Carbon Capture and Sequestration: Progress, Challenges, and Opportunities

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Notre Dame Energy Center Distinguished Lecture Series, October 15, 2009, Notre Dame, IN

CONSOL Energy Inc.

- Began mining coal in 1864
- 17 mine complexes in WV, PA, VA, KY, OH, UT
  - Largest producer of U.S. bituminous coal
  - Largest U.S. producer of underground mined coal
- CNX Gas subsidiary (83.3% ownership)
  - CBM and conventional gas plays in VA, PA, WV, and TN
- Production – 65 MM ton/y coal, 77 Bcf/y gas
- Reserves – 4.5 B ton coal, 1.4 Tcf gas
- $4.7 billion annual revenue
- ~8,000 employees
- Safety record ~2x better than industry average
- River Operations: 29 towboats, 700 barges
- Only U.S. coal company with an R&D department

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CONSOL Energy Inc. Research & Development
Greenhouse Gas Emission Reduction Projects

- Founding member of the FutureGen Industrial Alliance
  - Chair – board of directors and sub-surface technical sub-committee
- Participation in DOE Regional Carbon Sequestration Partnerships
  - Midwest Regional Carbon Sequestration Partnership
  - Southeast Regional Carbon Sequestration Partnership
- Demonstration of CO_2 sequestration and enhanced coal bed methane production in unmineable coal seams
- CO_2 capture research with The Ohio State University
  - Pre- and post-combustion capture using Ca looping
  - Coal Direct Chemical Looping
- Pilot-scale demonstration of pressurized fluidized bed combustion with CO_2 capture
- Participation in several CCPI-3 proposals for integrated carbon capture and sequestration demonstration projects involving >300,000 ton/y of CO_2
- Demonstration of coal mine methane emission abatement
  - Regenerative thermal oxidizer installed on simulated mine ventilation fan
  - Microturbine generator installed on coal mine methane vent

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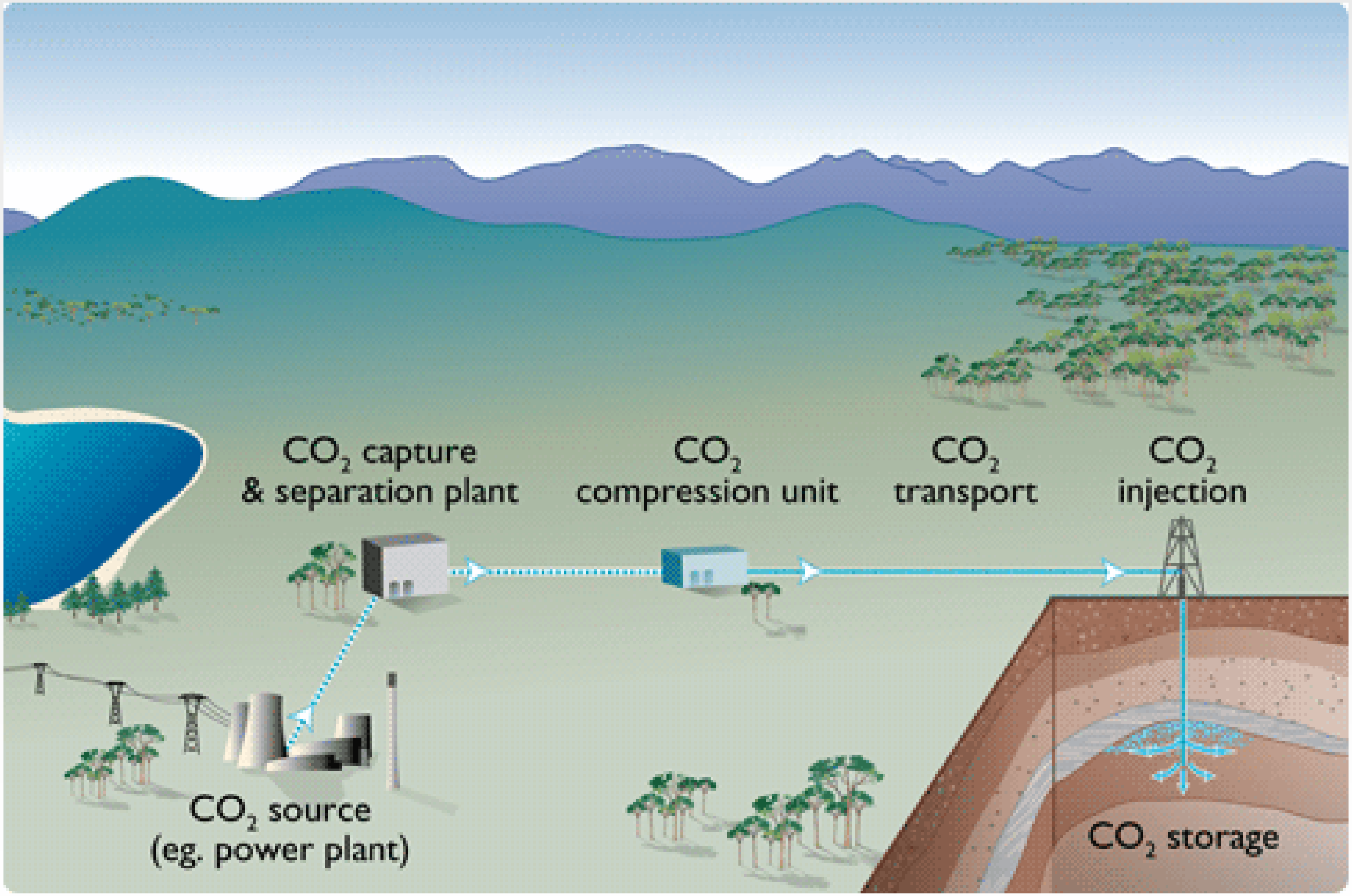
Carbon Capture and Sequestration (CCS)



Source: http://www.co2crc.com.au/aboutgeo/

Today's Talk

- Why CCS?
- CO_2 Capture
- CO_2 Transportation and Sequestration
- Integrated CCS Demos
- When and at What Cost?
- The Bottom Line

Why CCS?

Potential U.S. CO_2 Cap-and-Trade Legislation

	Percent Change in U.S. Greenhouse Gas Emissions Relative to 2005		
	Business as Usual[a]	American Clean Energy and Security Act (H.R. 2454)	Clean Energy Jobs and American Power Act
2012	+1	-3	-3
2020	+4	-17	-20
2030	+9	-42	-42
2050	+18	-83	-83

[a]Source: U.S. EPA Analysis of H.R. 2454

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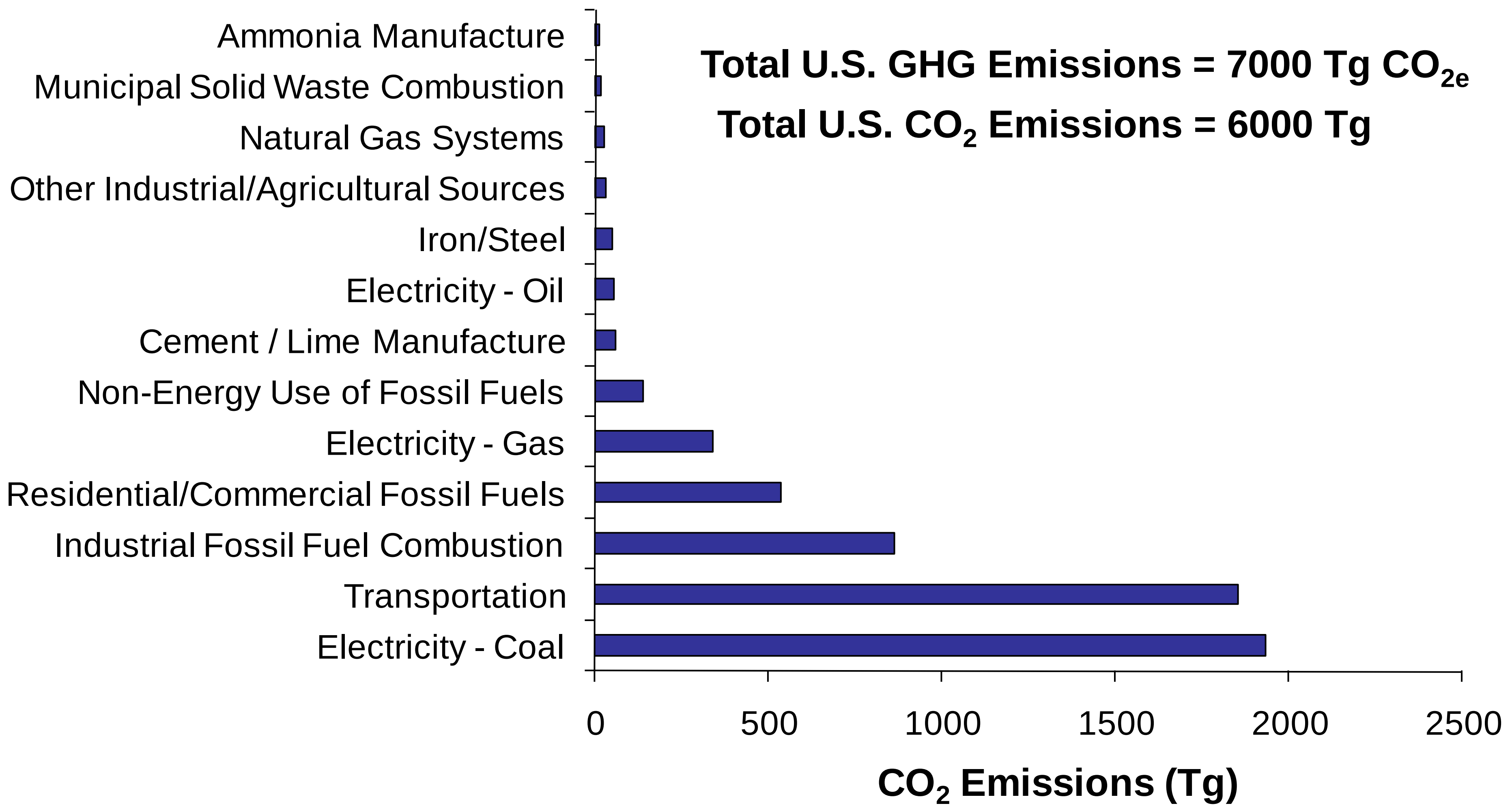
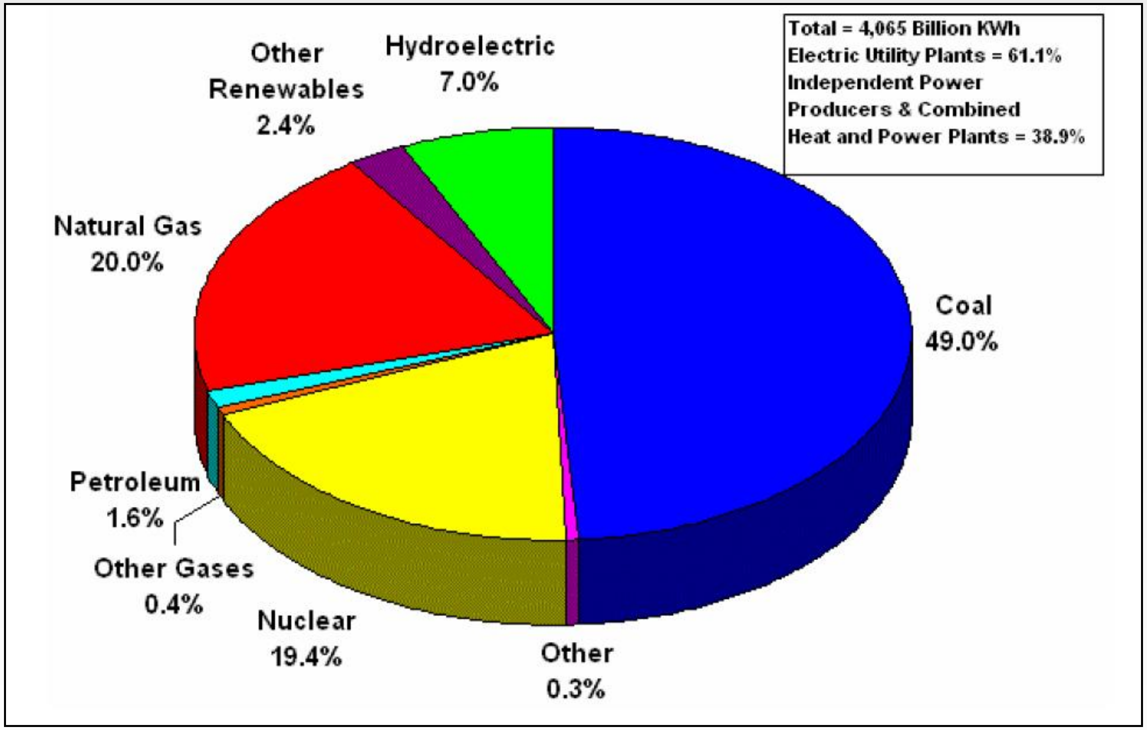
U.S. CO_2 Emissions by Source Type (2006)



