Fourth Annual Conference on Carbon Capture & Sequestration

Developing Potential Paths Forward Based on the Knowledge, Science and Experience to Date

Separation and Capture

Summary of Phase I Capture and Separation Activities of the Regional Carbon Sequestration Partnerships Program

José D. Figueroa
U.S. DoE National Energy Technology Laboratory

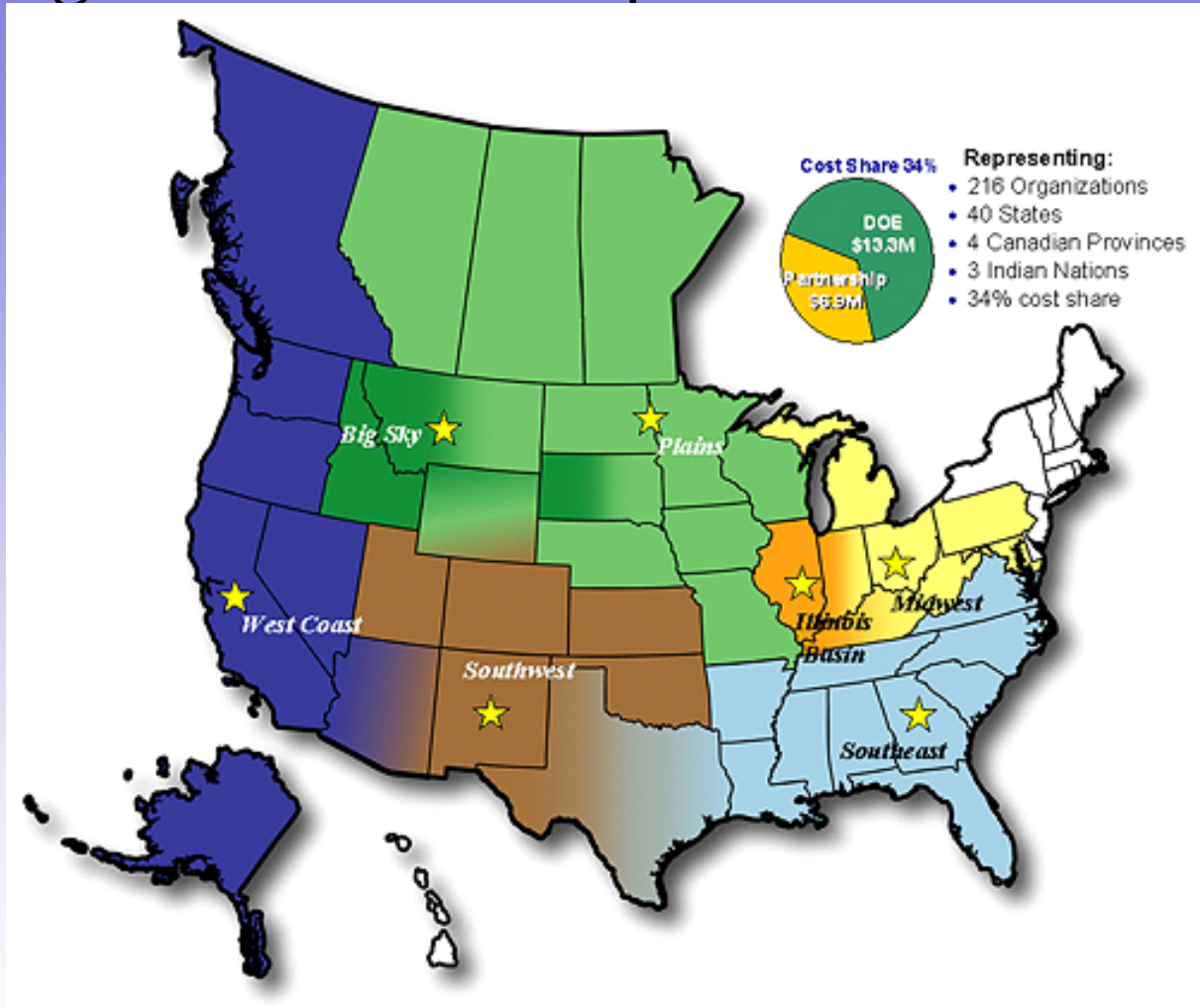
May 2-5, 2005, Hilton Alexandria Mark Center, Alexandria Virginia

Outline

- Overview of Regional Partnership and Program Phases
- Regional CO_2 emission sources
- Techno-Economic results from Phase I
- RP Capture Working Group Workshop
  - Conclusions
  - RP Proposed Phase II Action Items
- Acknowledgements

RP means Regional Partnerships

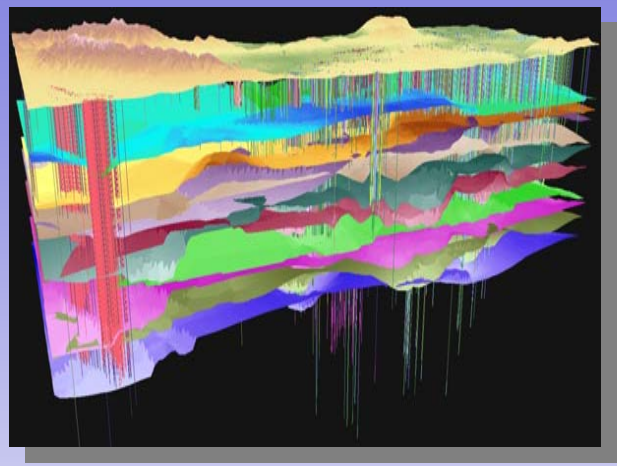
Seven Regional Carbon Sequestration Partnerships



Two-Phased Approach

Phase I (Characterization)

- **7 Partnerships (40 states)**
- **24 months (2003-2005)**
- **~$1.6 to 2.3 M DOE funding / project**
- **Overall ~ 34% cost share**
- **2 exceed 50% cost share**



Phase II (Field Validation Tests)

- **$100 million**
- **4 years (2005-2009)**
- **Full and Open Competition**
- **~$18 million DOE funding / project**
- **~ $2 to $4 M DOE funding / year / project**
- **Minimum 20% cost share**
- **Approximately 7 regions**

Regional Partnership Capture Working Group Members

Regional Partnerships:

- David Shropshire* - Big Sky
- Massoud Rostam-Abadi* - Illinois Basin (MGSC)
- Neeraj Gupta* & Bruce Sass* - MRSCP
- Melanie Jensen* - PCOR
- John Plodinec* - SECARB
- Dennis Leppin* - Southwest
- John Ruby* - WestCarb

U.S. DoE FE/NETL:

