/day)	Coal IGCC w/CCS Capacity That Might Provide the Needed CO_2 (GW_e)
	Assessed	EOR Favorable		
Alaska	34	32	703	7.8
California	172	88	301	4.4
Gulf Coast	242	158	210	3.3
Mid-Continent	222	97	566	5.9
North Central	154	72	548	0.7
Permian	207	182	986	14.9
Rockies	162	92	219	3.1
Texas, East/Central	199	161	785	9.4
Williston	93	54	46	0.6
Lousiana offshore	99	99	402	7.2
Total	**1584**	**1035**	**4274**	**57.3**

Exploiting economic potential requires 360 million tons of CO_2 per year

***Source*:** Robert H. Williams, "Coal Power In A Climate-constrained World," Lecture in MAE 328, 27/2/2007.

A sequence of CCS opportunities

	CAPTURE	STORAGE
Near-term (0-5 years)	Concentrated CO_2 streams: 1) natural gas separation; 2) hydrogen for refineries, chemicals (NH_3, urea)	Enhanced oil recovery (EOR)
Mid-term (5-15 years)	Coal, petcoke, and natural gas power plants Biomass power plants? Coal-to-synfuels plants?	Aquifer storage
Long-term (at least 15 years)	Coal-to-H_2 for distributed H_2 Direct capture from the air?	Mineral storage? Ocean storage? Deep sub-ocean storage?

How soon can CO_2 capture and storage be required at all new coal plants?

•A key goal of climate change policy should be to enable the arrival, at the earliest reasonable date, of a time after which *all* new coal plants, for both power and fuels, are built with CCS.

•During the transition period, every new coal policy and every new coal plant should contribute to the learning required to achieve this goal.

•The first N plants should be subsidized. What is N?

N may be 10, or even 20: a) many kinds of coal, b) capture concepts other than gasification, c) many kinds of reservoirs

•Coal must also become more clean "upstream."

Start Now to Gain Experience with the Permitting of Storage Sites

- *Public approval* – Openness, fairness, vigilance, responsiveness
- *Goals* – What constitutes victory? Retention time of 500 years?
- *Storage integrity: sudden vs slow escape*
  - Sudden escape could be catastrophic.
  - Slow escape from a few sites is inconsequential.
    - How can permitting assure no sudden escape yet promote early experience with a variety of sites?
- *Co-sequestration* – Can co-capture and co-storage allow avoidance of some pollution control (S, N, Cl, Hg)?

Uncertainties of permitting could dominate total sequestration costs.

How do we reduce emissions?

Three ways:

Be very smart, so no policy is needed.

“S < C “ (solar is cheaper than coal).

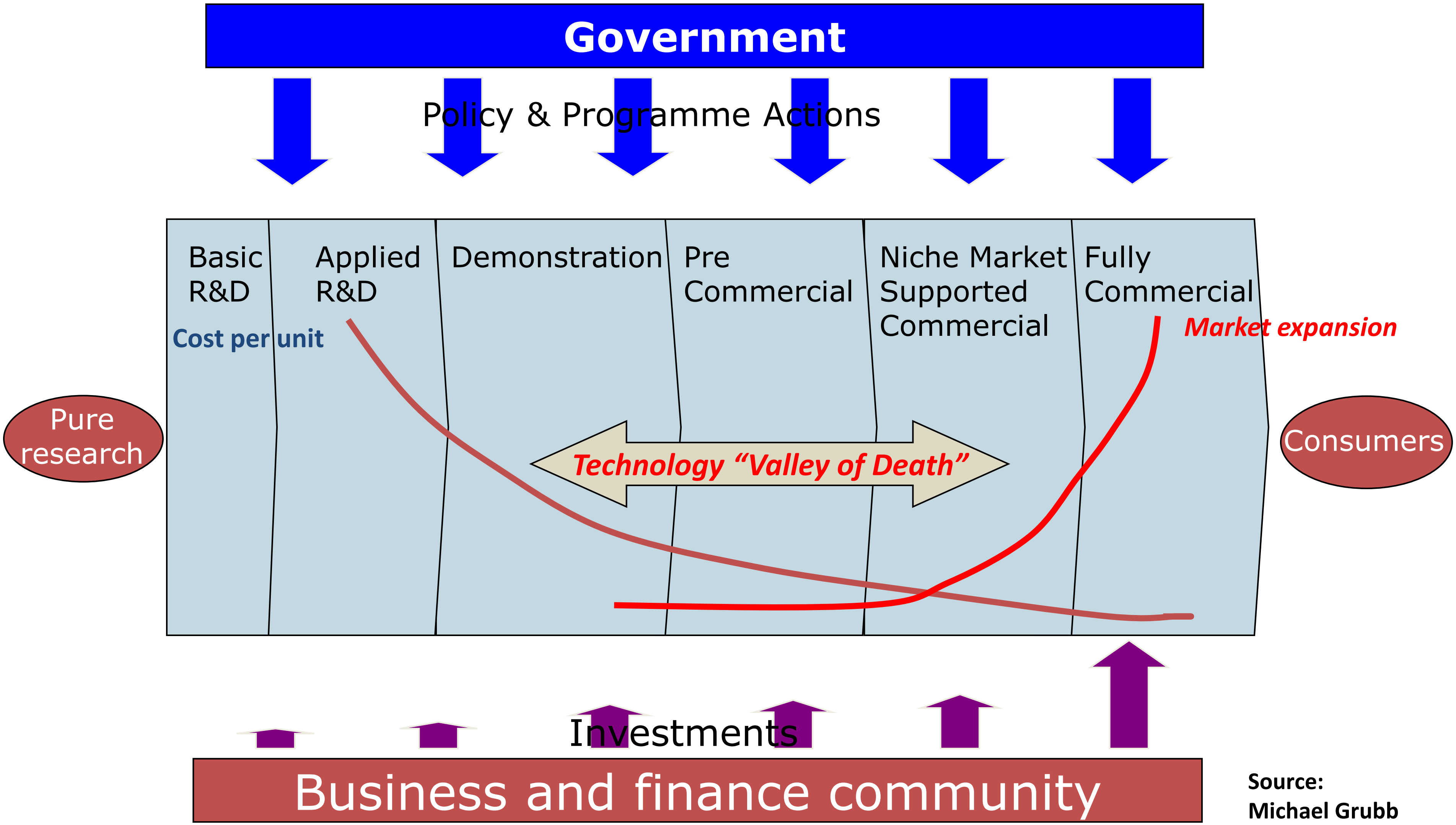
Regulatory policy and referenda: Forbid and require.

Market-based policies: Change relative prices.

Research and development (R&D) is an important and contentious policy arena

How much?
How close to market: “pre-competitive” vs. “picking winners”?
The Valley of Death

The Technology Innovation Chain – from R&D to Market



Source: Michael Grubb

How do we bend these curves?

Three ways:

Be very smart, so no policy is needed.

"S < C " (solar is cheaper than coal).

Regulatory policy and referenda: Forbid and require.

Market-based policies: Change relative prices.

Regulatory issues (“Command and Control”)

Rules and standards

- Framing (e.g., concentration vs. absolute amount – “the solution to pollution is dilution”)
- Timing

Subsidies and penalties

- Fines to automakers and Corporate Average Fuel Economy (CAFE)
- Production tax credit (PTC), Investment tax credit (ITC)

Regulation of electric utilities

- Regulated and deregulated states
- Best available control technology (BACT)
- Public Utilities Regulatory Policy Ace (PURPA) and “avoided cost”
- Dispatch rules
- Net metering

How do we bend these curves?

Three ways:

Be very smart, so no policy is needed.

“S < C “ (solar is cheaper than coal).

Regulatory policy and referenda: Forbid and require.

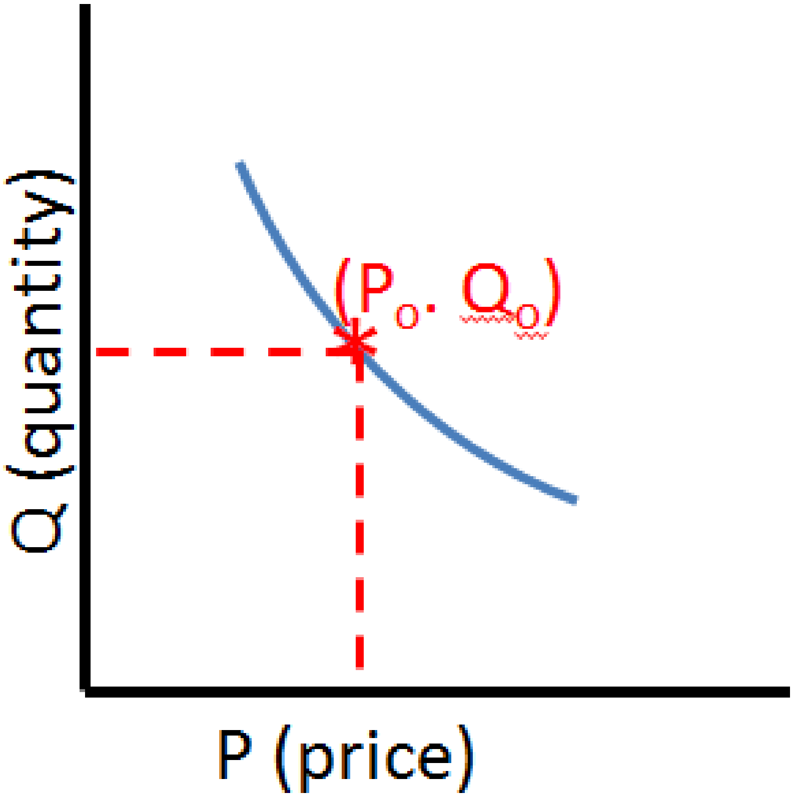
Market-based policies: Change relative prices.