Source: U.S. EPA

U.S. Electric Power Industry Net Generation (2006)

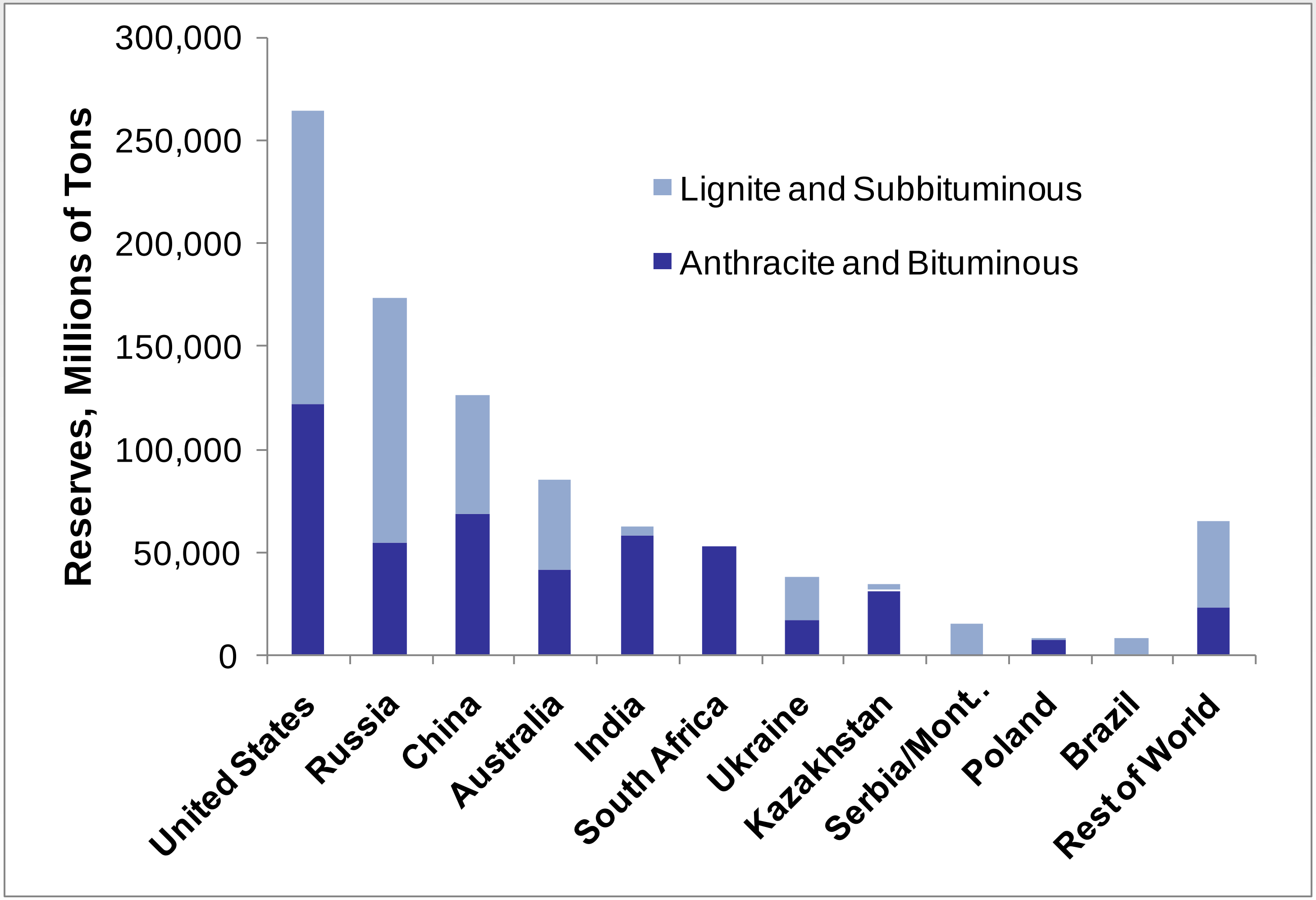


Source: U.S. Energy Information Administration

Why coal-fired power?

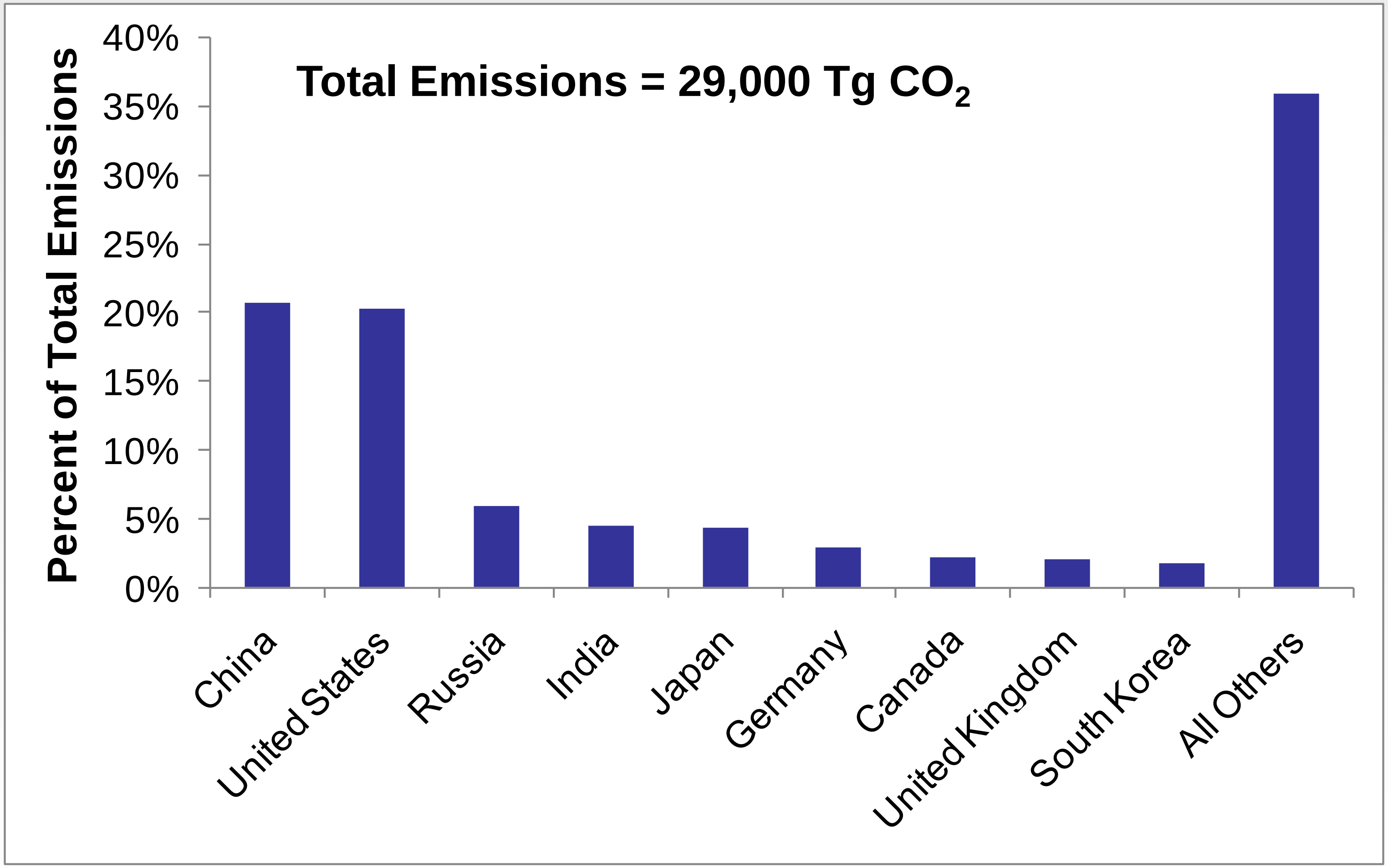
- Abundant, domestic fuel
- Low cost
- Reliable
- Large existing asset base

World Proven Recoverable Coal Reserves (2006)



Source: U.S. Energy Information Administration, *International Energy Annual 2006*

World CO_2 Emissions from Fossil Fuels (2006)



Source: U.S. Energy Information Administration

China's Coal Boom

United States

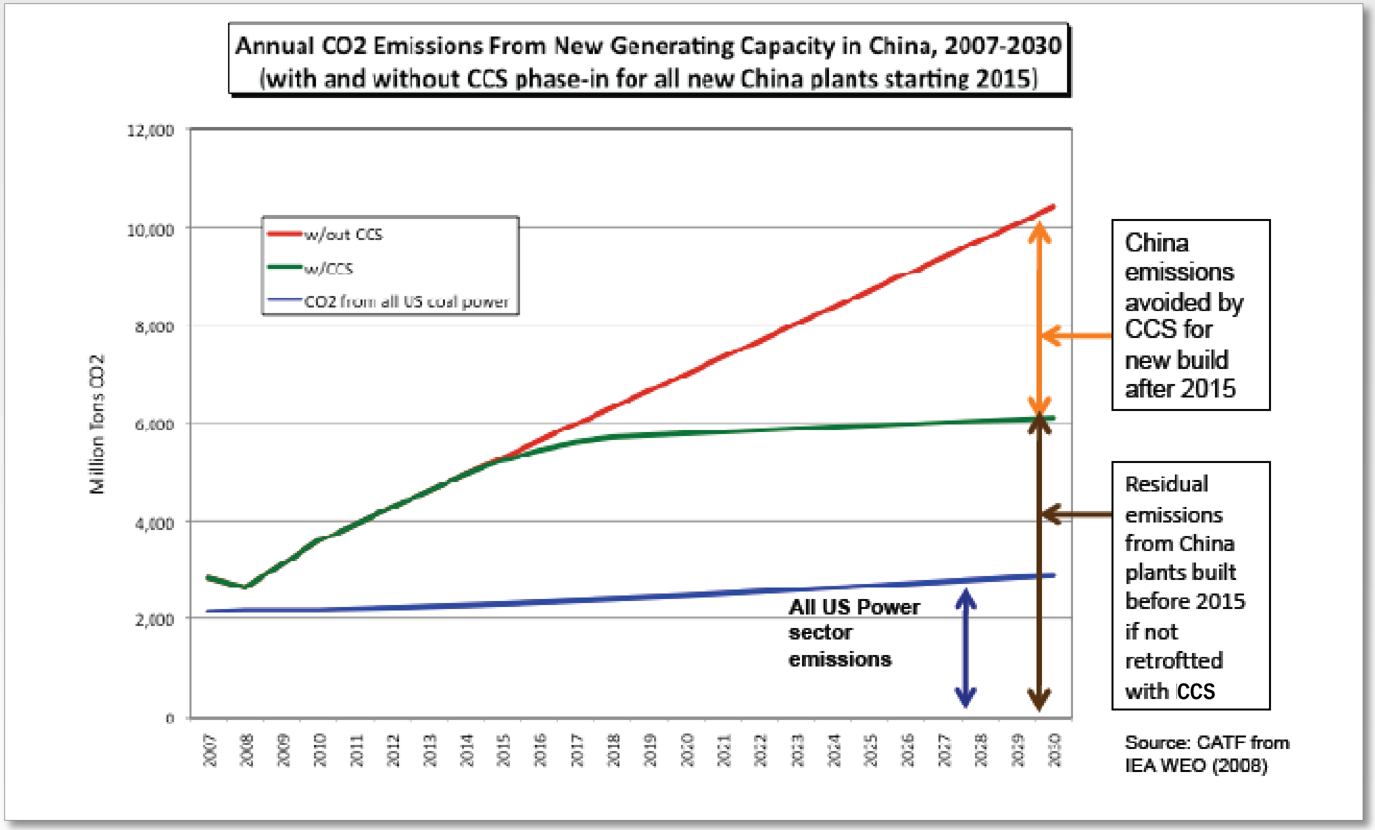
332 GW of coal-fired generating capacity

Average age = 35 years

China

417 GW of coal-fired generating capacity

More than half is less than 5 years old



China's coal consumption is expected to more-than double over the next 20 years, in spite of plans to construct 100 new nuclear plants during that period.