- José D. Figueroa
- Robert Wright

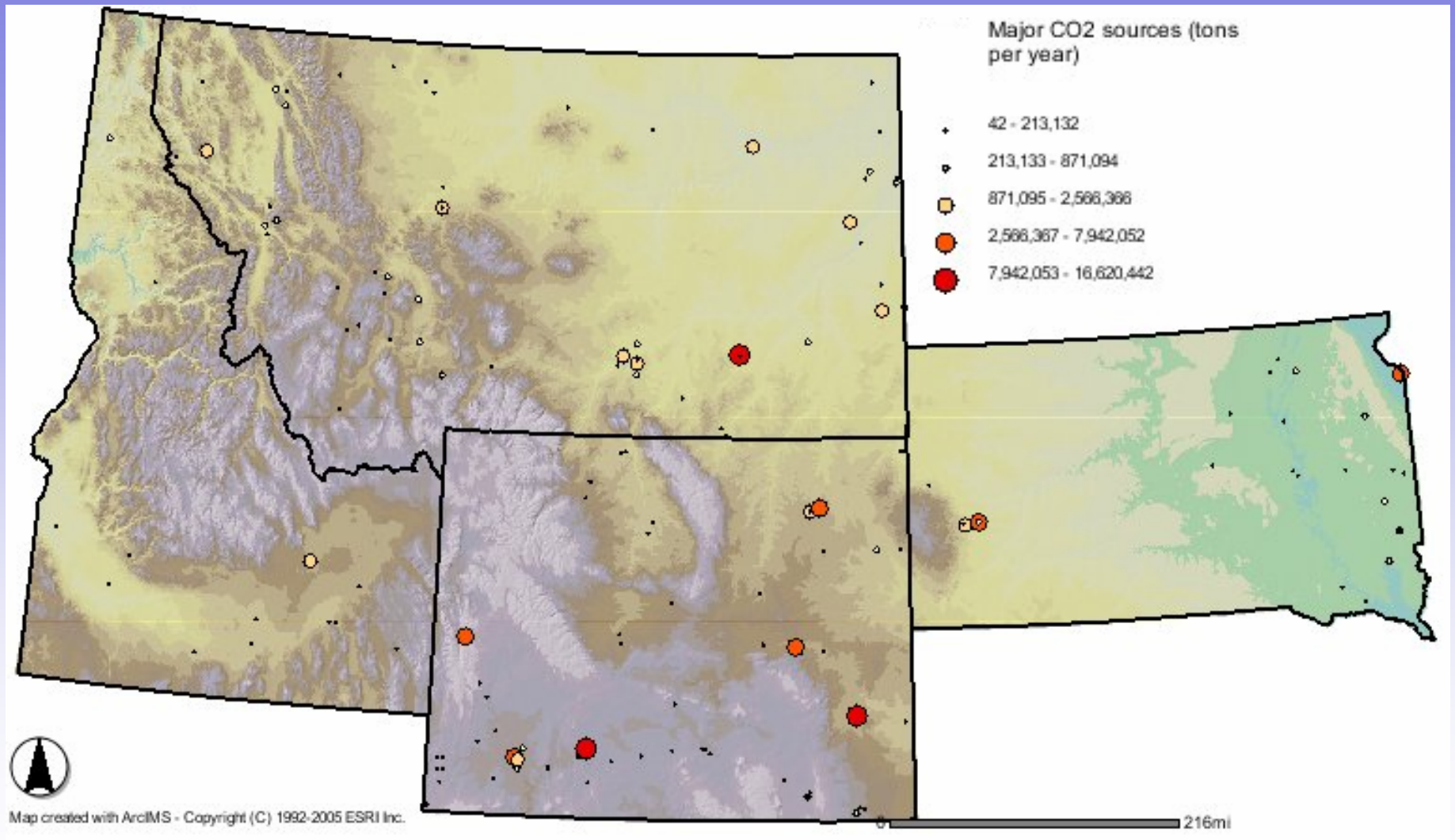
SAIC:

- Christopher Mahoney
- Ramesh Srivastava

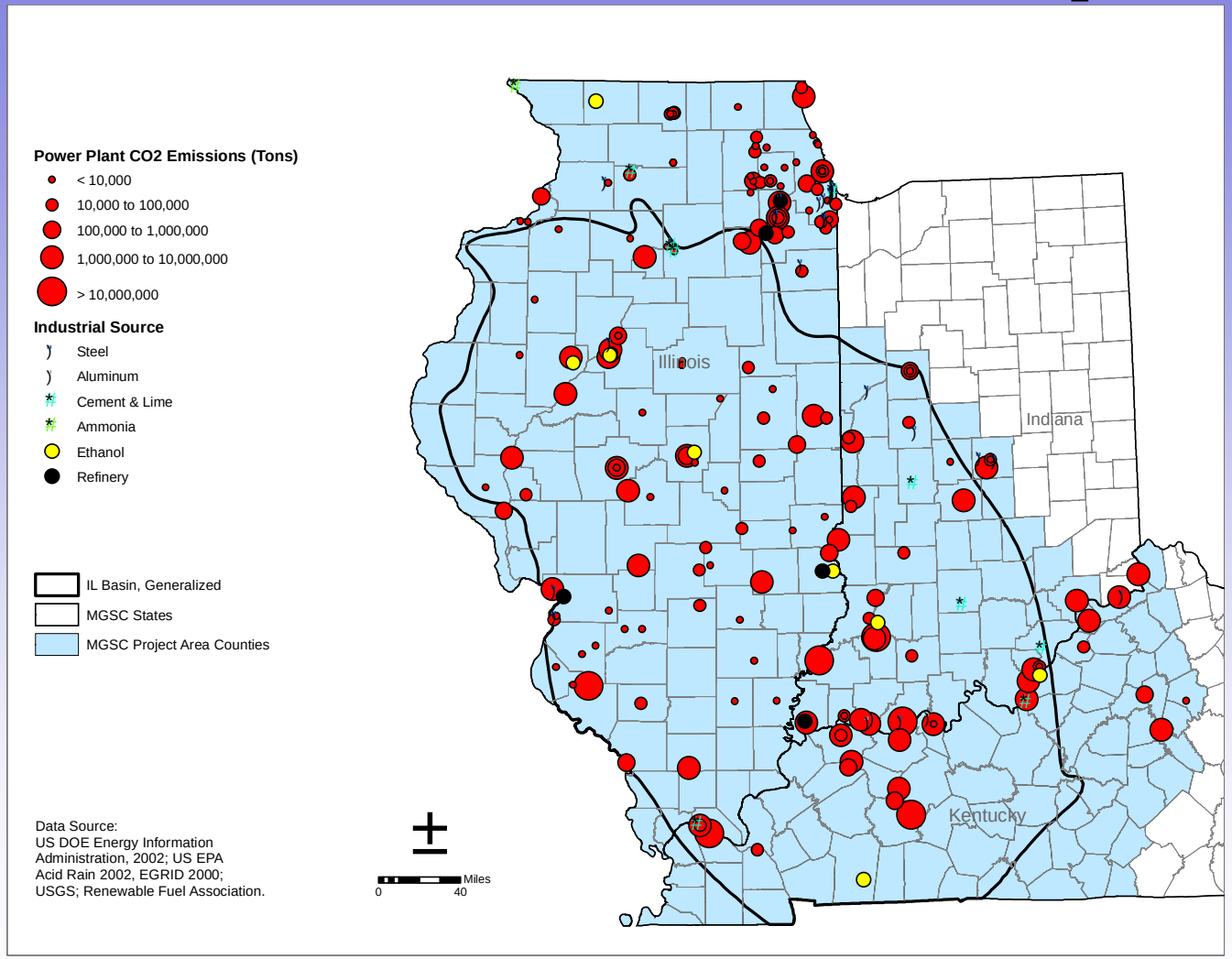
* Co-Authors

Regional CO_2 Emission Sources

Big Sky Regional CO_2 Emission Sources



Regional CO_2 Emission Sources MGSC Partnership



Total CO2 emissions in IL Basin: 283,270 kt in 2002 (11% of the U.S. totals)

Utility emissions: 92%
Non-utility point sources: 8%

Fossil fuel-fired electricity generation: 230,000 GWh (8.6% of the U.S. totals)