Ideal cap-and-trade = Ideal tax

Cap-and-trade and tax in their pure forms are identical.

Assume Q(P) exists:

- Cap-and-trade: Fix Q_o, then find P_o.
- Tax: Fix P_o, then find Q_o.



Design issues in cap and trade
(and in most other market mechanisms)

System boundary and offsets

Schedule of cap reductions or tax increases
    Mixed strategies (the collar)

Fines for non-compliance (the stick)

Auction or give for free? (the carrot)

Iteration: How soon? How often.

Iterative risk management

In another decade we'll know a lot more about the earth, both because of new climate science and because of what the earth tells us about itself.

We’ll also know more about the solutions themselves, thanks to both R&D and field experience.

All this argues for making decisions *iteratively*.

- Specifically, we can wait at least a decade before deciding whether 1) flat emissions are as heroic an outcome as we can achieve safely and equitably, or 2) whether we can achieve still more.

One must also invest in adaptation

Vexing problem: How to apportion effort between mitigation and adaptation.

Adaptation can be organized by:

The threat (extreme events, chronic change)
The sector most affected (farmers, the elderly, the poor)
The level of government most appropriately involved
Structural (dikes) vs. non-structural (land use zoning, evacuation) responses

The adaptation literature is sparse. I have been told often that a wedge model for adaptation is needed. What people mean is that disciplined thinking and typologies are needed. I see a paper here for one of you.

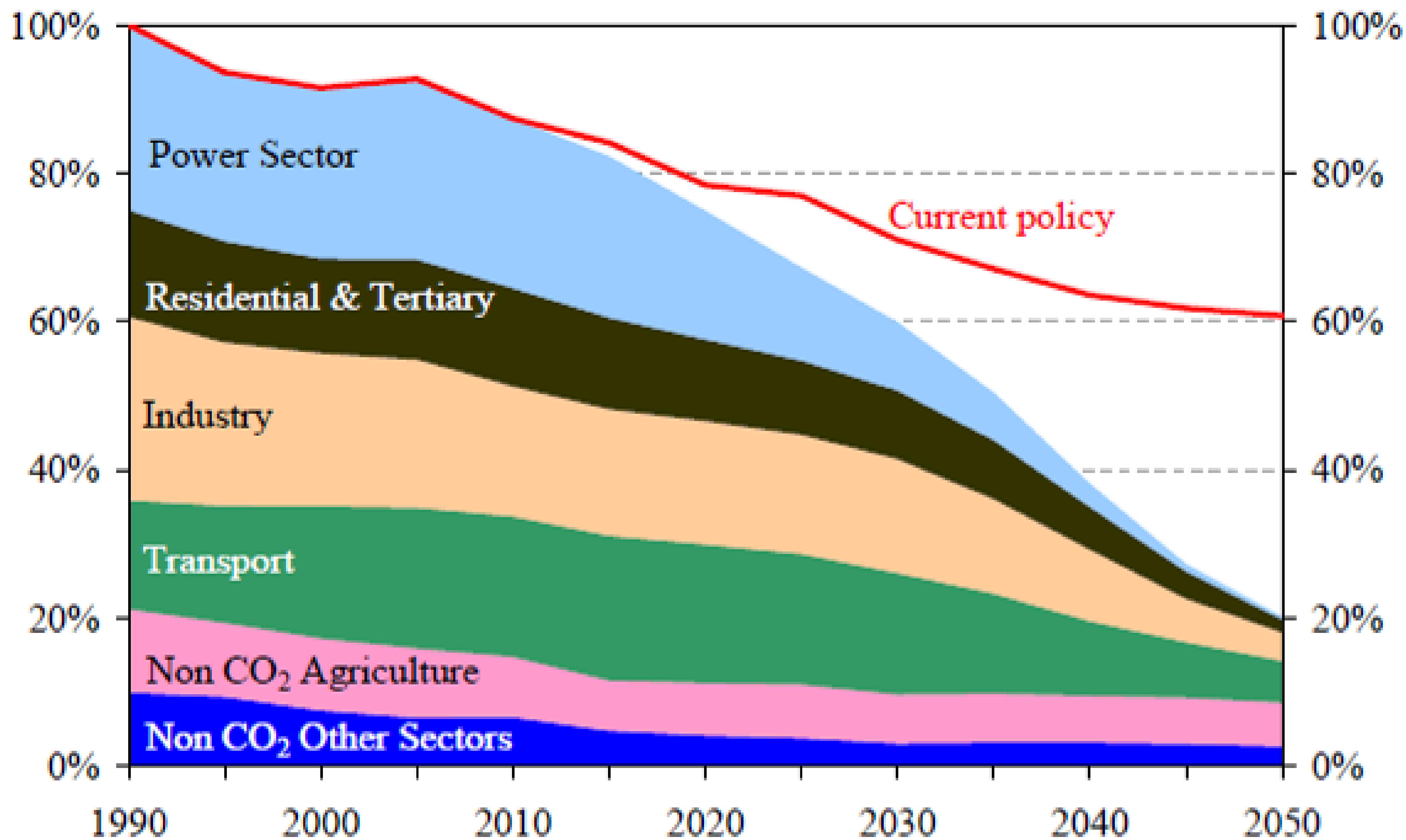
And one must set goals and make promises

Targets

- Long-term or interim?
- "Aspirational" or with compelling carrots and sticks?
- Conditional on the behavior of others?

Scenarios and road maps are important tools for exploring self-consistency.

Figure 1: EU GHG emissions towards an 80% domestic reduction (100% =1990)



Fonte: Roadmap for moving to a low-carbon economy in 2050
http://ec.europa.eu/clima/policies/roadmap/index_en.htm

Broad issues behind policy choices

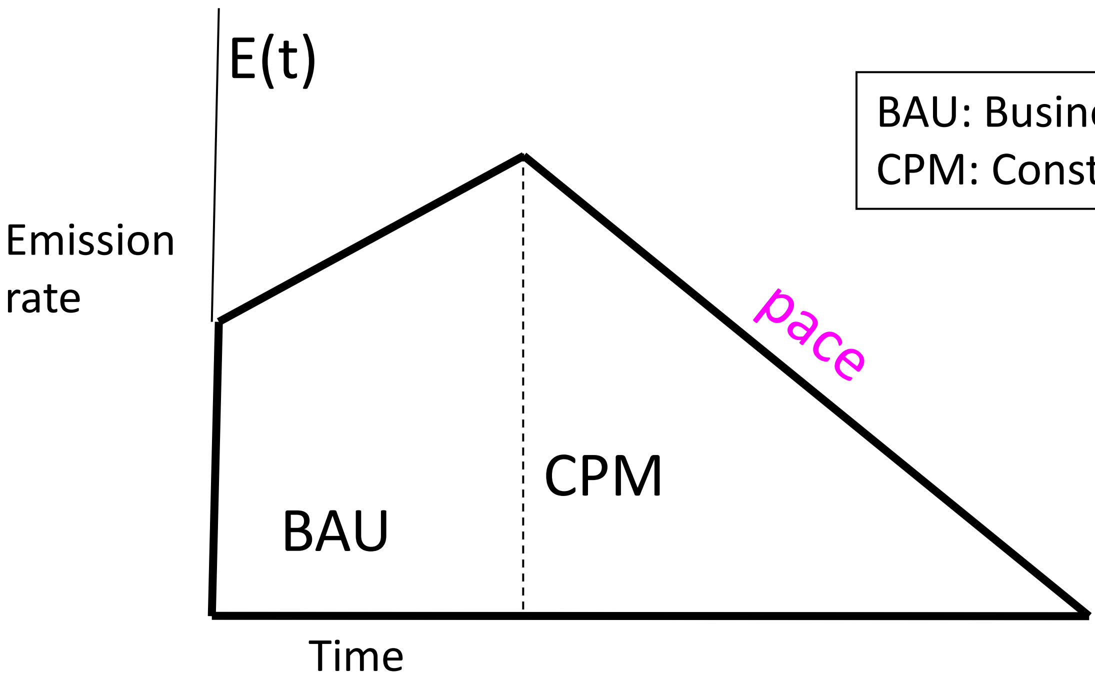
Why now?