Source: MIT Energy Initiative Symposium, March 23, 2009

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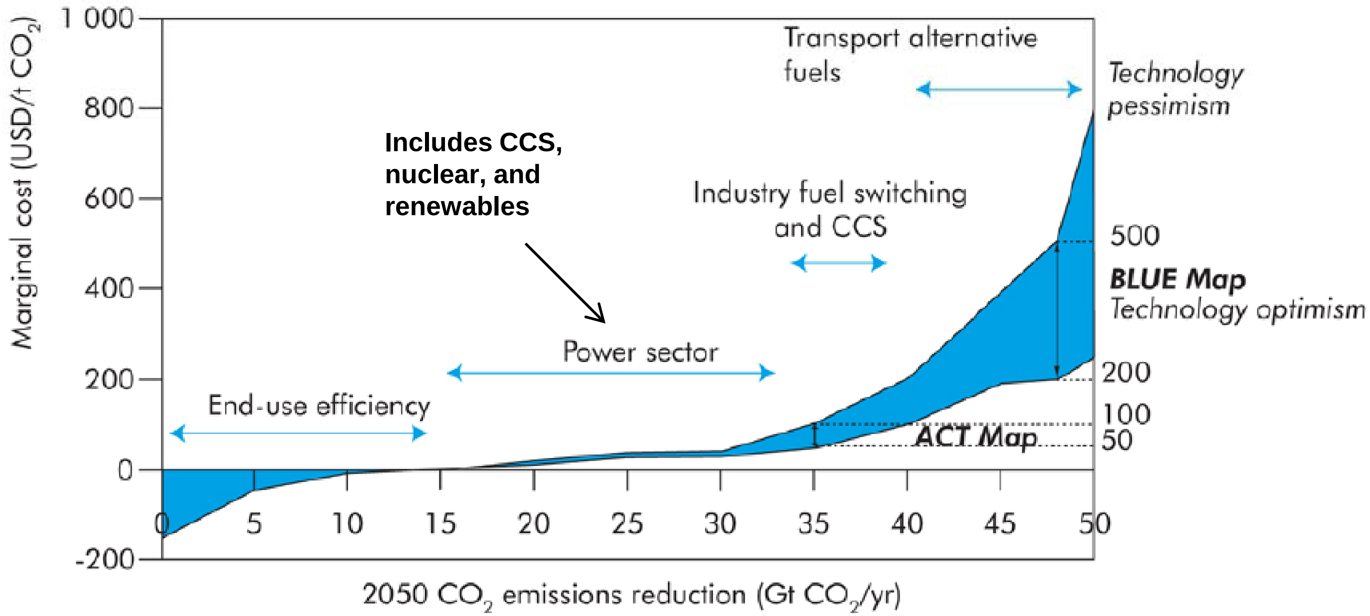
IEA Energy Technology Perspectives 2008

Marginal Emission Reduction Costs for the Global Energy System, 2050



ACT Map = Bring global CO_2 emissions back to current level by 2050
BLUE Map = Reduce global CO_2 emissions by 50% from current level by 2050

"CO_2 capture and storage … is the most important single new technology for CO_2 savings in both ACT Map and BLUE Map scenarios."

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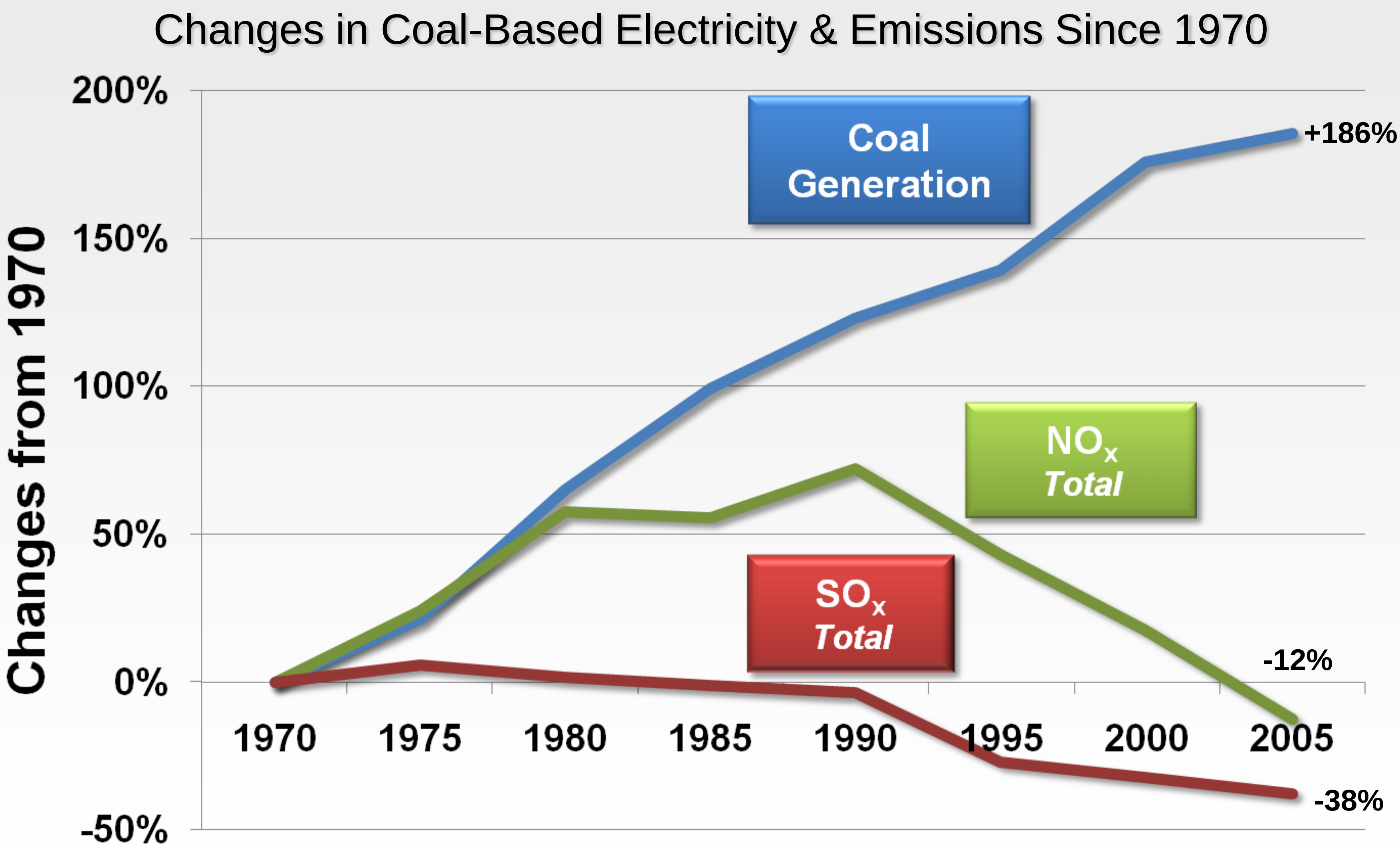
We've Done Similar Things Before …



Source: EIA Annual Energy Review, EPA National Air Pollutant Emission Trends

But CO_2 Presents a BIG Challenge

Chemical Composition
Pittsburgh Seam Coal
(CONSOL Blacksville No. 2)

	% (w/w), as received
Moisture	5.6
Carbon	72.0
Hydrogen	4.7
Nitrogen	1.4
Chlorine	0.1
Sulfur	2.5
Ash	7.7
Chlorine	0.1

Relative to other air pollution control systems, CO_2 control requires:

- More solvent/sorbent
- More waste disposal/storage
- More energy
- More $$$

CO_2 Capture

Candidate CO_2 Capture Technologies

- Wet chemical absorption
  - Amine scrubbing
  - Ammonia scrubbing
  - Alkaline salt solution scrubbing
- Physical absorption
- Hybrid absorption
- Gas separation membranes
- Gas absorption membranes
- Physical adsorption
- Solid chemical absorption
- Cryogenic separation
- Hydrate formation
- Electrochemical separation
- Biochemical separation

Status of CO_2 Capture Technologies

It is technically feasible to achieve 90% CO_2 capture from coal-fired power plants using commercially available or near-commercial technologies …

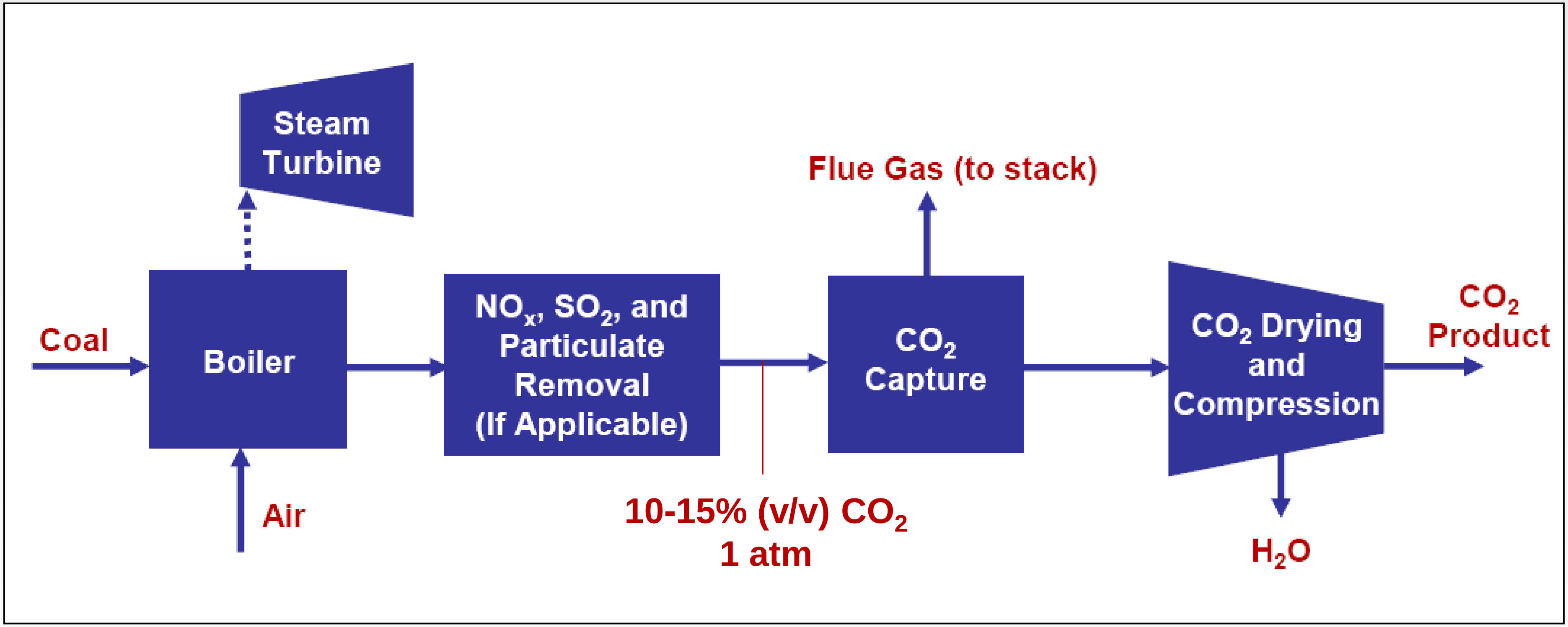
HOWEVER

… these technologies are expensive, with large capital and energy requirements, and would need to be applied in new ways and at an unprecedented scale to significantly reduce CO_2 emissions

CO_2 Capture Configurations for Power Plants

- Post-combustion capture
- Pre-combustion capture
- Oxyfuel combustion

Post-Combustion Capture



- Applicable to new and existing plants
- Leading technologies: amine scrubbing, ammonia scrubbing

Amine Scrubbing

$$2\ R\text{-}NH_2 + CO_2 \leftrightarrow R\text{-}NH_3^+ + R\text{-}NH\text{-}COO^-$$