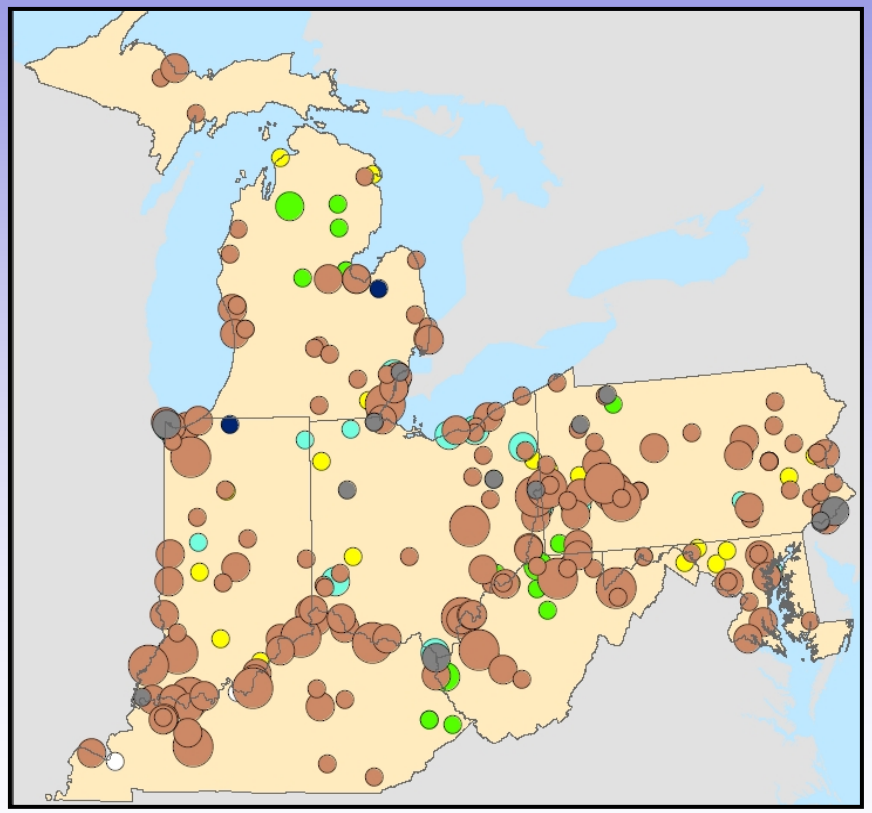
Regional CO_2 Emission Sources MRCSP

MRCSP Large CO_2 Point Sources (100+ kt CO_2/yr)

- Cement
- Ethanol
- Ethylene
- Gas processing
- Hydrogen
- Iron & steel
- Power
- Refineries

ktCO2/yr

- 100 - 2,000
- 2,000 - 10,000
- 10,000 - 20,000



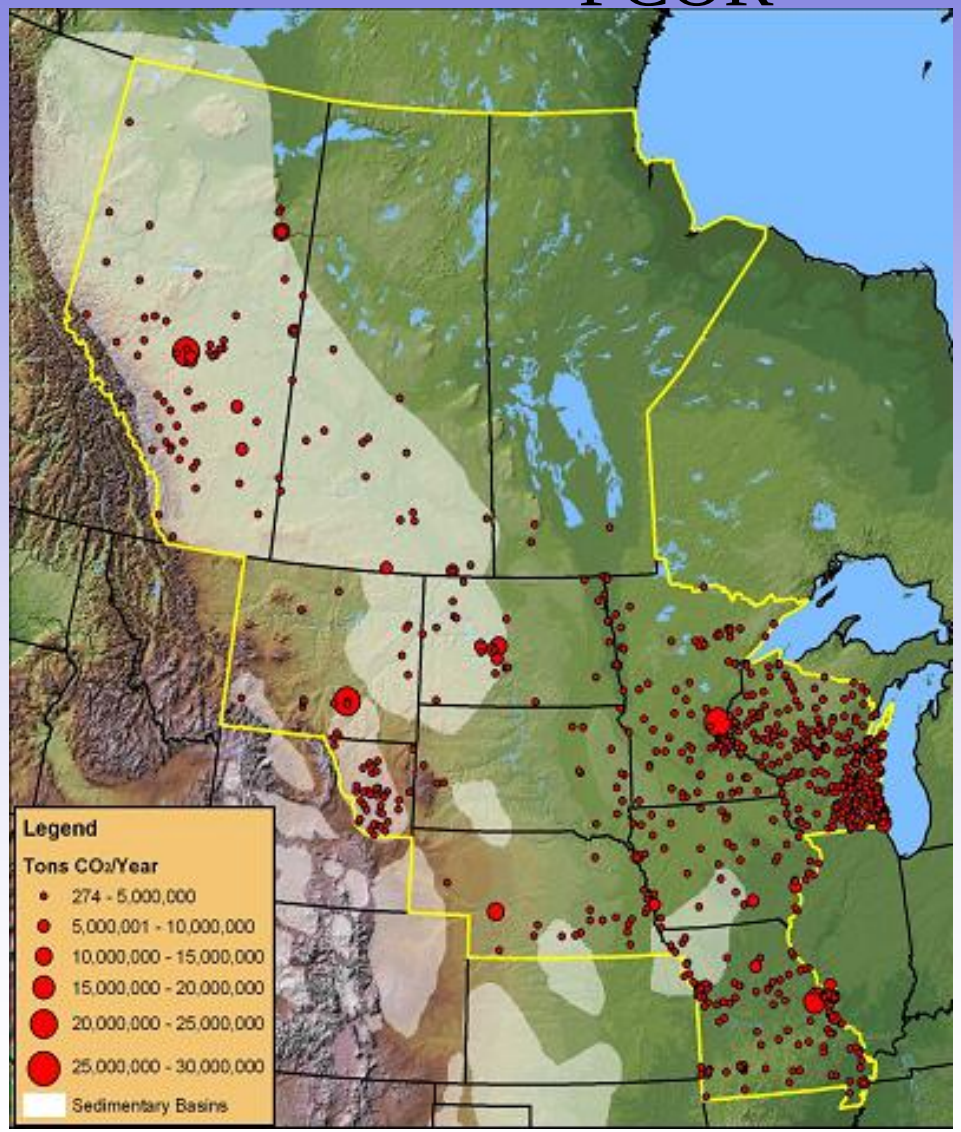
Population: 50.8 million (one in six Americans)

Gross Regional Product: $1,534 billion (16% of U.S. economy)

21.5 % of all electricity generated in the U.S.