Alliances and surrogate goals.

Getting to Yes. Just saying No.

Our collective destiny.

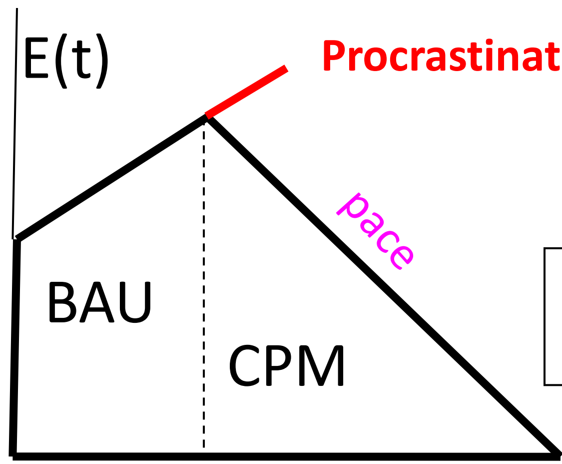
An idealization of mitigation



BAU: Business As Usual
CPM: Constant-Pace Mitigation

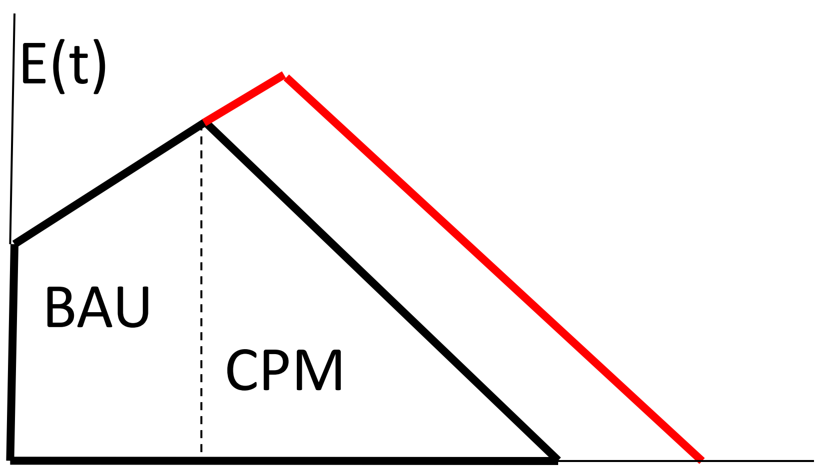
Today, approximately half of emissions are retained in the atmosphere and half move to other reservoirs.

Procrastination and "Pace"

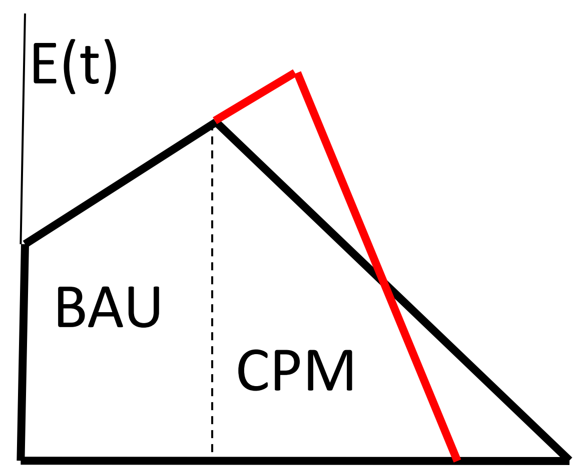


Procrastination can lead to…

BAU: Business As Usual
CPM: Constant-Pace Mitigation



(1) Extra total emissions, because pace cannot be increased,



OR (2) Constant total emissions, with a faster pace.

Arguments for Delay (1 of 2)

SCIENCE

- We don't know the science. Human activity may be having a negligible effect, swamped by natural variation.
- We may be having an effect, but the impacts are, on balance, favorable.

TECHNOLOGY

- We do not yet have the tools to solve the problem.
- The tools to solve the problem that we have are far inferior to the tools we will have if we conduct R&D for a few decades.
- We have tools that could solve the problem, but they are too dangerous. The cures are worse than the disease.

Arguments for Delay (2 of 2)

POLITICS, ECONOMICS

- The costs of mitigation are too high, relative to any willingness to pay.
- Government makes a mess of things when it intervenes in the economy.
- The world has more important things to do, notably to deal with world poverty.
- It is wasteful to engage developing countries in mitigation now, given that they will have much greater capacity for implementation later.
- Mitigation will hurt the poor in every country. Wait till we are richer.
- The net result will be to transfer wealth from rich to poor, not good policy.

PHILOSOPHY

- Government should not run our lives.
- People aren't ready to tackle climate change – the issue is too abstract.
- Whatever the impacts, we can adapt to them.
- We should not play God. We should not control nature.

Getting to Yes

The more we fear climate change, the less we can allow ourselves to be squeamish about imperfect "solutions."

We must remember that we want solutions to work. It can't be enough to identify what's wrong with a strategy as it is first proposed. We must ask: With what changes, would this strategy become acceptable? How might we get from here to there?

Getting to No

However, we may decide, in some situations, to forego an option.

This may be the result of a moral judgment. We will prefer enduring some amount of climate change to the compromises required to avoid it.

Surrogate Goals (1 of 3)

Definition of a surrogate goal

A person who holds Goal A strongly and Goal B weakly, but believes that achieving Goal B will also achieve Goal A, can pursue Goal B as a *surrogate* for Goal A.

Usually, Goal A will be revealed only in special circumstances. Recognizing that a multiplicity of surrogate goals is at play has considerable explanatory power.

Surrogate Goals (2 of 3)

Surrogate goals and climate change

In the formulation of policy to deal with climate change, the general objective of slowing the rate of climate change is often a surrogate for more strongly held goals, such as:

- Augmenting financial transfers to developing countries
- Bringing the fossil fuel era to a close
- Curtailing consumerism and human centeredness
- Promoting self-sufficiency, autonomous communities
- Diminishing the power of technological elites
- Promoting environmental science
- Encouraging entrepreneurship

Surrogate Goals (3 of 3)

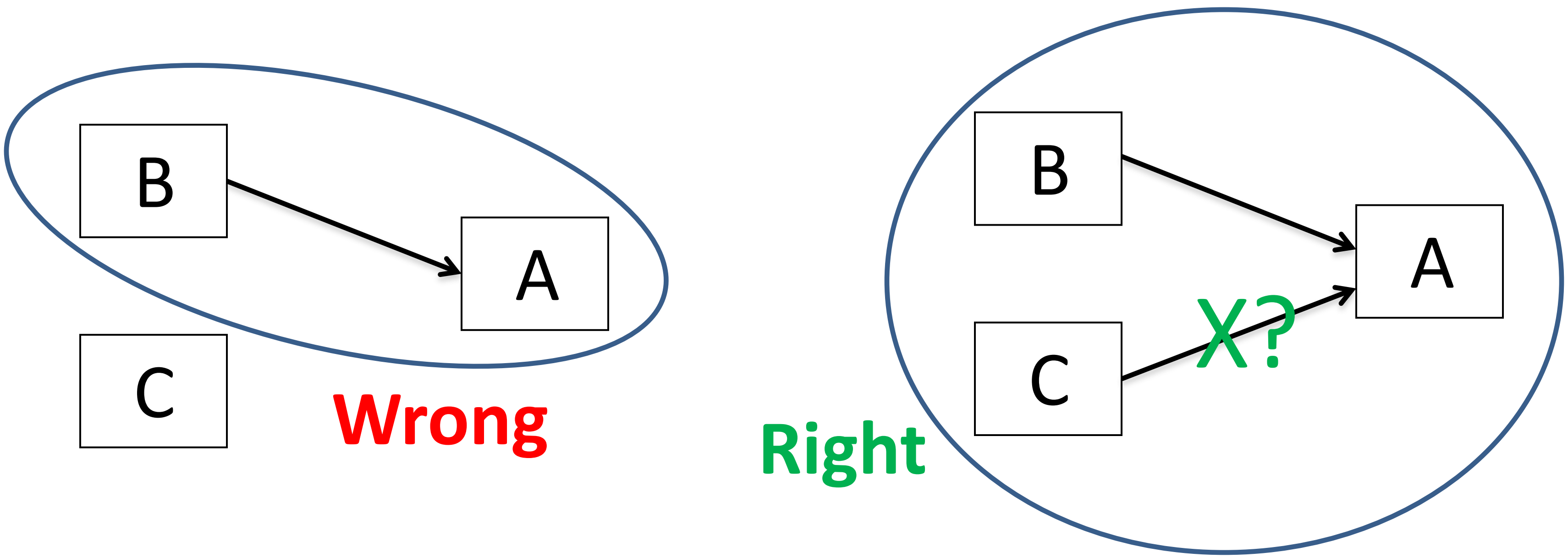
A problem arises when an action in support of the surrogate goal negates the person’s more strongly held goal.