- Exothermic reaction, can be reversed by applying heat
- Various amines can be used (primary, secondary, tertiary, sterically hindered, etc.)
- Commonly used for separating CO_2 from natural gas
- Several processes offered commercially for flue gas applications
  - Fluor Econamine FG Plus^{SM}
  - MHI / KEPCO KS-1 Process
  - Kerr-McGee / ABB Lummus Process
- Many groups working on development of advanced amine processes

http://www.co2captureandstorage.info/popup_warrior.htm

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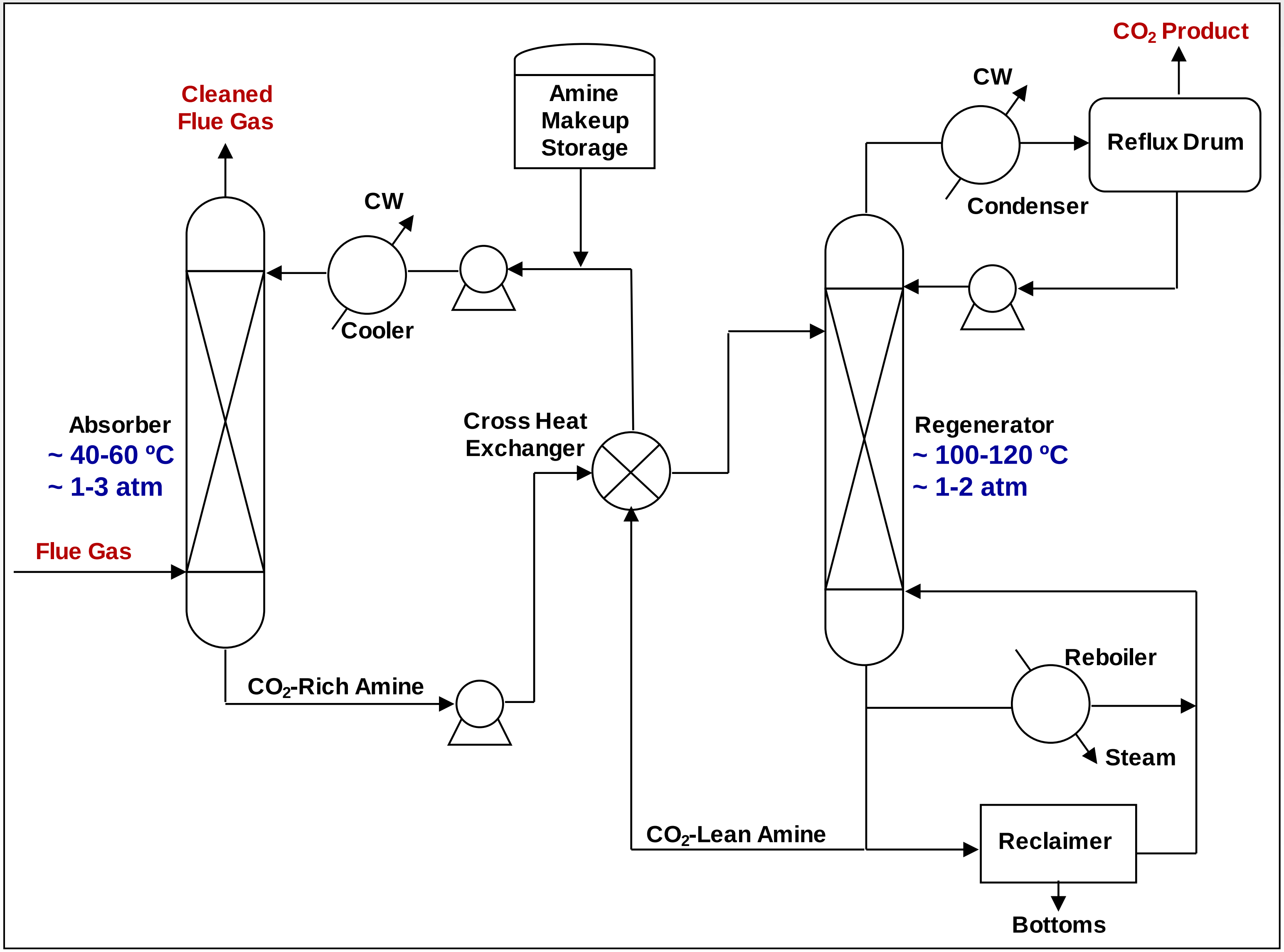
Amine Scrubbing Process Flow Diagram



Amine Scrubbing Commercial Experience
U.S. Coal / Natural Gas Flue Gas Applications

Name	Location	CO_2 Source	Approx Capture Rate (t CO_2/d)	CO_2 Use
Carbon Dioxide Technology	Lubbock, TX	Gas boiler	1000	EOR
IMC Global	Trona, CA	Coal boiler	726	Soda ash
Mitchell Energy	Bridgeport, TX	Gas heaters, engines, turbine	447	EOR
Northeast Energy Associates	Bellingham, MA	Gas turbines	320	Food-grade
AES Shady Point	Poteau, OK	Coal boiler (CFB)	181	Food-grade
AES Warrior Run	Cumberland, MD	Coal boiler (CFB)	150	Food-grade
N-ReN Southwest	Carlsbad, NM	Gas boiler + NH_3 reformer	90	EOR

90% capture from a 500 MW_e coal-fired power plant requires a capture rate of ~ 10,000 tonne CO_2 / day

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Amine Scrubbing Process Limitations

- Energy Penalty
  - 20-30% of plant's output for new plant
  - 30-40% of plant's output for retrofit
  - Large portion is solvent regeneration energy (heat of reaction + sensible heat + latent heat of vaporization)
  - Also includes compression energy and pump energy
- Footprint
  - At least 5-6 acres for 500 MW plant
- Loss of absorbent
  - SO_2, SO_3, and NO_2 can react irreversibly with amines
  - SO_2 typically limited to < 10 ppmv (may require polishing scrubber)
- Corrosion
  - Limits concentration of amine in aqueous sorbent solution
  - Inhibitors sometimes used
  - Sterically hindered amines often produce less corrosion than unhindered amines

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Ammonia Scrubbing

$$CO_2 + (NH_4)_2CO_3 + H_2O \leftrightarrow 2\ NH_4HCO_3$$

- Exothermic reaction, can be reversed by applying heat
- Solvent cycled between absorption and regeneration units
- Compared to amine scrubbing:
  - Lower energy penalty
  - Higher CO_2 loading capacity
  - Less reagent degradation
  - Lower reagent cost
  - Less corrosion risk
- Key challenges
  - Ammonia vapor losses (to flue gas and captured CO_2)
  - Flue gas cooling (32-80 ºF)

http://www.powerspan.com/FirstEnergy_ECO2.aspx

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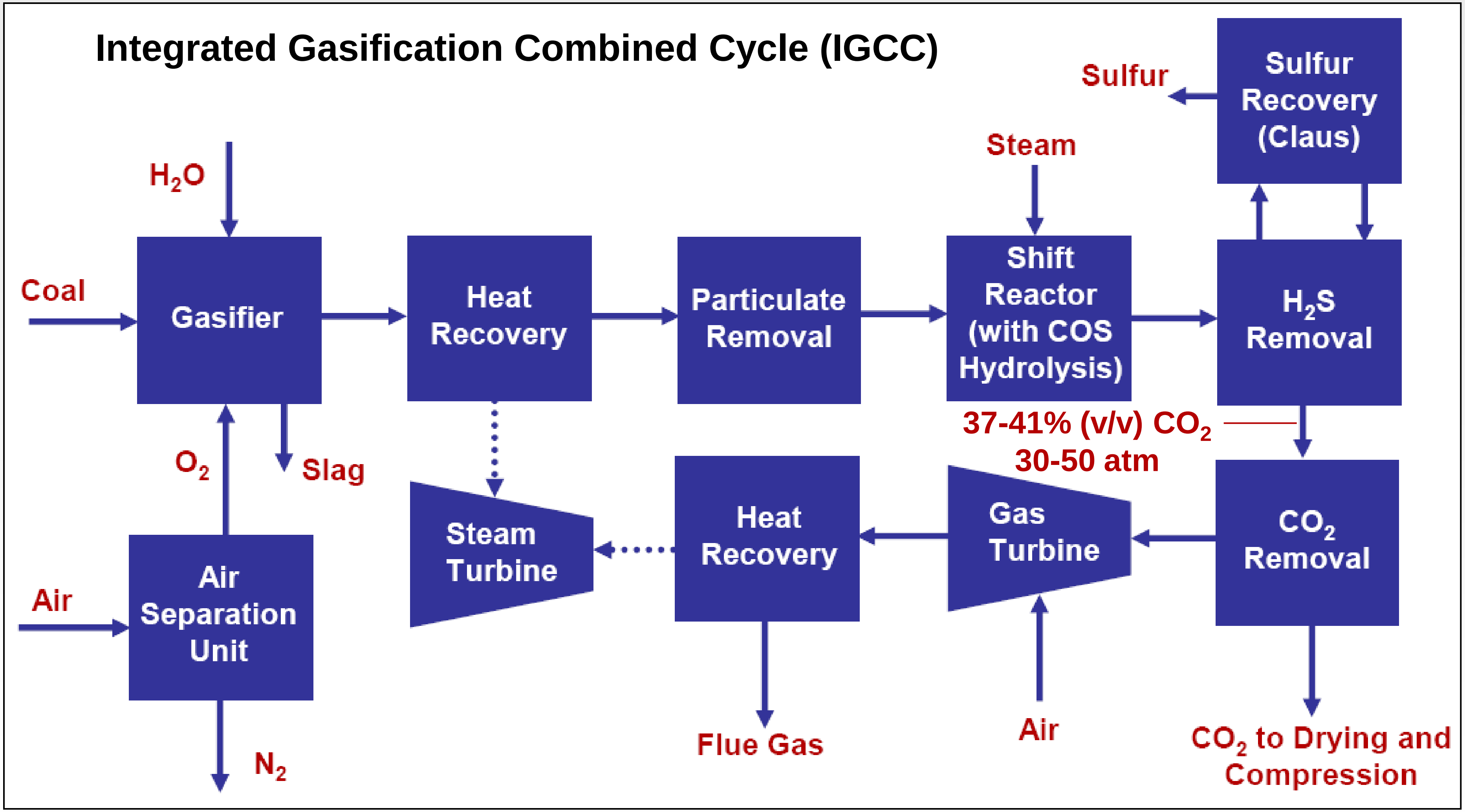
Ammonia Scrubbing Commercial Technologies

- Alstom Chilled Ammonia
  - 5 MW_{th} pilot plant operating at We Energy's Pleasant Prairie Power Plant in Wisconsin since June 2008
  - 5 MW_{th} pilot plant operating at E.ON's Karlshamn Power Plant in Sweden since mid-2009
  - 20 MW_e Product Validation Facility commissioned in September 2009 at AEP's Mountaineer Power Plant in WV
  - 40 MW_{th} Product Validation Facility planned at Statoil's Mongstad refinery in Norway (2011)
  - 235 MW_e demonstration proposed at AEP's Mountaineer Power Plant (2015)
- Powerspan ECO_2®
  - 1 MW_e pilot test underway at First Energy's R.E. Burger plant in Ohio since December 2008
  - 120 MW_e full-scale demo planned at Basin Electric's Antelope Valley Station in North Dakota (2012)

Pre-Combustion Capture



- **Applicable to new plants**
- **Leading technology: physical absorption**

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Physical Absorption Process Principles

- Solvent cycled between absorption / regeneration units
- Solvent physically dissolves CO_2 (Van der Waals or electrostatic forces)
  - Weaker bonds = less regeneration energy than chemical sorbents
  - Total energy penalty is ~10-20% for pre-combustion IGCC application
- Process behaves according to Henry's law
  - CO_2 capture favored by high pressures, low temperatures
  - Absorber typically operates at > 20 atm, may operate below ambient temperature
  - Regeneration by pressure reduction and/or heating
- Numerous commercially available solvents
  - Selexol, Rectisol, Purisol, Fluor Solvent, Sepasolv, Morphysorb

Status of IGCC with Pre-Combustion CO_2 Capture

- IGCC has been commercially demonstrated without CO_2 capture
  - Wabash River (Indiana) - 262 MW
  - Tampa Electric Polk Station (Florida) - 250 MW
- CO_2 capture from coal-derived syngas has been commercially demonstrated
  - Great Plains Synfuels Plant (North Dakota)
  - Eastman Coal-to-Chemicals (Tennessee)