77% of electricity generated from coal

Regional CO_2 Emissions Sources PCOR



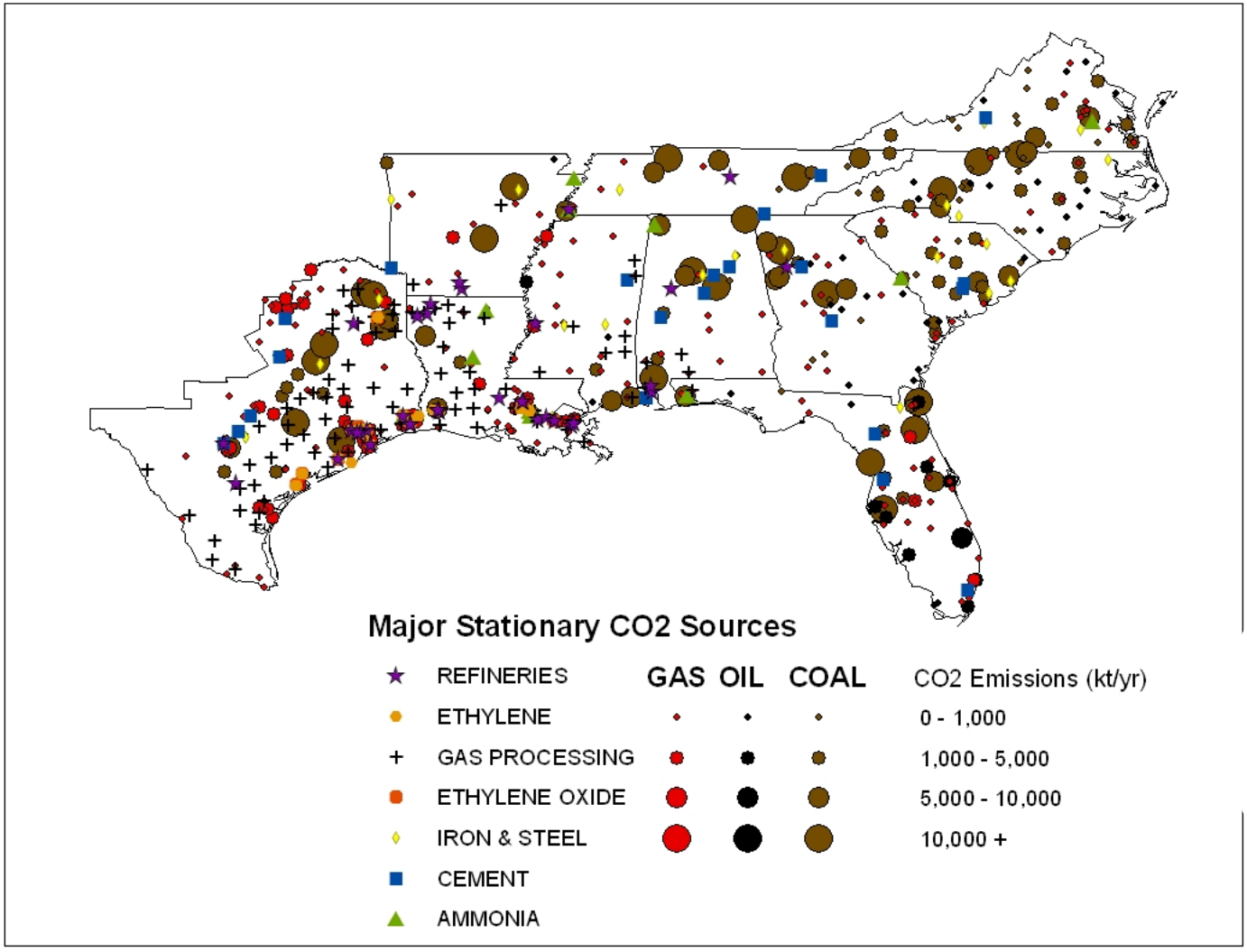
PCOR Composition:

- Six States
- Parts of 2 others
- 3 Canadian Provinces

Population:
28 million

66% of regions CO2 emissions from electric generating stations

Regional CO_2 Emissions Sources SECARB



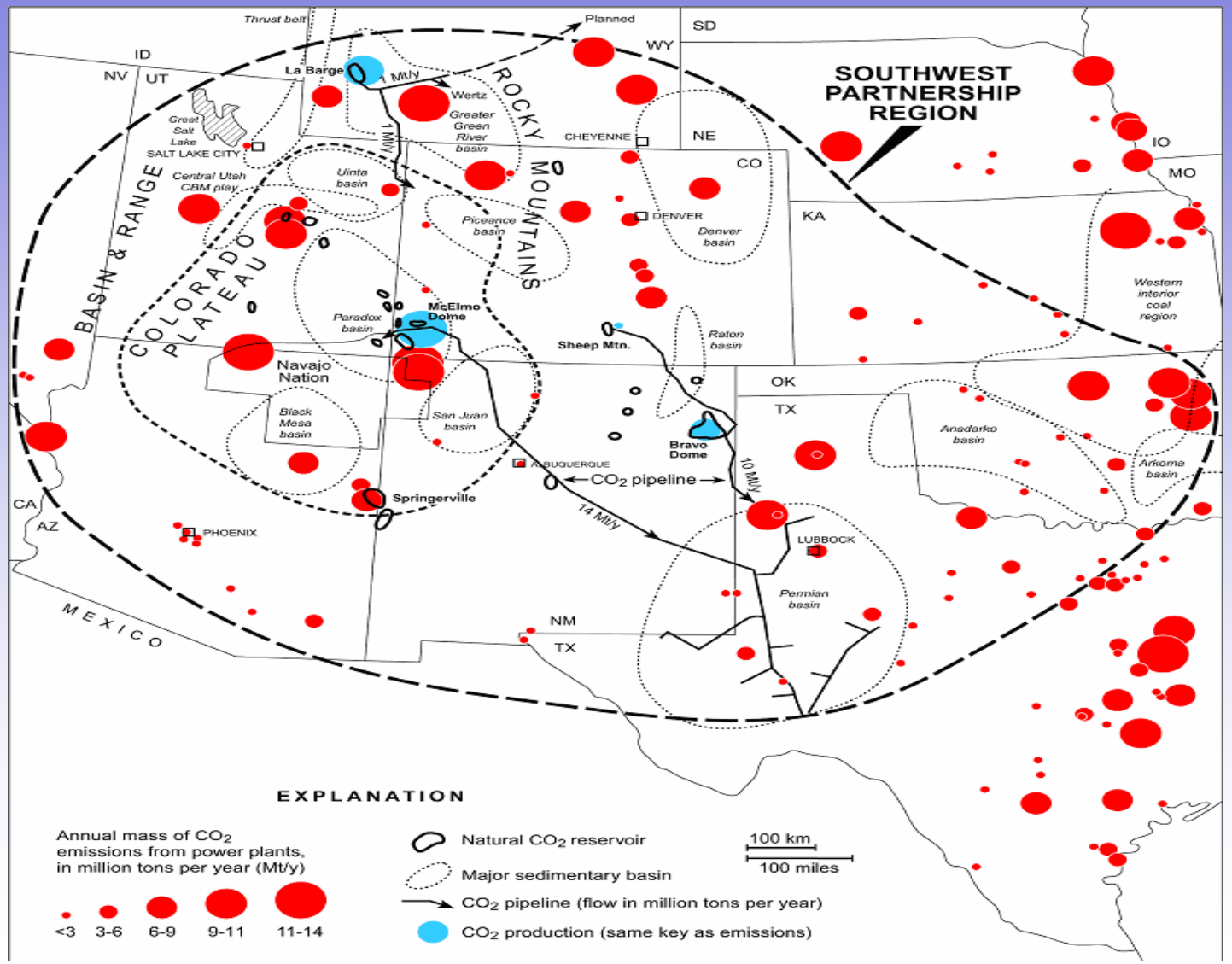
18% of Population live in SECARB

Produce 1Gt of CO_2 per year

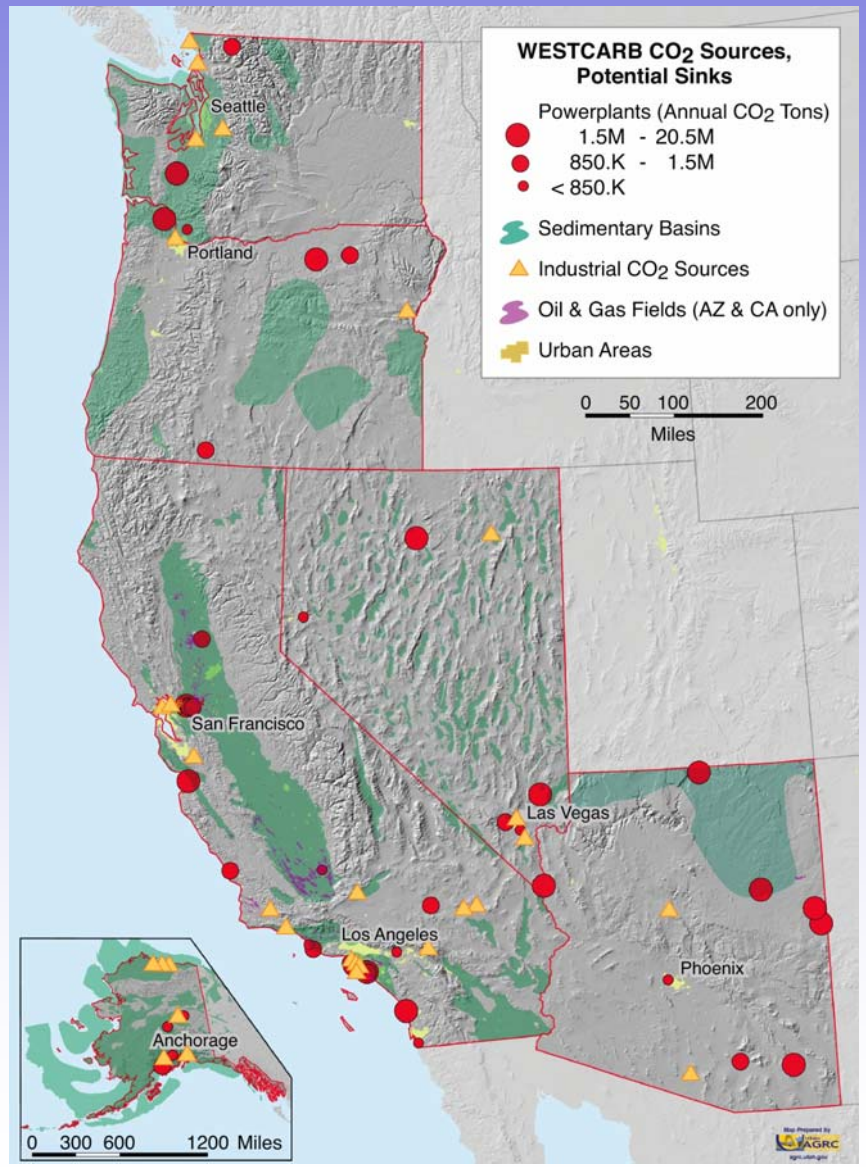
86% of CO_2 emissions from power production