Capturing and storing CO_2 prolongs the fossil fuel era.

Large and distant solar arrays and windfarms do not promote local self-reliance.

Be careful how you wish for what you wish for.

Principle: You want A. You figure out that B will get us to A, and you like B. You foster B. But *there is always a C that someone else likes and you don't like at all*, which also gets us to A. Unless you are alert, your efforts enable C.



***Message*: Add conditionality; bargain or walk away.**

EXTRA SLIDES

Fuel Switching: Coal to gas

Photo by J.C. Willett (U.S. Geological Survey).

Effort needed by 2063 for one wedge:

Replace the output of 1400 GW of coal-fired electric plants with natural-gas-fired plants.

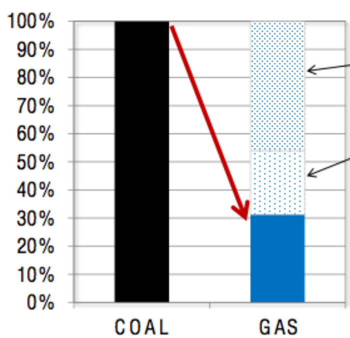
A wedge requires an amount of natural gas equal to that used for all purposes today.

A wedge requires 50 LNG tanker deliveries every day, or the equivalent of 50 Alaska pipelines

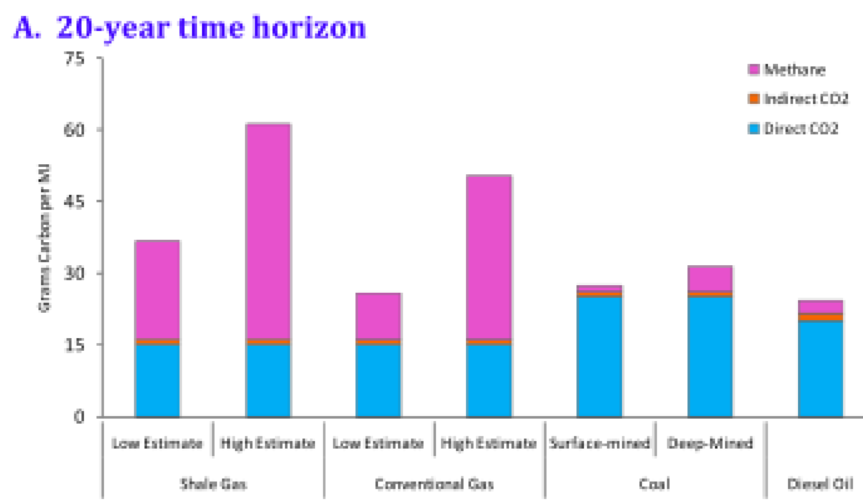
Gas power vs. coal power from a climate perspective

Gas is cleaner than coal in most respects. It is better for climate in almost all respects. But the methane leaks erode the advantages of gas a lot.

Replacing old coal with new gas cuts CO_2 emissions by 70%.



- Carbon emissions:
  - Chemical advantage: Gas burning emits 46% less CO_2 than coal.
  - Efficiency advantage of new gas CCGTs versus old coal boilers: 55-60% vs. 31-33%.
  - Carbon emissions savings from fuel cycle as well.
- Other pollutants reduced or prevented, especially sulfur, particulates.



Source (with permission): David McCabe (Clean Air Task Force), Princeton lecture, 1 October 2012.

Gasification: a common route to power and synfuels

But, in both cases, it has competition:

POWER | **SYNFUEL**

Pulverized-coal steam cycles ⟷ Coal gasification ⟷ Direct liquefaction by H_2 addition

Historic path, but higher-cost CO_2 capture

Lower quality fuel

“No CTL without CCS”

1. Climate-change concerns will dominate the future of coal.
2. Key question is whether coal-to-liquids (CTL) option is competitive in a carbon-constrained world.
3. Incremental costs of CO_2 capture and storage (CCS), relative to costs with CO2 venting, are likely to be lower at CTL plants than at coal power p[lants.
4. Competitiveness of CTL with CCS, *vs*. many other options, is uncertain:
    a. CCS costs will come down with experience, but
    b. CCS costs could rise if public distrust inhibits CO_2 storage.
5. Policy conclusion: **CTL, starting with the first pilots, should proceed only with CCS.**

How deep? CO_2 Phase Diagrams

Note: 1 bar ≈ 10 meters of water

Geothermal gradient ≈ 25°C/km = 25°C/100 bar

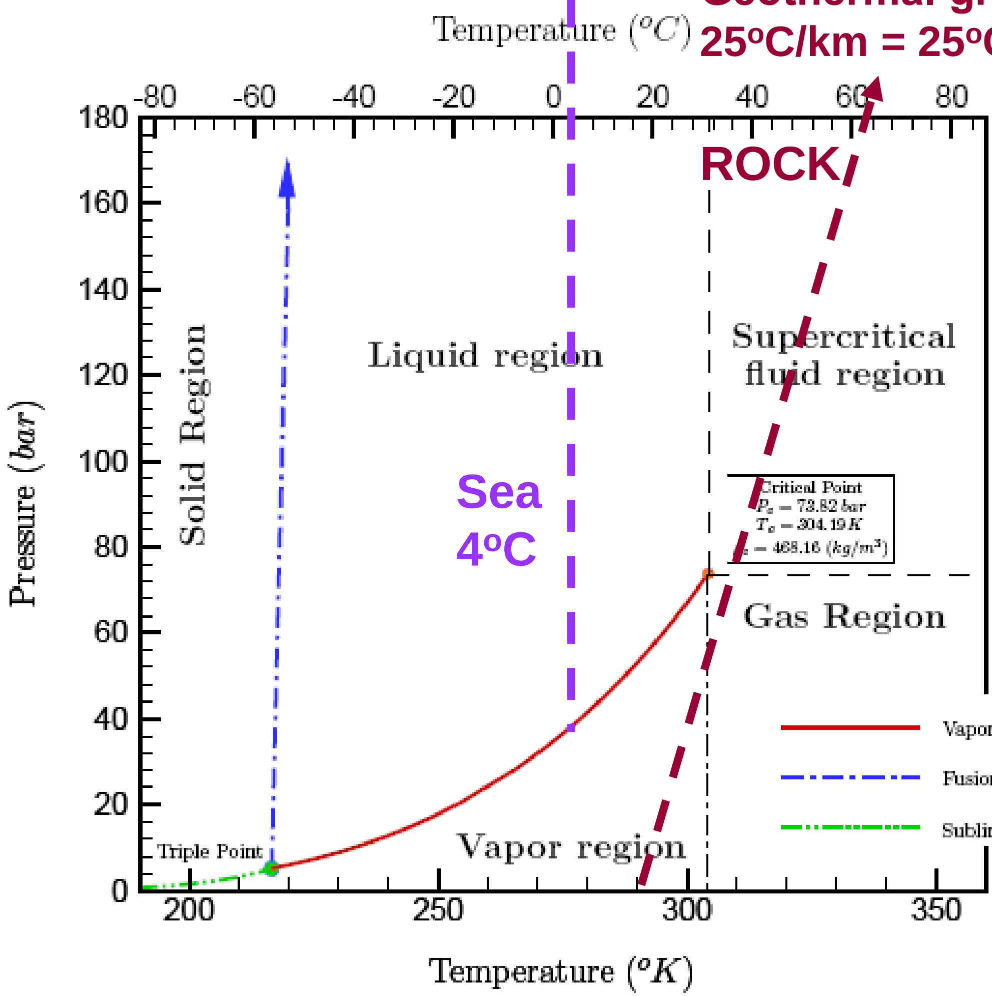


Figure 2.1: Pressure-temperature diagram for pure carbon dioxide

Critical CO_2 pressure: 7.38 MPa (740 m hydrostatic pressure)

At about 350 bar, CO_2 at 4°C has a density greater than seawater → CO_2 lakes on seafloor?