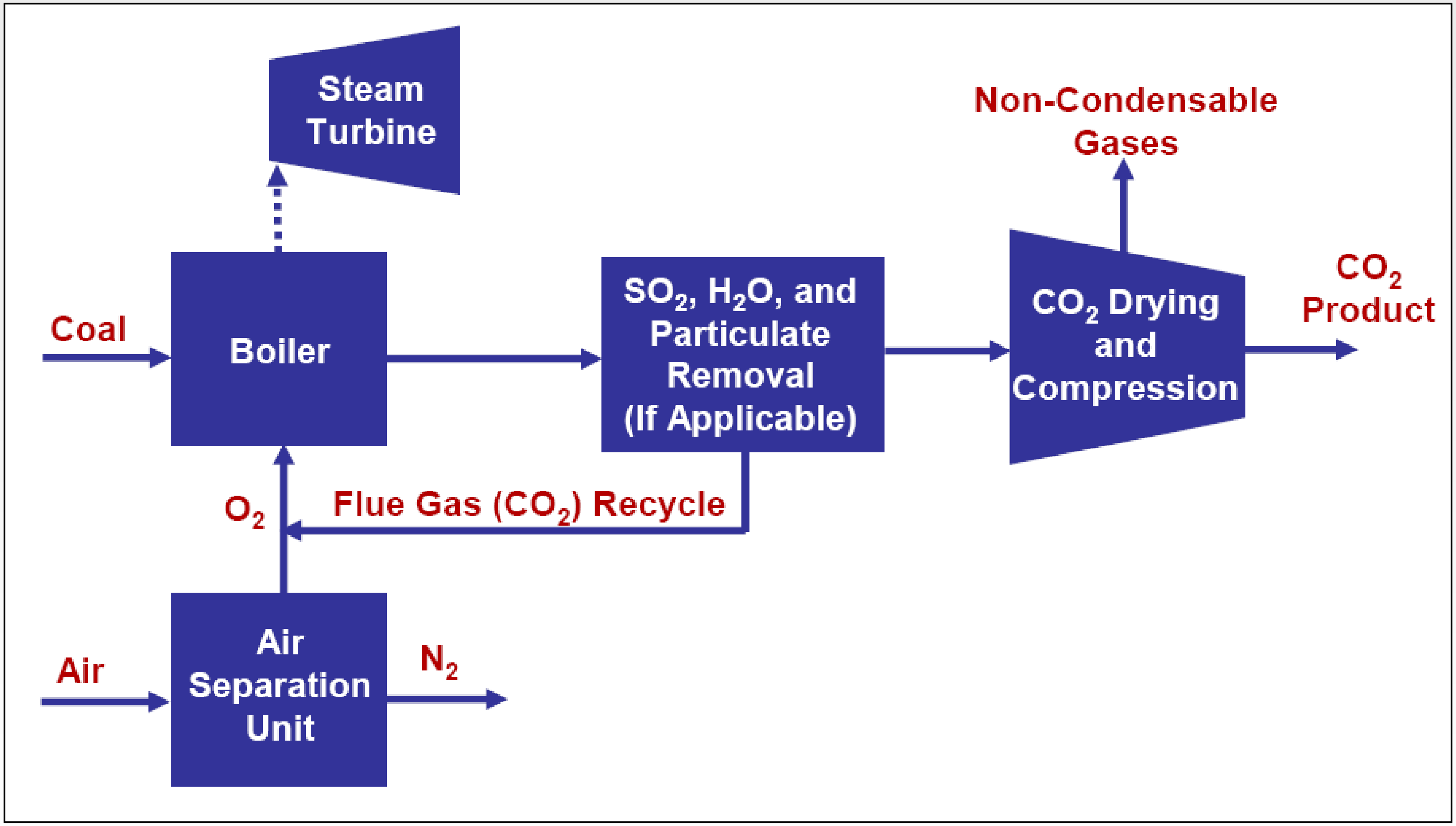
Source: http://www.dakotagas.com/News_Center/Media_Gallery/Photo_Gallery/index.html

Still no integrated demonstration of IGCC with pre-combustion CO_2 capture

Challenges for Commercial Deployment of IGCC with CCS

- High capital costs
- Questionable reliability / availability
- Uncertain performance of hydrogen turbine
- Need to sustain / expand economic incentives

Oxyfuel Combustion



- **Applicable to new and existing plants**

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Oxyfuel Combustion Development Status

- Doosan Babcock
  - 40 MW_{th} pilot tests underway in Scotland
- Babcock & Wilcox
  - 30 MW_{th} pilot tests underway in Ohio
- Vattenfall
  - 30 MW_{th} pilot plant operating in Germany
- CS Energy
  - 30 MW_e Callide Oxyfuel Project in Australia (2011)
- Various larger-scale demonstrations proposed or in development
  - Vattenfall Janschwalde – Germany (250 MW_e)
  - KOSEP/KEPRI Youngdong – South Korea (100 MW_e)
  - Black Hills Corporation – Wyoming (100 MW_e)
  - Holland Board of Public Works – Michigan (78 MW_e)
  - Jamestown Board of Public Utilities – New York (50 MW_e)

http://www.babcock.com/about/history.html

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Oxyfuel Combustion Challenges / Uncertainties

- Large energy requirements for cryogenic air separation
  - Energy penalty similar to or slightly less than post-combustion amine scrubbing
  - Novel technologies such as oxygen transport membrane (OTM), ceramic autothermal recovery (CAR) being researched to reduce energy requirement
- Combustion characteristics / temperature control
  - CO_2 recycle
  - Fluidized beds
- Air in-leakage (especially for retrofits)
- Corrosion
- CO_2 purity requirements
  - Is additional polishing required?

Emerging CO_2 Capture Technologies

Post-Combustion Capture

- Gas absorption membranes
- Gas separation membranes
- Solid chemical absorbents
  - Amine-impregnated sorbents
  - Na_2CO_3
  - CaO
- PFBC with K_2CO_3 scrubbing
- Piperazine-promoted K_2CO_3 scrubbing
- Ionic liquids
- Metal organic frameworks
- Enzymes (e.g., carbonic anhydrase)

Objectives are to reduce the energy penalty, cost, and footprint associated with CO_2 capture systems

Pre-Combustion Capture

- Gas separation membranes
  - Polymer – e.g., polybenzimidazole (PBI)
  - Immobilized liquid membranes (ILMs)
  - Palladium alloys
  - Group IV-VB elements
  - Hydrotalcite-deposited ceramic
- Membrane water-gas shift reactor
- Solid chemical absorbents
  - CaO
  - Li_4SiO_4

Oxyfuel Combustion

- Oxygen and ion transport membranes
- Ceramic autothermal recovery
- Chemical looping combustion

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CO_2 Transportation and Sequestration

CO_2 Transportation

Existing CO_2 Pipeline Infrastructure in the U.S.

Source: http://www.europeanenergyforum.eu/archives/european-energy-forum/environmental-matters/

<u>Existing CO_2 Pipelines</u>

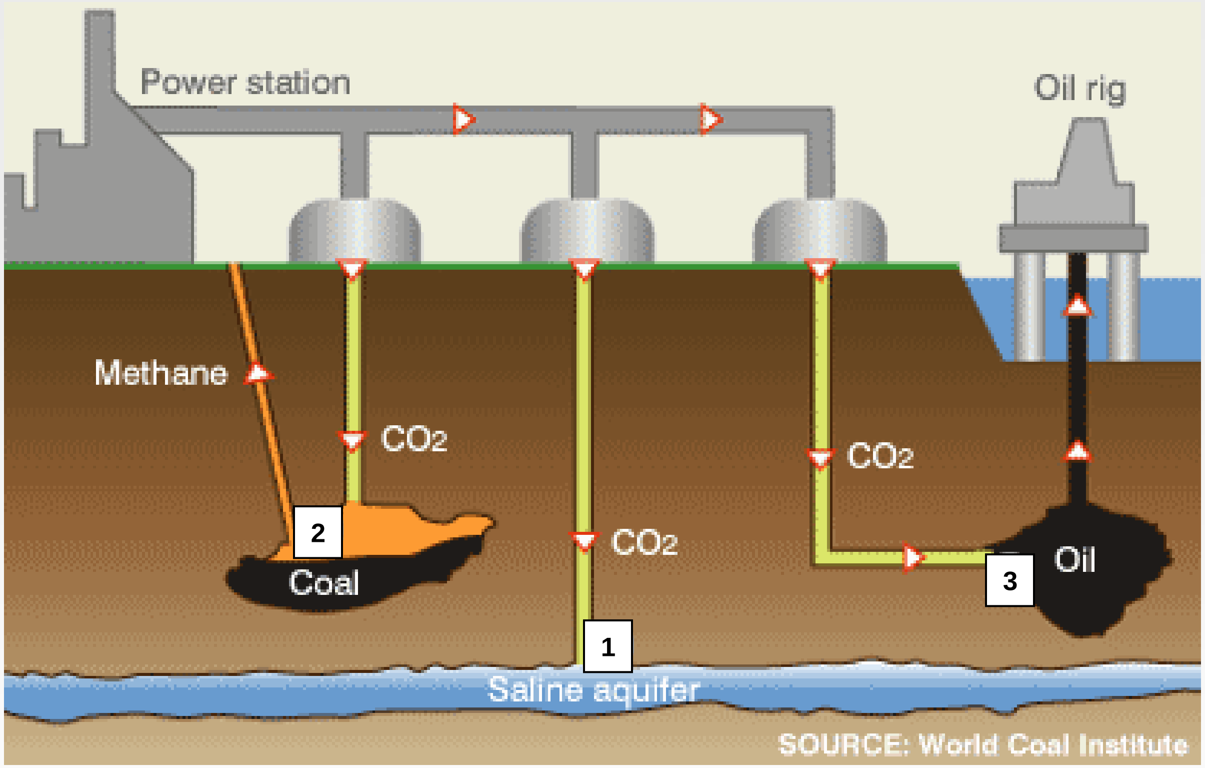
3,900 miles

<u>Existing Natural Gas Pipelines</u>

305,000 miles

- CCS may require construction of 11,000 – 23,000 miles of CO_2 pipeline by 2050 (Dooley et al., 2009)
- Challenges are manageable
  - Siting, permitting, liability, impurity specifications, etc.

Options for Geologic CO_2 Sequestration



1. Saline formations
2. Unmineable coal seams
3. Oil and gas reservoirs

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Estimated North American CO_2 Storage Potential

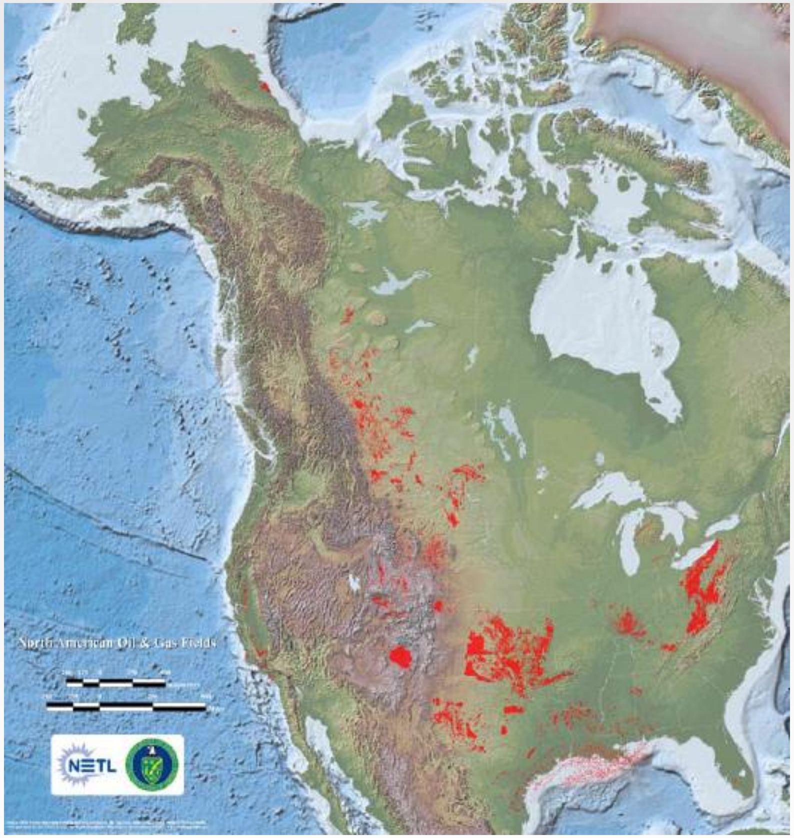
	Low Estimate (billion tonnes)	High Estimate (billion tonnes)
Saline Formations	3,300	12,600
Unmineable Coal Seams	160	180
Oil and Gas Reservoirs	140	140