Future CO_2 emission growth from ethanol and biodiesel production

Regional CO_2 Emissions Sources Southwest Partnership



Regional CO_2 Emissions Sources
WESTCARB

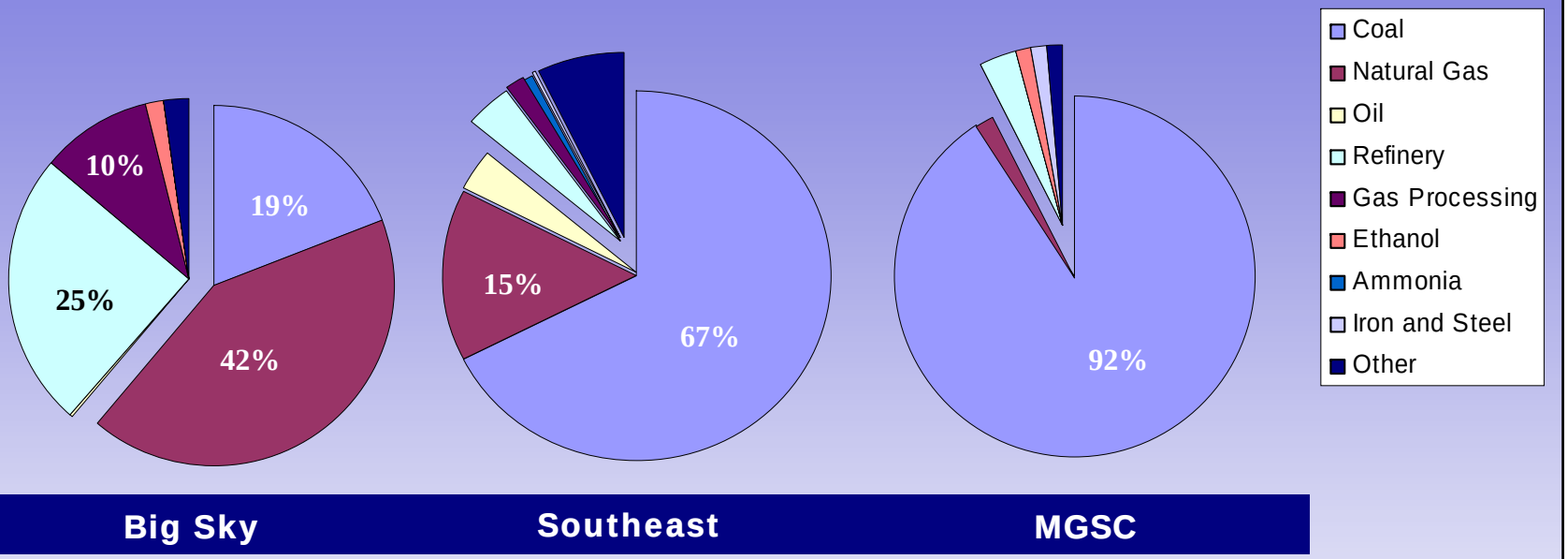


Composition:
- 5 Western States
- Alaska
- British Columbia Province

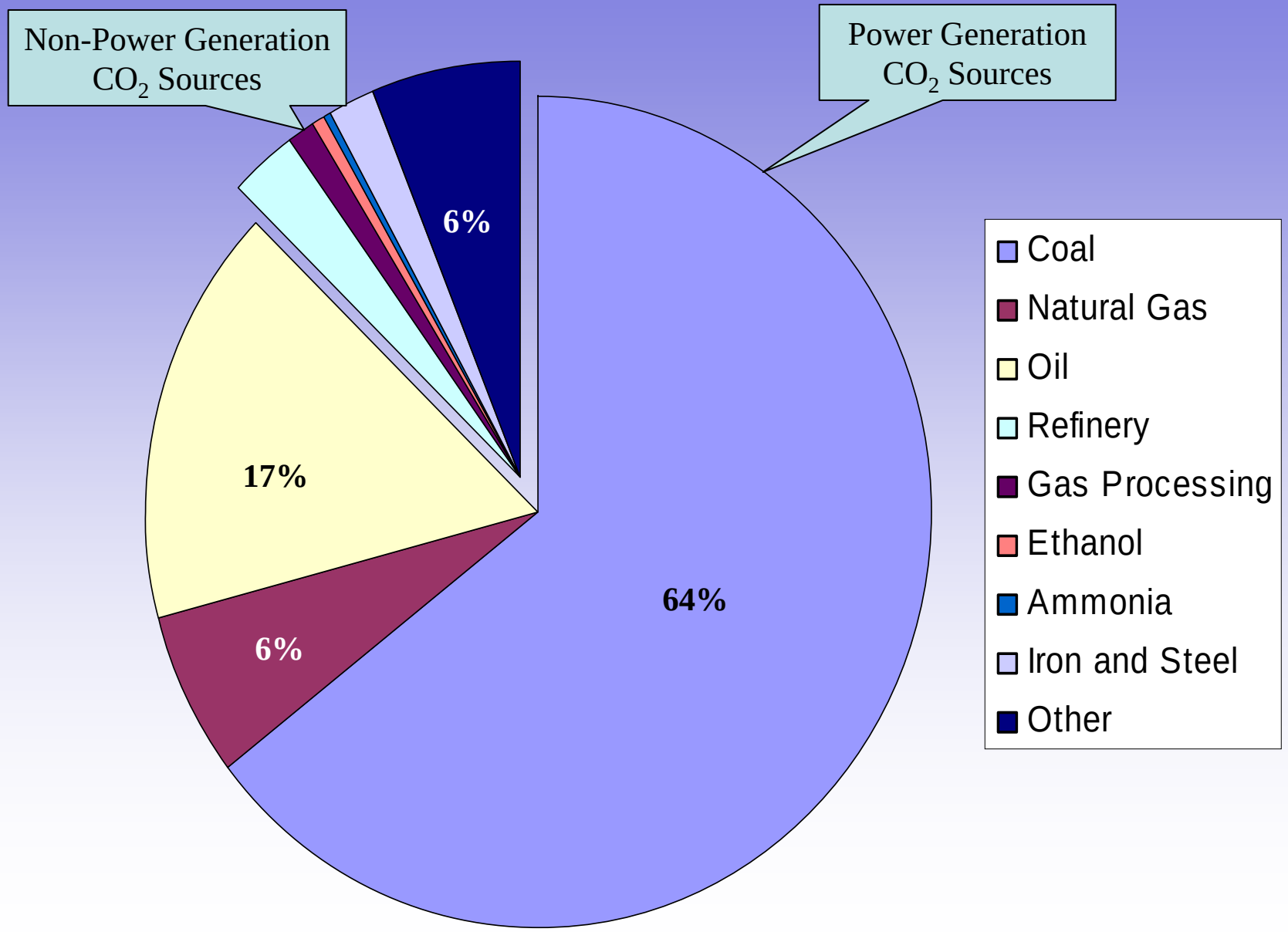
Opportunities for Enhanced Oil/Gas Recovery are initially in Alaska and California.

Regional power plants:
- Generally fired with natural gas
- Several coal-fired power plants
  - Arizona, Nevada and Washington contribute heavily.

Regional Partnership Emission Profile



Regional Partnerships Emission Profile



Techno-Economic Results from Phase I

Preliminary Matrix Assessment

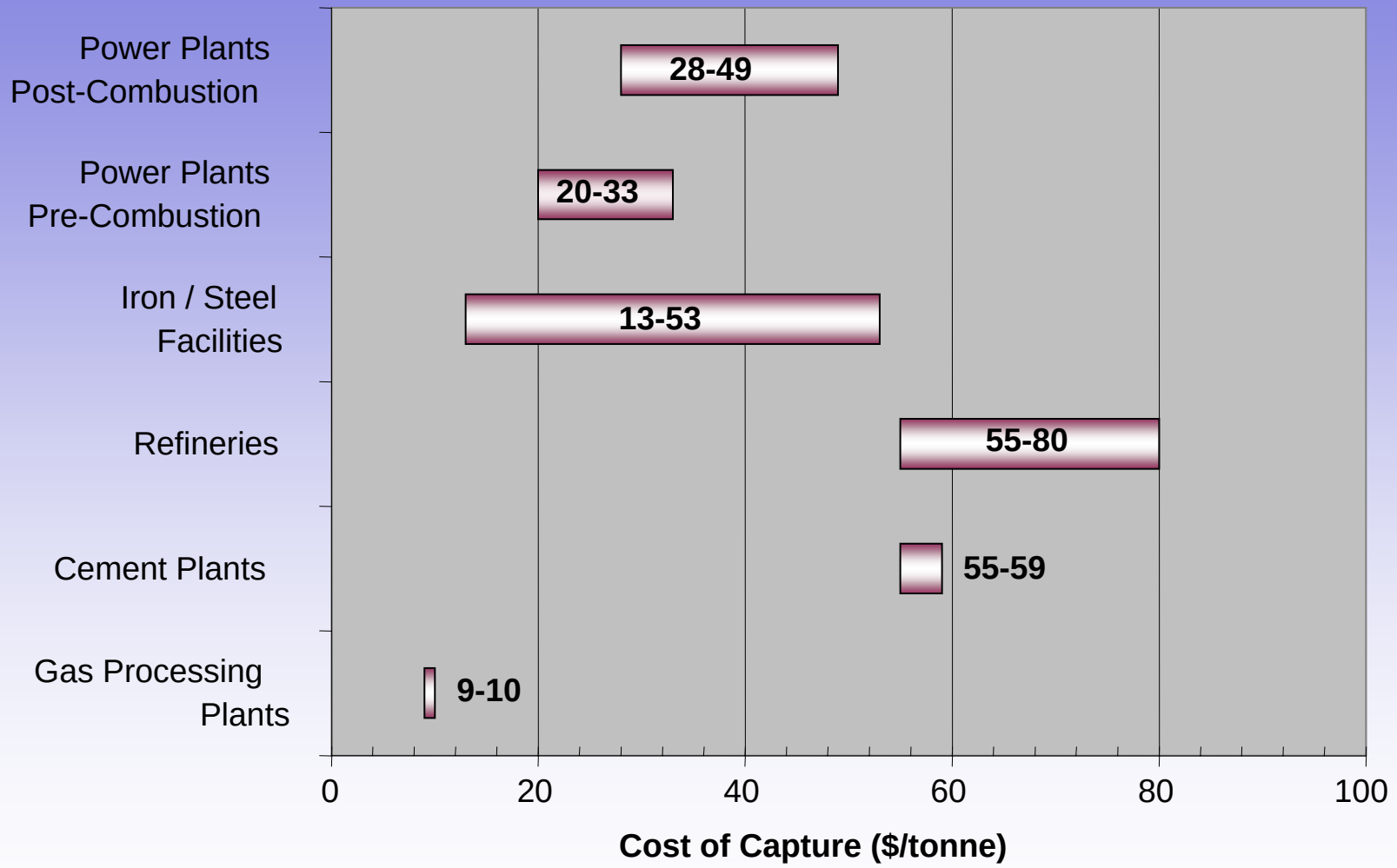
Candidate CO_2 Capture Technologies for Example Sources

Source Type	Point of Capture	Amine Scrubbing	Ammonia Scrubbing	Physical Absorption	Gas Separation Membrane	Gas Absorption Membrane	Oxyfuel + Drying/ Compression	Simple Drying /Compression
Power Plants Post Combustion	Flue Gas	1	2	--	2	2	2	--
Power Plants Pre-Combustion	Shifted Syngas	--	--	1	2	--	--	--
Iron / Steel Facilities	Blast Furnace Gas	1	--	1	2	3	--	--
Refineries	Heater/Boiler Flue Gas	1	3	--	2	3	2	--
Cement Plants	Kiln Flue Gas	1	3	--	3	3	3	--
Gas Processing Plants	Vented CO_2	--	--	--	--	--	--	1