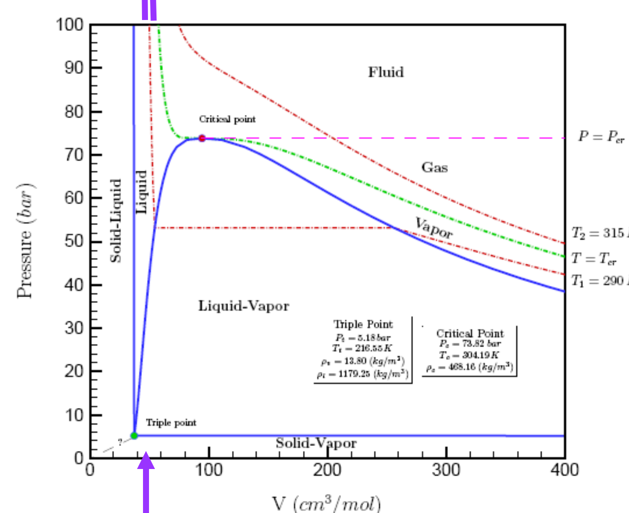
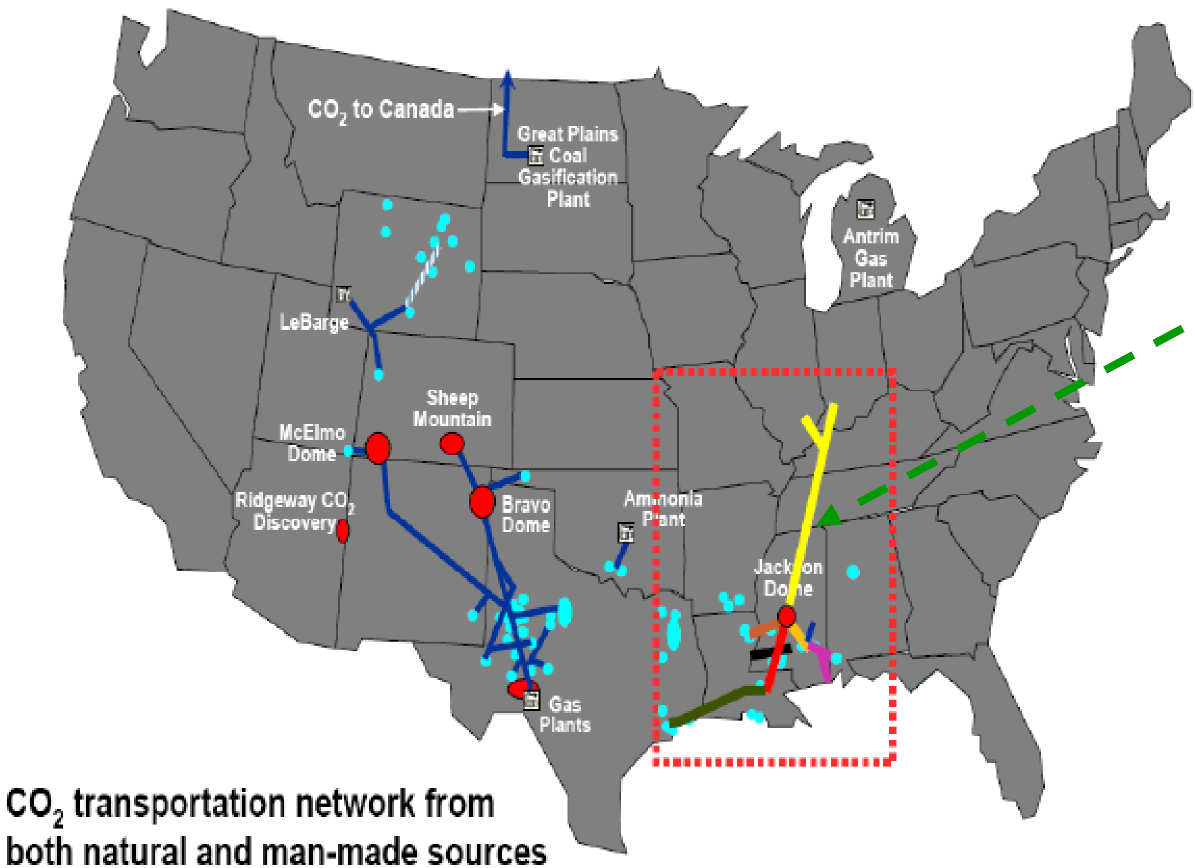


Figure 2.2: Pressure-volume diagram for pure carbon dioxide

44 cm³/mole CO_2 = same density as water

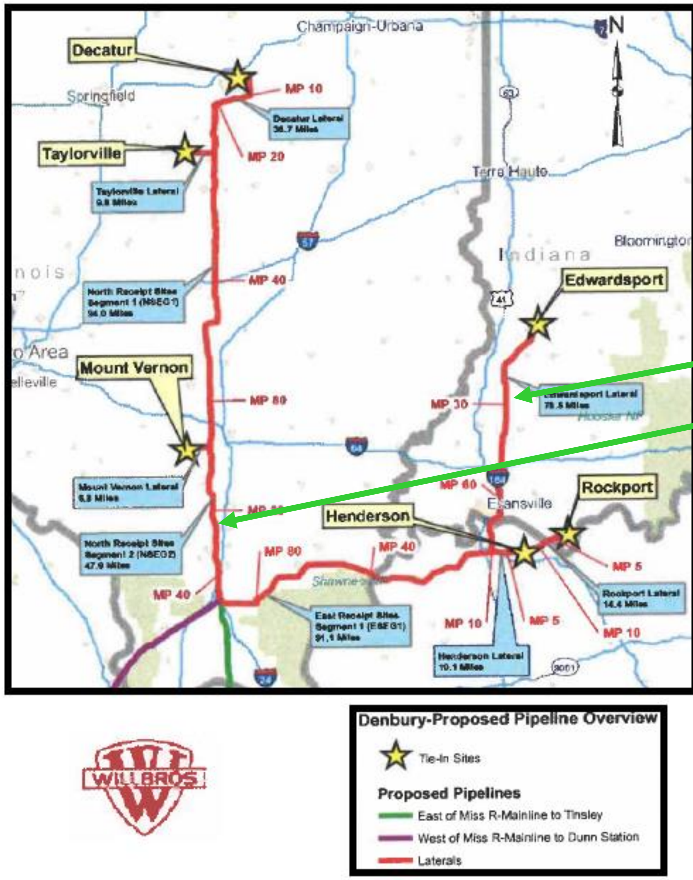
U.S. CO_2 pipeline infrastructure



Denbury proposes to send Ohio Valley CO_2 to the Gulf states for Enhanced Oil Recovery.

Source: "Reducing CO2 Emissions from Coal-Fired Power Plants," John Wheeldon, EPRI, presented at the CCTR Advisory Panel Meeting, Vincennes University, Vincennes IN, September 10, 2009. Reproduced in Science Applications International Corporation, *Indiana and Coal: Keeping Indiana Energy Cost Competitive,* June 2010, Fig. 2-15, submitted to Indiana Center for Coal Technology Research

Denbury's proposed CO_2 pipelines through Indiana and Illinois



Denbury's proposed CO_2 pipeline: Indiana and Illinois laterals

Source: "Reducing CO2 Emissions from Coal-Fired Power Plants," John Wheeldon, EPRI, presented at the CCTR Advisory Panel Meeting, Vincennes University, Vincennes IN, September 10, 2009. Reproduced in Science Applications International Corporation, *Indiana and Coal: Keeping Indiana Energy Cost Competitive,* June 2010, Fig. 2-15, submitted to Indiana Center for Coal Technology Research