Source: 2008 Carbon Sequestration Atlas of the United States and Canada

- We have hundreds of years of geologic CO_2 storage potential at our current CO_2 emission rate of ~6 billion tonnes per year
- Carbon sequestration demonstrations should focus primarily on saline formations

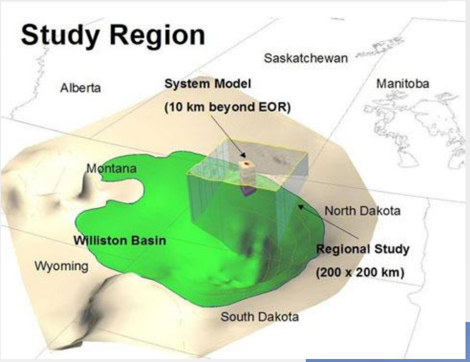
Oil and Gas Reservoirs

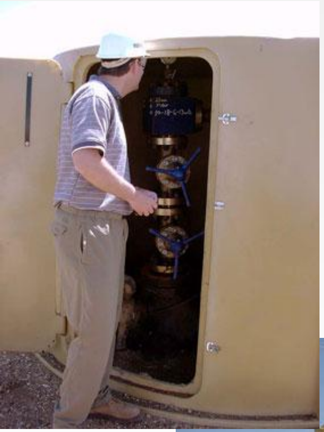
- Have held oil and gas for millions of years (consist of permeable rock beneath caprock)
- CO_2 is used commercially in enhanced oil recovery (EOR) to increase oil production by 10-15%
- 20-50 million tonnes of CO_2 used for EOR in the U.S. each year
- Current work focused on increasing the amount of CO_2 that remains sequestered after EOR injection
- Enhanced gas recovery also possible



Mature technology that provides experience and early opportunities for CO_2 sequestration with favorable economics, but limited capacity.

Weyburn-Midale CO_2 Project





- Project began in September 2000
- About 8,000 tonne/day CO_2 captured from Great Plains Synfuels Plant in Beulah, North Dakota
- Transported via 320 km pipeline to Weyburn, Saskatchewan, Canada
- CO_2 is used for EOR in the Weyburn and Midale oil fields; project aims to store almost all of the injected CO_2
- Projected impact over 30-year project life:
  - > 40 million tonnes CO_2 stored
  - 222 million barrels incremental oil production
- Project includes extensive monitoring program to address long-term fate and security of stored CO_2

Source: http://www.ptrc.ca/

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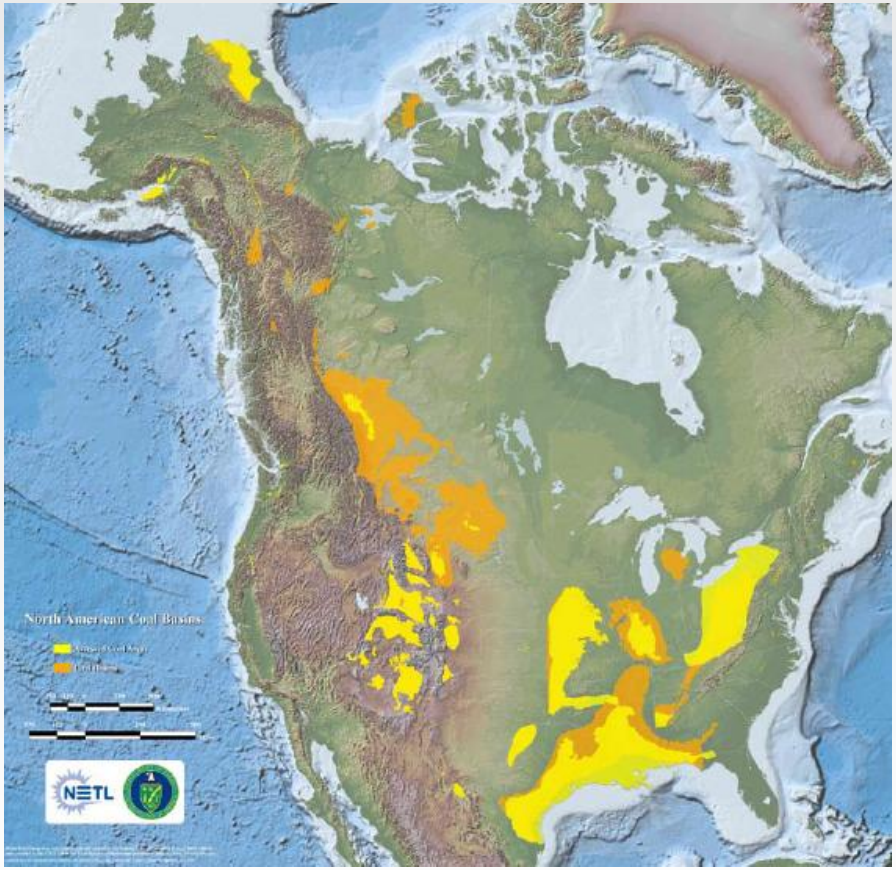
Unmineable Coal Seams

- Not economically mineable because of depth, thickness, or other reasons
- CO_2 is adsorbed onto pore surfaces
- CO_2 can displace methane, leading to enhanced coalbed methane recovery
- Challenges
  - Limited experience
  - Coal seams are shallow relative to other reservoirs
  - Coal swelling



Potential for CCS with some economic offset, but opportunities are limited and further development and demonstration are needed

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CONSOL's CO_2 Sequestration / ECBM Project

- About 25 tonnes/day of CO_2 injected in gaseous state into Upper Freeport coal seam (385 m deep) in northern West Virginia
- CO_2 injection used to promote enhanced coal bed methane production
- Horizontal drilling used to minimize coal swelling issues
- CO_2 injection began in September 2009
- 20,000 tonnes of CO_2 will be injected over project life
- Thorough monitoring program being conducted to verify permanence of injected CO_2

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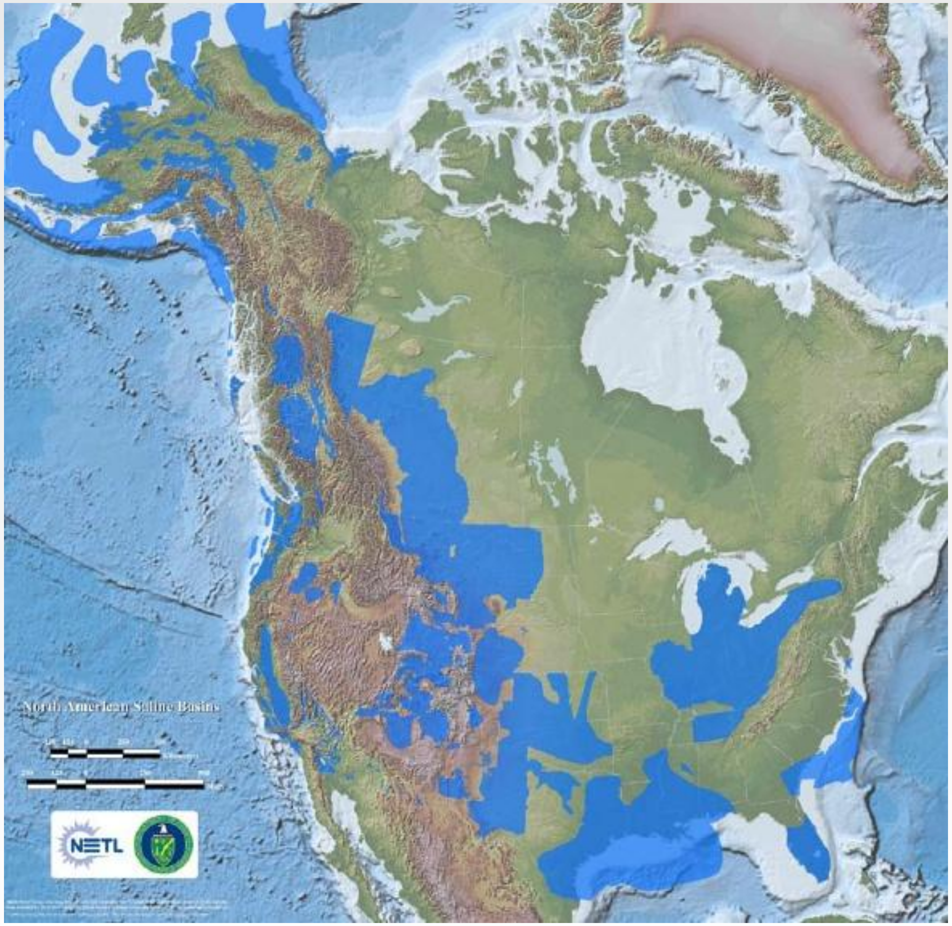
Deep Saline Formations

- Layers of porous sedimentary rock saturated with brine
- CO_2 can be trapped physically or chemically
- Very extensive, huge CO_2 storage potential
- Less well-characterized than oil/gas reservoirs and coal seams



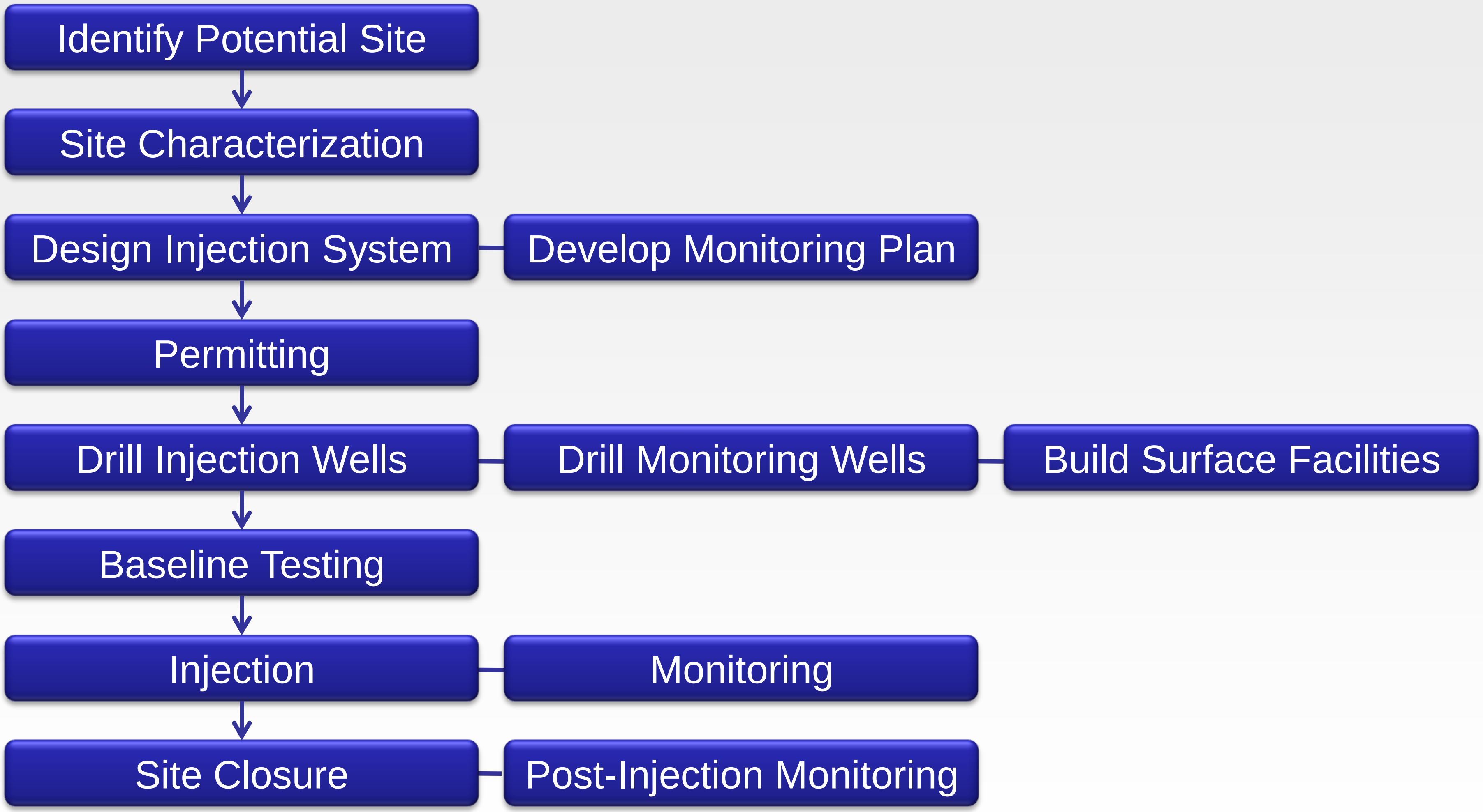
Widespread opportunity for CO_2 sequestration, with huge potential storage capacity, but more demonstrations needed at commercially relevant scale