1 –Commercially available; 2 –Actively being developed; 3 –Very early stage of R&D

Source: Midwest Partnership

Preliminary Cost Estimates for CO_2 Capture Using Best Available Technologies



(Based on literature review; includes cost of compression to pipeline pressures)

Source: Midwest Partnership

Regional Partnership
Capture Working Group Workshop

Conclusions

Capture Working Group Workshop

- March 30, 2005:
  - Hosted by Illinois Basin RCSP, ISGS, and University of Illinois
- Presentations on Phase I capture activities from all 7 Regional Partnerships
- Participation from technology developers, utilities, and a climate change expert
  - UOP, Ameren, ConocoPhillips, and University of Illinois
- Analysis of CO_2 capture technologies costs and rankings
- Developed proposed Phase II capture and separation action items for NETL consideration

Capture Working Group Workshop Conclusions

- Few commercial capture technologies currently available
- Capture is major part of total sequestration costs
- Impacts of Developing Technologies in Capture and Separation – Technologies Examined:
  - Amine Scrubbing, Alkaline Salt Scrubbing, Ammonia Scrubbing, Physical Absorption, Hybrid Absorption, Gas Separation Membrane, Gas Absorption Membrane, Physical Adsorption, Solid Chemical Absorption, Cryogenic, Hydrate Formation, Electrochemical Separation, Biochemical Separation, Oxyfuel, Chemical Looping Combustion
- Action Items for Phase II

Regional Partnership
Capture Working Group Workshop

Proposed Phase II Action Items

Proposed
Phase II Action Items

1) Identify potential regional impacts for various levels of implementation of capture and separation technologies:
   - Replacement power (quantity and generation types)
   - Other emissions reductions (SO_2, NO_x, PM, Hg, etc.)
   - Resource Availability (e.g. water, land)
   - Consider new sources with capture

Proposed
Phase II Action Items

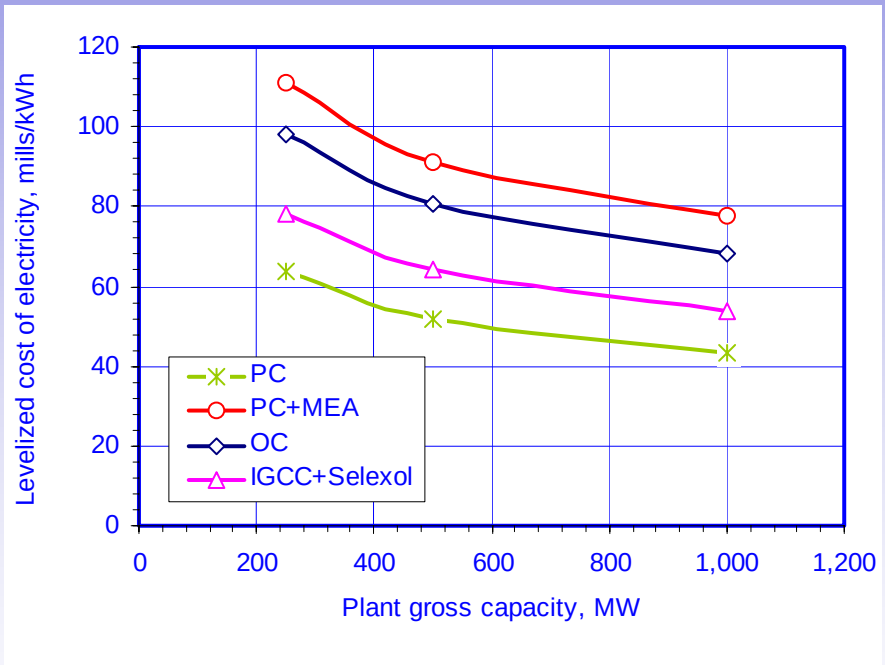
2) Development of a common database of point source types matched with possible commercial and emerging capture technologies that each point source type can utilize
   - Identify cost of each technology per point source type
   - Identify sub-total capital cost for each technology and total CO_2 capture per point source type (by region, state, industry)

Proposed
Phase II Action Items

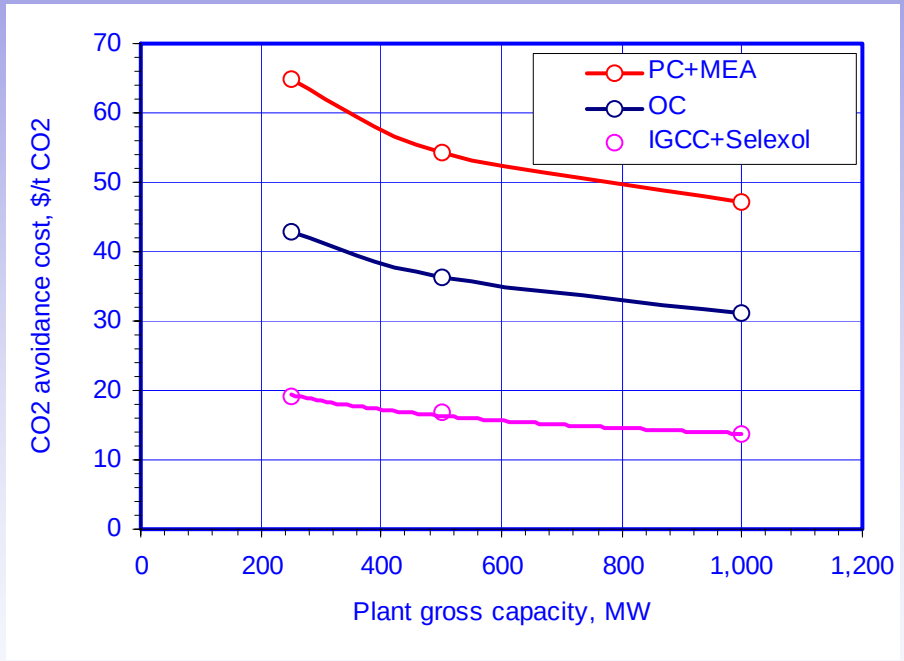
3) Use of NETL sponsored Carnegie Mellon University's IECM-CS model, if applicable, by all Partnerships
4) Carbon capture case study with inputs from industrial partners
   - Rolled into final Regional Implementation Plans
   - Identify Technology Portfolio
     - Techno-economic studies of
       - Super-critical PC
       - Ultra-critical PC
       - Advanced MEA
       - Other technologies

Techno-Economic Analysis
Illinois Basin Partnership

New power plants (IL coal)



Cost of electricity



CO_2 avoidance cost

Source: Illinois Basin Partnership

Acknowledgements

Acknowledgements

- **Big Sky**
  - Bob Smith, Fred Gunnerson, Eric Peterson, John Klaehn, Alan Wertsching, Patrick Pinhero David Shropshire
- **Illinois Basin**
  - Shiaoguo (Scott) Chen, Scott M. Frailey, Damon A. Garner , Christopher P. Korose, Yongqi Lu, Massoud Rostam-Abadi, Robert J. Finley
- **MRCSP**
  - Dan Connell, Dick Winschel, Bob Dahowski, Casie Davidson, Jim Dooley, David Ball
- **PCOR**
  - Mark Musich, Melanie Jensen, John Ruby, Jim Evans
- **SECARB**
  - Richard Rhudy, Howard Herzog, Mark Bohm, Jerry Hill, John Plodinec
- **Southwest**
  - Brian McPherson, Howard Meyer, Mike Hirl, Barry Biediger , Orman Paananen
- **WESTCARB**
  - Larry Meyer, Richard Rhudy, John Ruby, Howard Herzog, Dale Simbeck