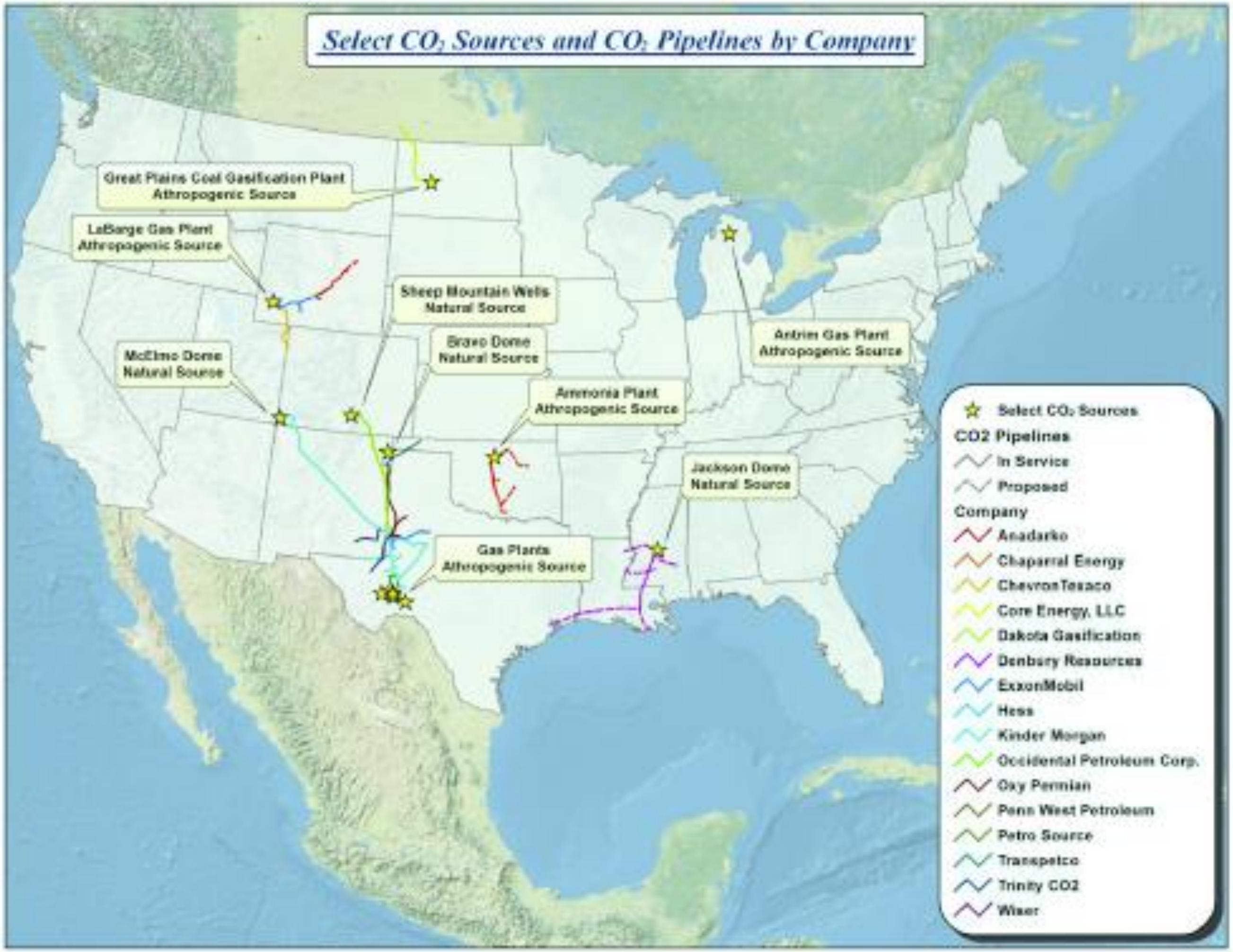
Table B-1. CO_2 Pipeline Summary

Company	In Service Pipeline System Length (Miles)	Proposed Pipeline System Length (Miles)	Total Pipeline System Length (Miles)	Number of State Border Crossings
Anadarko	261.6	302.0	563.6	0
Chaparral Energy	22.2	0.0	22.2	0
ChevronTexaco	147.6	0.0	147.6	2
Core Energy, LLC	10.3	0.0	10.3	0
Dakota Gasification	215.6	0.0	215.6	1 (U.S. /Canada)
Denbury Resources	202.6	599.3	801.9	3
ExxonMobil	362.7	0.0	362.7	1
Hess	43.4	0.0	43.4	0
Kinder Morgan	1,108.5	0.0	1,108.5	3
Occidental Petroleum Corp.	390.4	0.0	390.4	1
Oxy Permian	293.5	0.0	293.5	1
Penn West Petroleum	7.0	0.0	7.0	0
Petro Source	147.1	0.0	147.1	0
Transpetco	120.6	0.0	120.6	2
Trinity CO_2	223.5	0.0	223.5	4
Wiser	26.7	0.0	26.7	0

Source: NETL Generated from Energy Velocity Database, April 2010.

Source: Report of the Interagency Task Force on Carbon Capture and Storage, August 2010

Figure B-1. Existing and Planned CO_2 Pipelines in the United States with Sources



In Salah (Algeria) & Natuna (Indonesia)

Up to 10% CO_2; came online in 2004 to supply gas to Spain & Italy

More than 50% CO_2; plans are uncertain.

EFFICIENCIES, GENERATION COSTS, AVOIDED COSTS (CO_2 VENTED, CAPTURED)

	CO_2 vented		CO_2 captured		Avoided cost*, $/tCO_2$
	efficiency, %	Generation cost, $/MWh	Efficiency, %	Incremental cost, $/MWh	
IGCC (GE current)	38.0	40.8	31.5	9.7	14
Supercritical steam, MEA	45.3	32.8	33.0	22.3	39
Supercritical steam, advanced amine, high heat integration	45.3	32.8	36.5	17.0	29
IGCC, 2020	48.1	36.1	43.2	8.2	8

* CO_2 transport and storage: add $5 - $15/tCO_2

***Source*:** Robert H. Williams, "Coal Power In A Climate-constrained World," Lecture in MAE 328, 27 February 2007.

America's Climate Choices

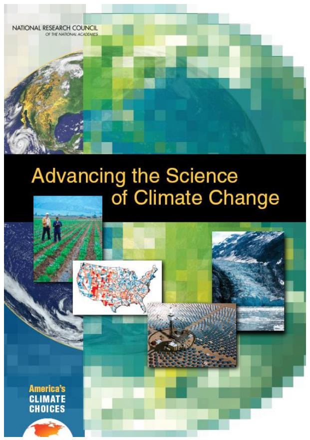
A congressional initiative in 2008 to:

> **"…investigate and study the serious and sweeping issues relating to global climate change and make recommendations regarding what steps must be taken and what strategies must be adopted in response to global climate change, including the science and technology challenges thereof."**

***Products already*: A summit (March 2009), four reports from "panels," and a Final Report from the overarching "*Committee on America's Climate Choices*" (of which I was a member).**

Information at http://americasclimatechoices.org

Four panel reports

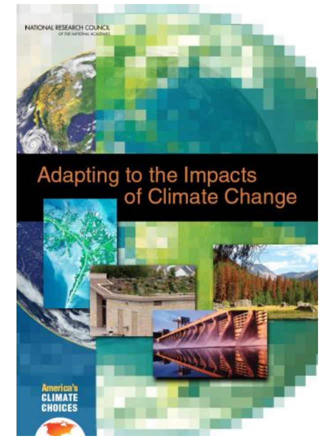


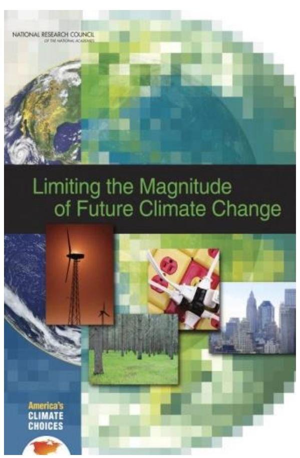
Advancing the Science of Climate Change

"Science panel"

Adapting to the Impacts of Climate Change

"Adapting panel"



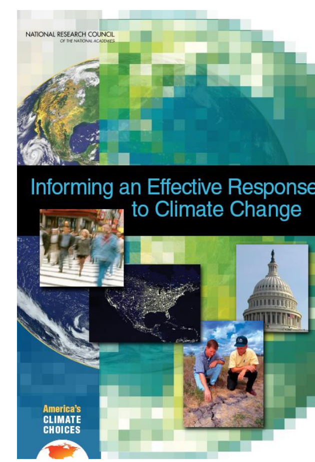


Limiting the Magnitude of Future Climate Change

"Limiting panel"

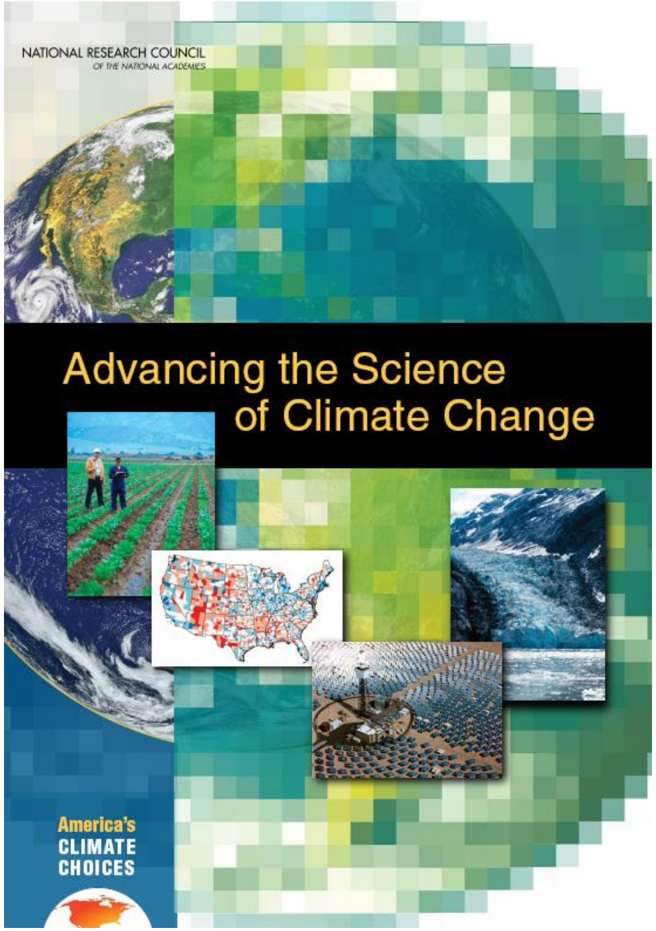
Informing an Effective Response to Climate Change

"Informing panel"



Available at http://www.nap.edu

Science Panel: Sorry, it's real.