Sleipner Project

Source: http://www.netl.doe.gov/technologies/coalpower/turbines/refshelf/asme/asmeturbo07STATOILCO2.pdf

- Project began in 1996
- Located in the North Sea, about 250 km off the coast of Norway
- About 1 million tonne/year CO_2 captured from Statoil's Sleipner West gas field using conventional amine system
- CO_2 is injected into a saline aquifer (Utsira) more than 800 m below the seabed for permanent storage
- Almost 11 million tonnes of CO_2 sequestered through the end of 2008
- About 20 million tonnes of CO_2 will be stored over the project life
- Seismic testing used to monitor the fate and transport of the injected CO_2

Stages of a CO_2 Sequestration Project



CO_2 Sequestration Site Selection Criteria

- Capacity (porosity and thickness)
- Injectivity (permeability)
- Presence and robustness of caprock / confining unit
  - Faults, fractures, and wells can provide leakage pathways
- Stability of geologic environment
- Protection of underground sources of drinking water
- Presence of fossil fuels
- Site accessibility

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CO_2 Monitoring Techniques

- Introduced and natural tracers
- Water composition
- Subsurface pressure
- Well logs
- Time-lapse 3D seismic imaging
- Vertical seismic profiling
- Crosswell seismic imaging
- Passive seismic monitoring
- Electrical/electromagnetic techniques
- Time-lapse gravity measurements
- Land surface deformation
- Visible/infrared imaging
- CO_2 land surface flux monitoring
- Soil gas sampling

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CO_2 Sequestration – Challenges

Technical Uncertainties

- Storage capacity
- Permanence
- Injectivity
- Lateral plume migration
- Best practices for:
  - Site characterization
  - Monitoring
  - Modeling

Legal/Social Uncertainties

- Permitting requirements still being developed
- Pore space ownership
- Long-term liability for the sequestered CO_2
- Public acceptance
  - "NUMBY"
  - Public opinion of field tests ranges from strong support to fierce opposition

Resolving legal/social uncertainties is just as important as resolving technical uncertainties

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DOE Regional Carbon Sequestration Partnerships

More than 350 participating organizations

Characterization Phase

- 2003-2005
- Identify CCS opportunities
- $16M DOE funds

Validation Phase

- 2005-2010
- Small-scale field tests
- $120M DOE funds

Development Phase

- 2008-2017
- Large-volume demonstrations
- ~$500M DOE funds

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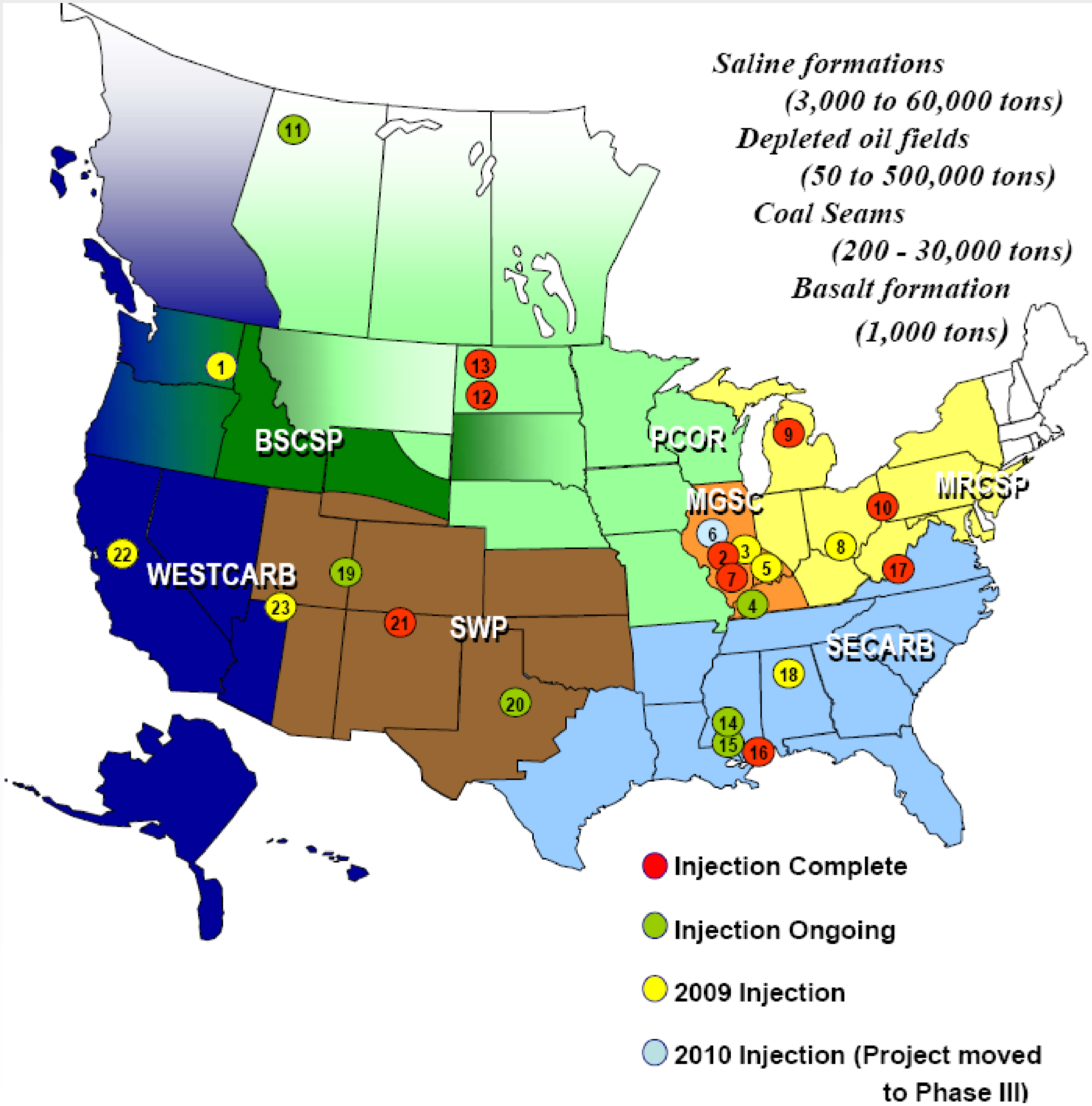
DOE Regional Carbon Sequestration Partnerships

Validation Phase Geologic Field Tests



Source: Plasynski, S. Sequestration Program Overview, July 21, 2009

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DOE Regional Carbon Sequestration Partnerships

Development Phase Large-Volume Geologic Tests

RCSP	Geologic Formation	Depth (ft)	CO_2 Source	Total CO_2 Injection (tonnes)
BSCSP	Nugget Sandstone (saline)	11,000	He / Natural Gas Processing Plant	2,700,000
MGSC	Mt. Simon Sandstone – Illinois Basin (saline)	5,000-7,000	Ethanol Plant	1,000,000
MRCSP	Mt. Simon Sandstone – Cincinnati Arch (saline)	3,000-3,600	Ethanol Plant	1,000,000
PCOR	Williston Basin (oil)	12,000	Coal-Fired Power Plant	5,000,000
PCOR	Alberta Basin Sandstone (saline)	5,000	Natural Gas Processing Plant	5,000,000
SECARB	Lower Tuscaloosa Sandstone (saline)	10,500	Natural Source	1,500,000
SECARB	Tuscaloosa Massive Sand Unit (saline)	9,500	Coal-Fired Power Plant	400,000
SWP	Farnham Dome Sandstones (saline)	5,000+	Natural Source	2,900,000
WESTCARB	San Joaquin Basin Sandstone (saline)	7,000+	Oxy-Fuel Power Plant	1,000,000

Injection to begin in 2009-2011

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Integrated CCS Demos

AEP Mountaineer CCS Product Validation Facility

Source: http://www.power.alstom.com/home/about_us/clean_power_today/carbon_capture_storage_ccs/pilots_and_demonstrations/50490.EN.php

- 20 MW_e slipstream
- 90% CO_2 capture with Alstom's Chilled Ammonia Process
- CO_2 sequestered into one of two saline aquifers ~8,000 ft below site
- More than 100,000 tonne/y of CO_2
- Injection began October 1, 2009

- First integrated demonstration of CO_2 capture from a coal-fired power plant and geologic sequestration in a saline formation
- 235 MW_e demonstration proposed to DOE
  - Total project cost estimated at $668 million
  - Equipment expected to occupy 6-7 acres of land
- Targeted energy penalty: 15-22%

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FutureGen

- 275 MW_e IGCC
- Mattoon, Illinois
- 90% pre-combustion CO_2 capture
- CO_2 sequestered in Mt. Simon Sandstone (saline)
- 1,000,000 tonne/y CO_2

- Project funded by DOE and FutureGen Alliance
- Total estimated cost ~$2 billion
- Preliminary design, cost estimate, funding plan development, and subsurface characterization underway
- Go/No-Go decision in 2010

Clean Coal Power Initiative - Round 3

- Up to $1.4 billion of DOE funding available (50% recipient cost share)
- Project requirements
  - Coal-fired power plants (at least 55% coal input and at least 50% electricity output)
  - At least 50% CO_2 capture efficiency, with progress toward 90%
  - At least 300,000 ton/y CO_2 captured and sequestered or put to beneficial reuse
- Two projects already selected (July 1, 2009)
  - Basin Electric Power Cooperative, North Dakota - $100 million in DOE funding (120 MW_e, post-combustion capture, EOR)
  - Hydrogen Energy International LLC, California - $308 million in DOE funding (250 MW_e IGCC with pre-combustion capture, EOR)
- About $1 billion still available for projects submitted under second solicitation closing date (August 24, 2009)

Carbon Capture and Sequestration from Industrial Sources

- Up to $1.3 billion of DOE funding available
- Project requirements
  - Large-scale CCS from industrial sources (e.g., cement plants, refineries, chemical plants, manufacturing facilities, etc.)
  - Coal-fired power plants (>55% coal, >50% electric power output) are ineligible
  - Progress toward 75% capture and sequestration of CO_2 from treated stream
  - Goal of 1 million ton/y CO_2 captured and sequestered by 2015
- Twelve projects selected on October 2, 2009, for seven-month project definition phase
- Subset of these projects will be selected for continuation in 2010