CONCLUSION #1: Climate change is occurring, is caused largely by human activities, and poses significant risks for a broad range of human and natural systems.

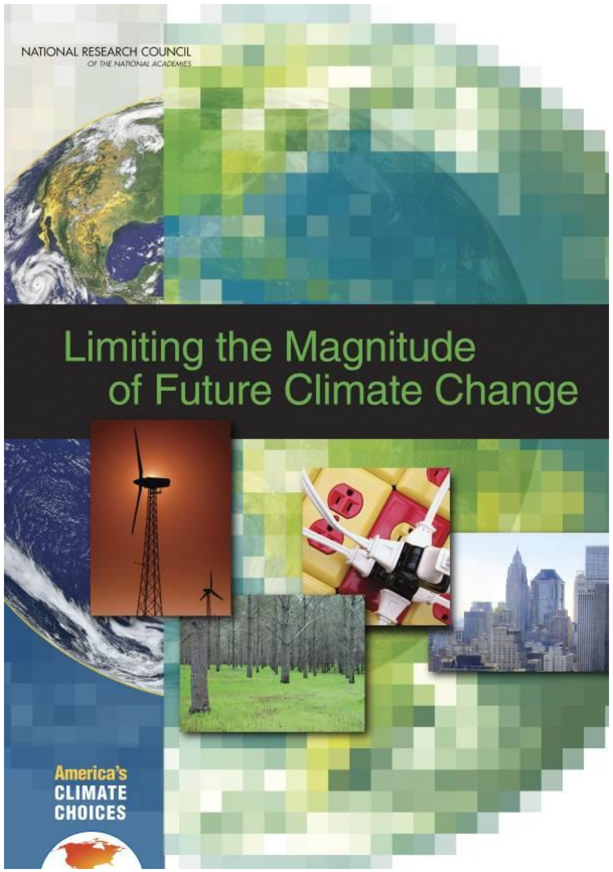
Science Panel: "A new era of climate research"

The nation needs a comprehensive and integrative climate change science enterprise that not only contributes fundamental understanding but also informs and expands America's climate choices.

Scientists need to engage stakeholders/citizens in order to build trust, access local knowledge, and learn about priorities.

The federal climate change research program should develop, deploy, and maintain a comprehensive observing system that supports all aspects of understanding and responding to climate change.

Limiting Panel: Prompt, sustained efforts



A robust U.S. response requires:

- **An inclusive national framework for aligning the goals and efforts of actors at all levels**
- **Aggressive pursuit of all major near-term emission reduction opportunities *and* R&D to create new options**
- **Iterative management of policy responses**

Limiting Panel: Recommendations*

1. **Adopt a mechanism for setting an economy-wide price on carbon.**

2. **Complement the carbon price with policies to:**
   - Realize the practical potential for energy efficiency and low-emission energy sources;
   - Establish the feasibility of carbon capture and storage and new nuclear technologies;
   - Accelerate the retirement, retrofitting or replacement of GHG emission-intensive infrastructure.

3. **Create new technology choices by investing heavily in research and crafting policies to stimulate innovation.**

*first three of seven recommendations

Limiting Panel: Recommendations

4. Consider potential equity implications when designing and implementing climate-change policies, with special attention to disadvantaged populations.

5. Establish the United States as a leader to stimulate other countries to adopt GHG reduction targets.

6. Enable flexibility and experimentation with policies to reduce GHG emissions at regional, state, and local levels.

7. Design policies that balance durability and consistency with flexibility and capacity for modification as we learn from experience.

The logic of national targets

Target: **limiting global mean temperature increase**
(e.g., 2 deg, 3 deg)

What is a 'safe' amount of climate change?
Depends on impacts associated with given temp targets; willingness of society to tolerate risks

----

Target: **limiting global atmospheric GHG concentrations**
(e.g., 450 ppm, 550 ppm)

How does GHG concentration translate into global temp change (and other impacts)?
Depends on climate sensitivity and the strength of other forcing factors (e.g., aerosols)

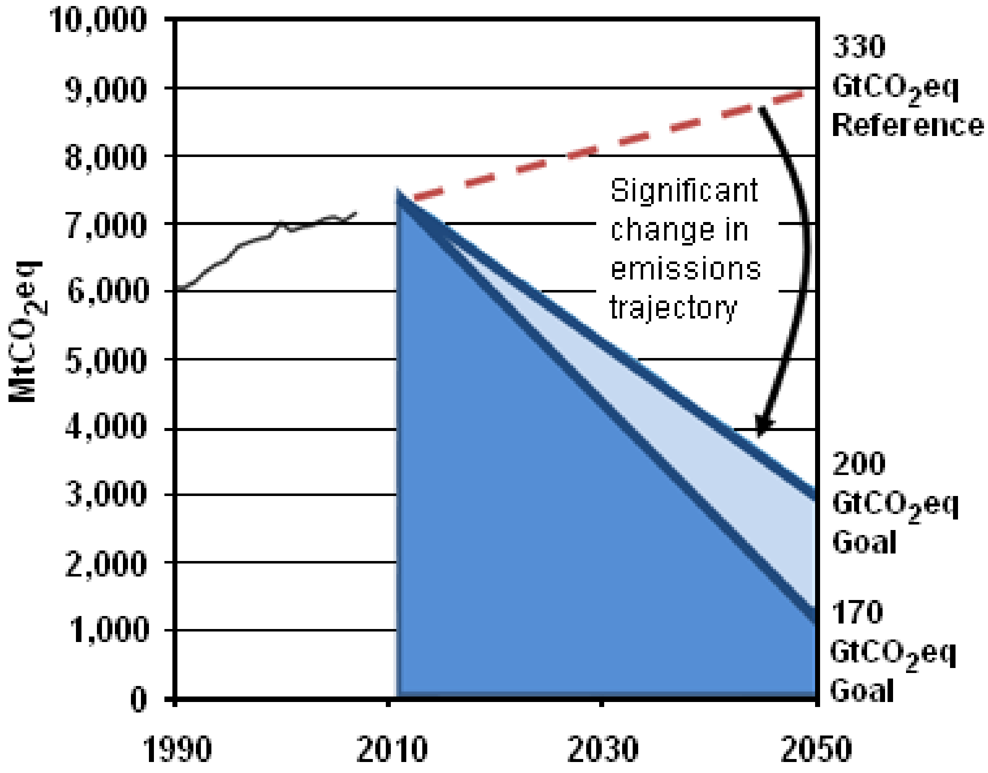
Target: **limiting global GHG emissions**
(e.g. global emission budget, or percent reduction)

How does a given level of emissions translate into atmospheric GHG concentrations?
Depends on carbon cycle dynamics and timing of emissions (e.g., are overshoots allowed?)

Target: **limiting U.S. GHG emissions**
(e.g. national emission budget, or percent reduction)

What is a 'reasonable' share of U.S. emission reductions relative to the global targets?
Depends on political, practical, economic, and ethical considerations

Limiting Panel: U.S. budget to 2050



'Representative' budget: 170–200 Gt $CO_{2\text{-eq}}$, 2012–2050.

Business-as-usual consumes this budget well before 2050.

AR5 WG1 (global) and ACC (US) budgets

AR5 WG1: 1000, 1200, 1500 GtC ever = 33%, 50%, 66% chance of not exceeding "2^{o}C" (the average surface temperature excess relative to "pre-industrial times."

500 GtC emitted already.
Note: non-CO_2 greenhouse gases must be included.
700 GtC = 2600 $GtCO_2$

America's Climate Choices: 170-200 $GtCO_{2e}$ between 2012 and 2050.