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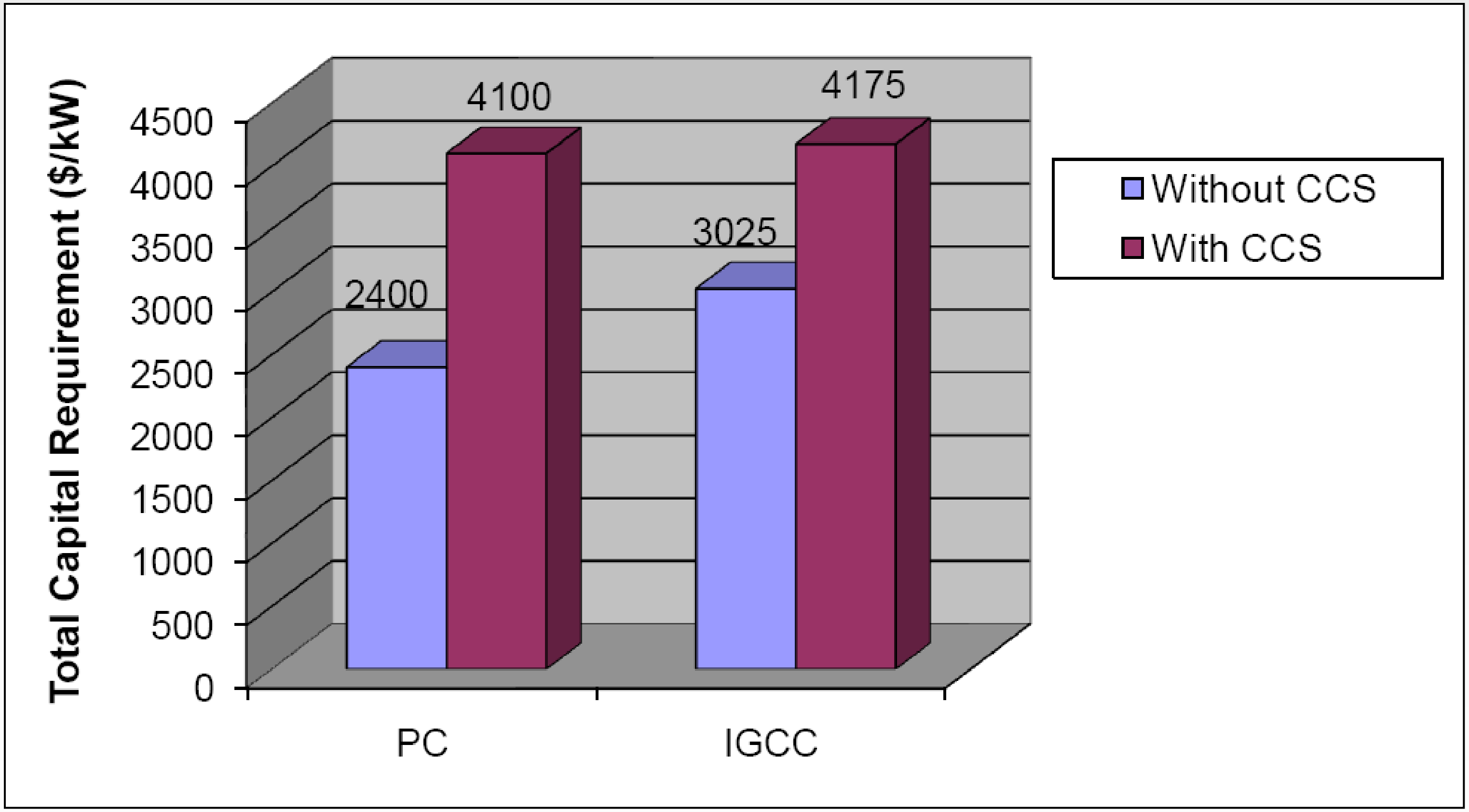
When and at What Cost?

Capital Costs - New Power Plants

Source: EPRI – Holt and Booras (2008)



Capital cost for new PC or IGCC plant with capture is 70-75% greater than cost for new PC plant without capture

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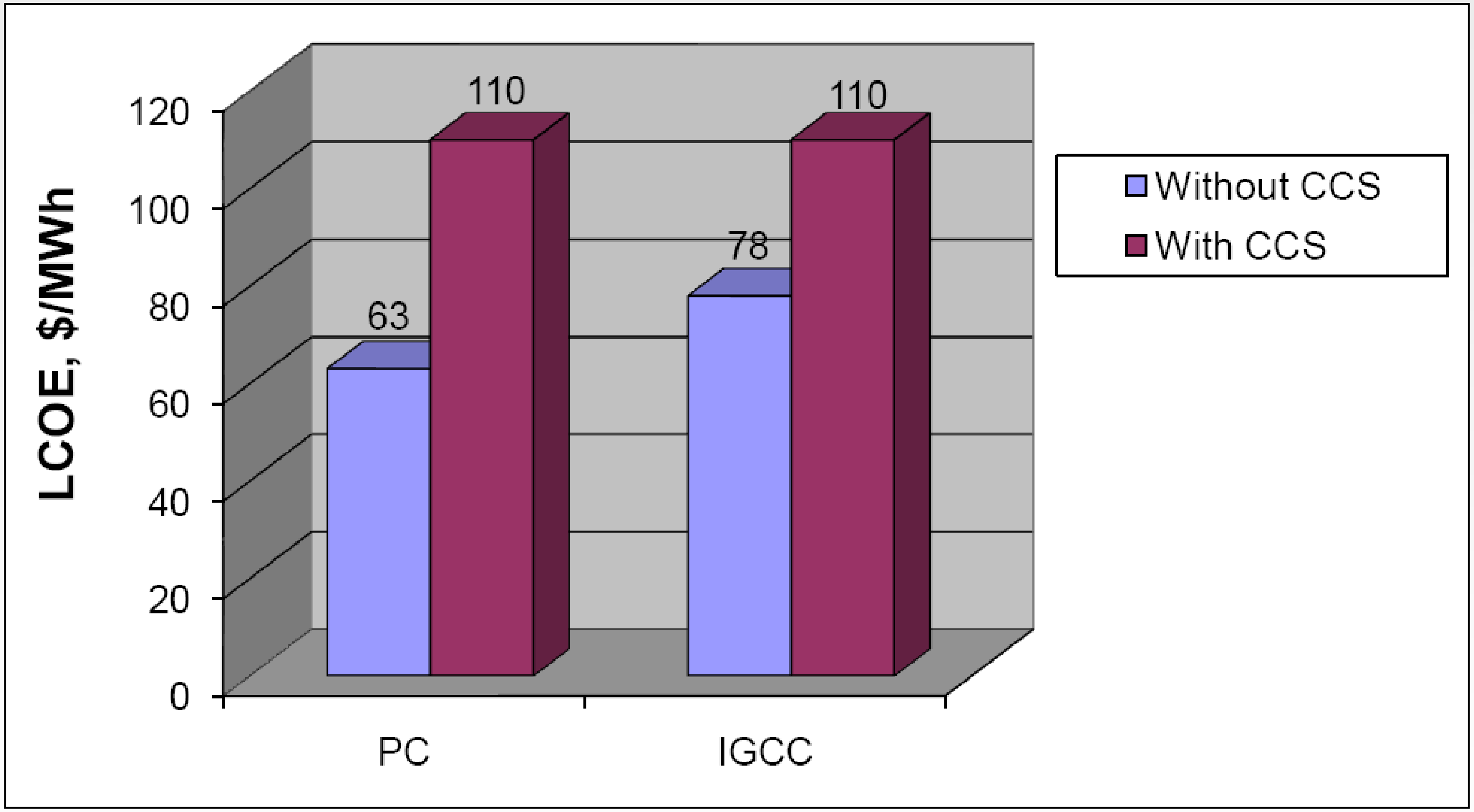
Levelized COE - New Power Plants

Source: EPRI – Holt and Booras (2008)



Cost of electricity for new PC or IGCC plant with capture is ~75% more than COE for new PC plant without capture

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Carbon Capture Retrofit Costs – Coal-Fired Plant

Source: EPRI – Holt and Booras (2008)

	Existing PC No Capture	MEA Retrofit for Post-Combustion Capture
Net generation (MW)	600	-29% → 425
Capital cost ($/kW)		900
COE ($/MWh)	20	+210% → 62
Replacement power (MW)		175
Capital cost of replacement power via PC or IGCC + CCS ($/kW)		+280% 4100
Cost of replacement power PC or IGCC + CCS ($/MWh)		110
COE including replacement power ($/MWh)		76
$/tonne of CO_2 avoided		74

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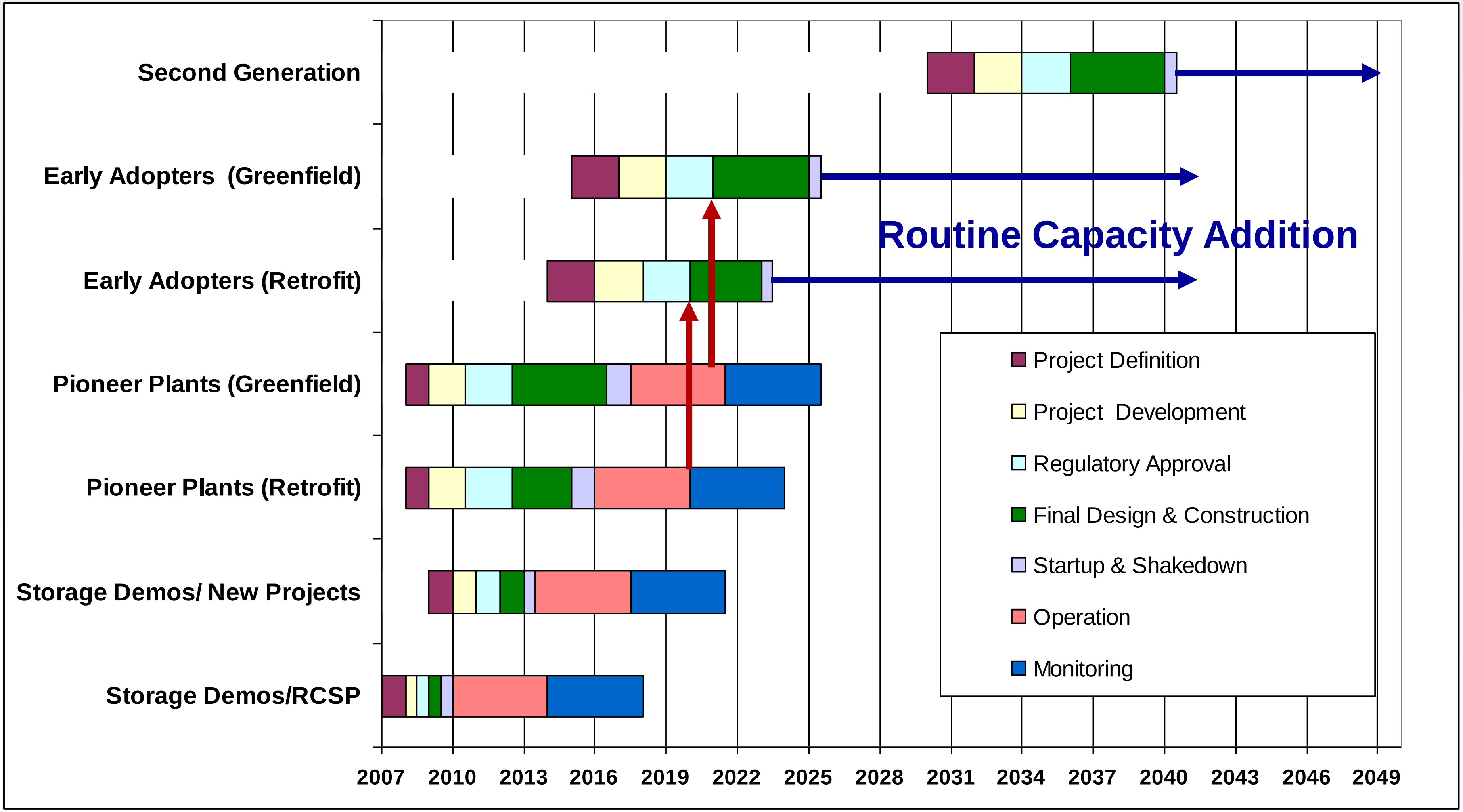
CCS Timeline for Coal-Fired Plants



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The Bottom Line

What Do We Know?

- Widespread deployment of CCS from coal-fired power plants is essential to meet the level of GHG reductions being contemplated in the U.S. and worldwide
- CO_2 reductions in the U.S. will have little impact without similar reductions from developing countries (e.g., China, India)
- Commercial technologies are technically capable of capturing CO_2 from coal-fired power plants, but these are expensive and consume a lot of energy
- Retrofits will be important (space constraints, integration)
- CO_2 sequestration looks promising, but we need more/bigger/longer tests, public outreach, and resolution of legal and regulatory issues
- Integrated CCS demos from coal-fired power plants are just now beginning at small scale, and widespread commercial deployment likely will not begin until after 2025
- Several emerging technologies show potential for improving the economics of CCS

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Where Do We Go From Here?

- Integrated CCS Demos at Coal-Fired Power Plants
  - Large/commercial scale
  - New and retrofit
  - Variety of capture technologies (post-, pre-, and oxy-combustion)
  - Focus on saline
  - Aggressive timeline and funding
- Resolution of legal and regulatory issues
  - Permitting
  - Pore space ownership
  - Long-term liability
- Effective public education
- Development of improved capture technologies
  - Solvents/sorbents with low regeneration energy
  - Membranes capable of withstanding flue or fuel gas conditions
  - Advanced air separation technologies

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The Challenge

Today's
Best Available CCS Technologies

> 90% capture
75% increase in COE
Unconfirmed storage permanence

2009

DOE Goal
Commercial CCS Technologies

> 90% capture
< 10-35% increase in COE
>99% storage permanence

2020

We have a lot of work to do,
and we need a lot of money!