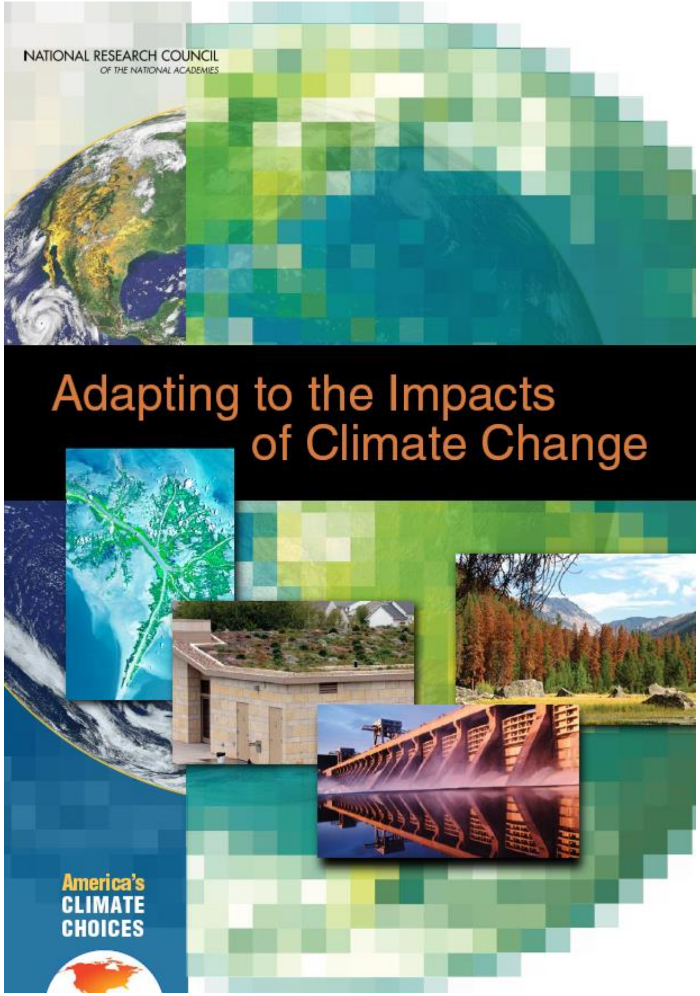
So, non-CO_2 greenhouse gases are included.

Limiting Panel cautionary note

Meeting an emissions budget in the 170–200 Gt CO_2-eq range could be technically possible, but it is very difficult.

Essentially all available options (e.g. efficiency, renewables, CCS, nuclear, biofuels) would need to be deployed at levels close to what is estimated as technically possible; and these estimates are based on very optimistic assumptions.

Adaptation: A U.S. perspective



There is a real risk that impacts could emerge rapidly and powerfully. Mobilizing now to increase the nation's adaptive capacity can be viewed as an insurance policy against an uncertain future.

Key sectors: ecosystems, agriculture and forestry, water, health, transportation, energy, and coastal regions.

Adaptation to extreme events

Example: The Hot Weather–Health Watch/Warning System, Philadelphia, 1995

Whenever the National Weather Service issues a heat wave warning, local media are required to provide information on how to avoid heat-related illnesses and how to help elderly persons.

Those involved include

- Philadelphia Corporation for the Aging
- Department of Public Health
- Local utility company and water department (halt service suspensions)
- Fire Department Emergency Medical Service (increase staffing)
- Senior centers (extend hours of operation of air-conditioned facilities)

Adaptation to the new normal

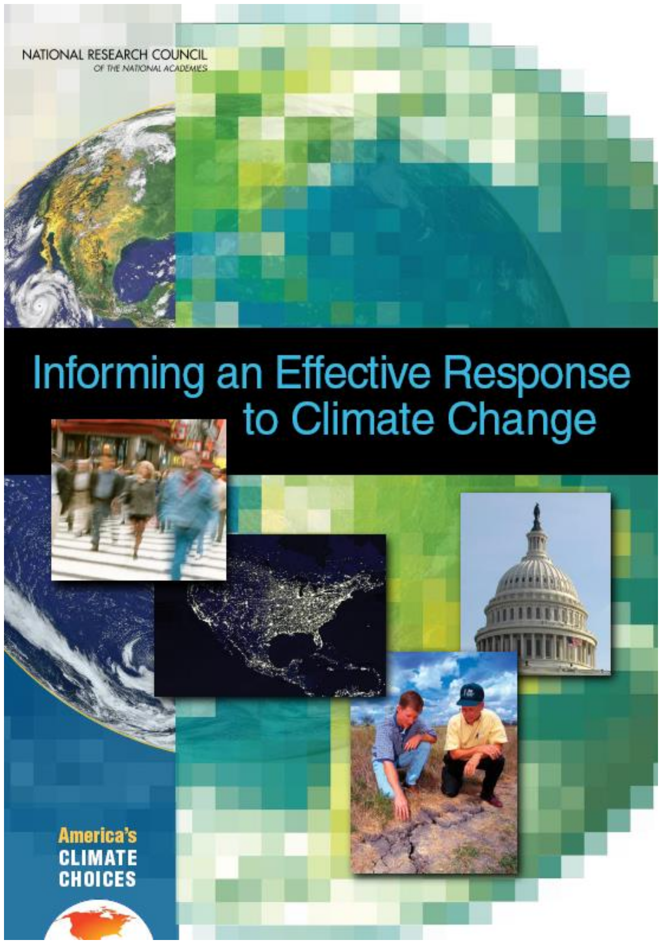
A "new normal" requires transformational adaptations:

- Movement of people and facilities away from vulnerable areas
- Changes in ecosystem and land management objectives
- Revisions of water-rights law

Contingency planning for high-impact/low-probability outcomes requires vigilant monitoring to detect early signals and continuous assessment of the adequacy of responses.

Adaptation needs to be adaptable.

Informing Panel: Improved information systems



- **Federal coordination of diverse decision-making**
- **Institutions that will produce improved tools**

Informing Panel: All sorts of decisionmakers

Climate response is and will always be decentralized.

Federal roles include:

- **clear leadership**
- **regular evaluation and assessment**
- **aggregation and dissemination of “best practices”**
- **development and diffusion of decision-support tools**
- **training of researchers and practitioners.**

The federal government must avoid preemption that discourages productive decisions by other actors.

Policy slides from Phil Hannam October 15, 2013

General Policy Design Principles

1. Every independent policy goal requires at least one independent policy instrument
2. Policies should strive to attain the necessary degree of macro-control with the *minimum* sacrifice of micro-level freedom and variability
3. Policies should leave a margin of error because of biological uncertainties *[spaceship earth]*
4. Policies must recognize that we must always start from historically given initial conditions *[e.g. the market is here to stay; owners of private property will not relinquish it, etc]*
5. Policies must be able to adapt to changing conditions
6. Design policies at the scale of their effects *[e.g. local problems need local solutions; global problems need global solutions]*

[Adopted from Daly and Farley 2003]

Policy Tools

Direct Regulation >>>Command-and-Control regulations

Positive Features

- Limits pollution/ harvest to acceptable level
- Directly addressed biological limits
- Can be tailored to all, or some, individuals
- Familiar to most policy makers and easy/cheap to monitor and administer

Negative Features

- Low allocative efficiency
- No incentive to surpass the goal (mercury example)
- Does not allow micro-flexibility (violates our policy principles)

General Policy Design Principles
Property Rights

Coase theorem:

As long as property rights are assigned (and there are negligible transaction costs) the market can efficiently allocate resources

Three types of property rights:

- Property Rule: One person is free to interfere with another, or free to prevent interference
- Liability Rule: One person is free to "interfere" with another or prevent interference, but must pay compensation
- Inalienability Rule: If a person is entitled to the presence or absence of something, then no one can legally take that right away for any reason.

Policy Tools

- Direct Regulation
- Pigouvian Taxes
- Pigouvian Subsidies
- Tradable Permits

Policy Tools

Pigouvian Taxes >>> LIABILITY RULE (polluter pays principle)

Positive Features

- Ideally, the tax operates at the marginal external cost (effectively a market correction)
- Cost effectively reduces environmental costs
- Tax per unit of pollution creates an incentive for further reductions!
- If a firm is driven out of business, it implies it the social benefit was lower than the social cost

Negative Features

- If economy grows, more firms come online, who can still increase pollution/ extraction
- Assumes that revenue from the tax is used to remedy the environmental/ social harm
- Incentivizes outsourcing of the pollution

Policy Tools

Pigouvian Subsidies >>>Assume polluter has right to pollute!
(but society pays him/her not to)

Positive Features

- If the abatement costs are lower than the subsidy, the firm reduces pollution
- Useful as an incentive for ecosystem restoration (paying you to reforest your land)
- Useful as an international mechanism to get sovereign nations to reduce

Negative Features

- The subsidy might attract new entrants, thus increasing pollution (Example: HFC's in China)
- Reward goes to the polluter!

Policy Tools

Tradeable Permits >>> Impose a property right to the entity owning the quote (rights to absorptive capacity of a medium)

Positive Features

- Assigns rights to a rival good made excludable by quotas
- Distribution of the quotas can be designed to achieve other social goals
- If the economy grows, the quota does not
- Allows micro-level freedom: Harnesses power of markets

Negative Features

- Determination of the proper quota level is difficult and contentious
- If demand rises, or the quota is reduced, prices can spike (supply/ demand), creating political pressure.