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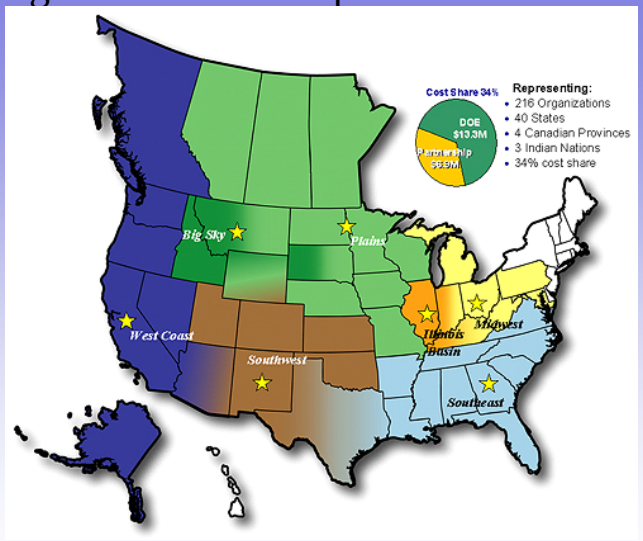

Phase I

- •7 Regional Partnerships
- •216 Organizations
- •40 States
- •4 Canadian Provinces
- •3 Indian Nations
- •34% Cost Share

Phase II

- •Expected 7 Awards

Two-Phased Approach

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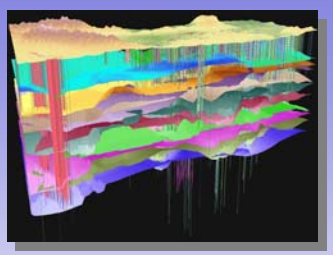

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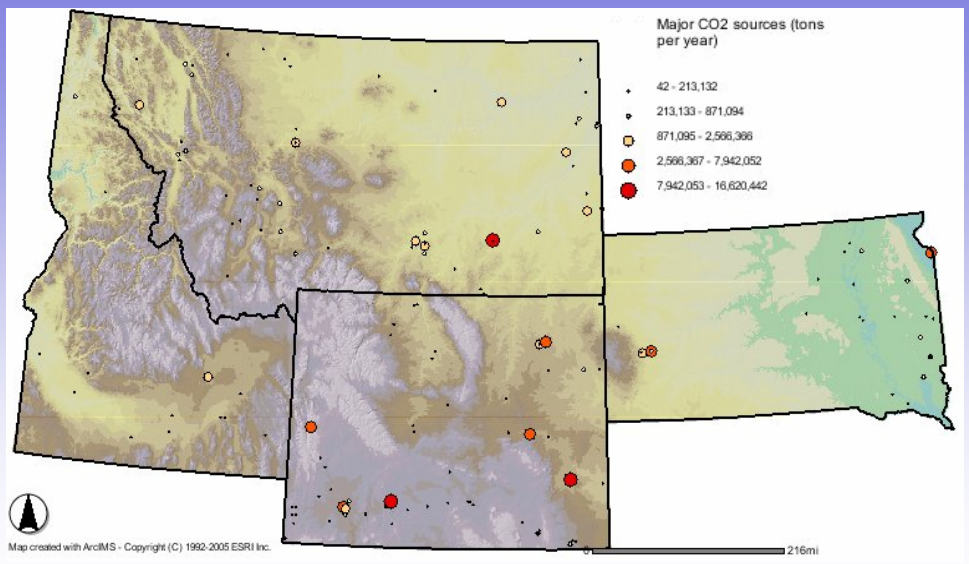
Regional CO_2 Emission Sources

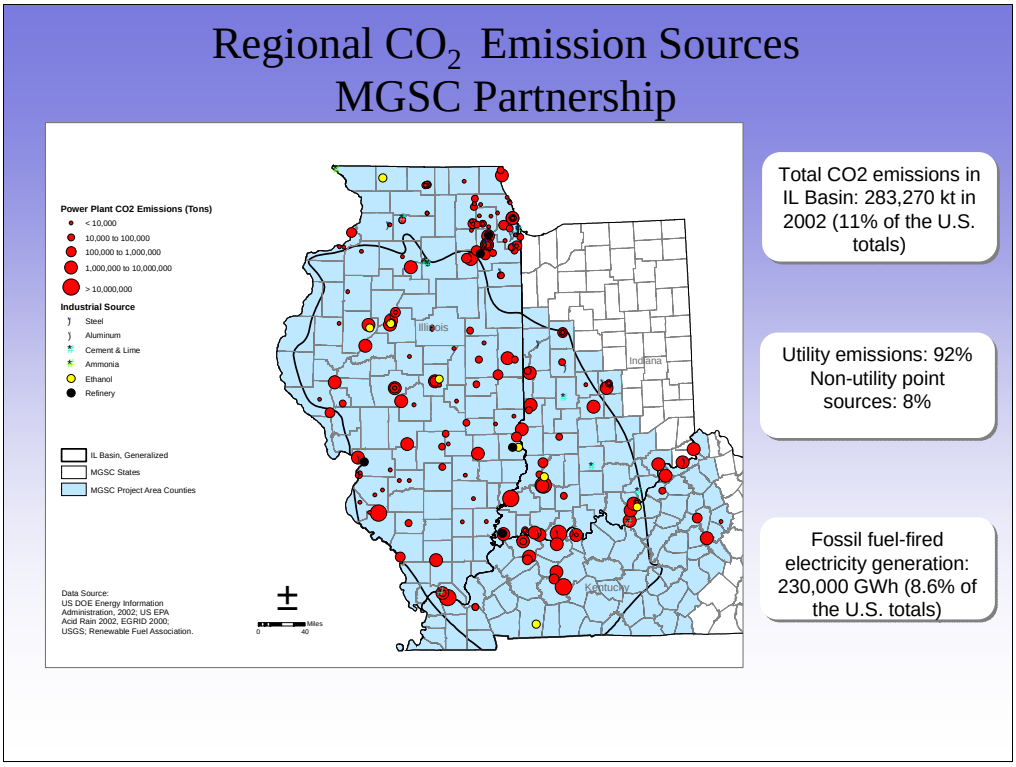
Big Sky Regional CO_2 Emission Sources



The geographic region defined by the Big Sky Partnership includes land area encompassing the states of Montana, South Dakota, Idaho, Wyoming, and eastern Washington and Oregon.

In Montana and Wyoming, refining and other energy and heavy industries constitute the largest GHG source category. Idaho has few emission sources due to high reliance on hydroelectric resources, so as a state it would be most impacted by growth and the need for energy development from fossil energy. South Dakota emissions are largely contributed by ethanol production, which is expected to increase in the future.

Potential emissions from future energy development using regional fossil-fuel resources are conservatively estimated to be an *order-of-magnitude higher*, depending on transmission capacity and other energy demand factors.



-122 fossil fuel-fired power plants in the IL basin with a total capacity of 53 GW

- About 230 TWh electricity is generated annually, 8.6% of the U.S. totals

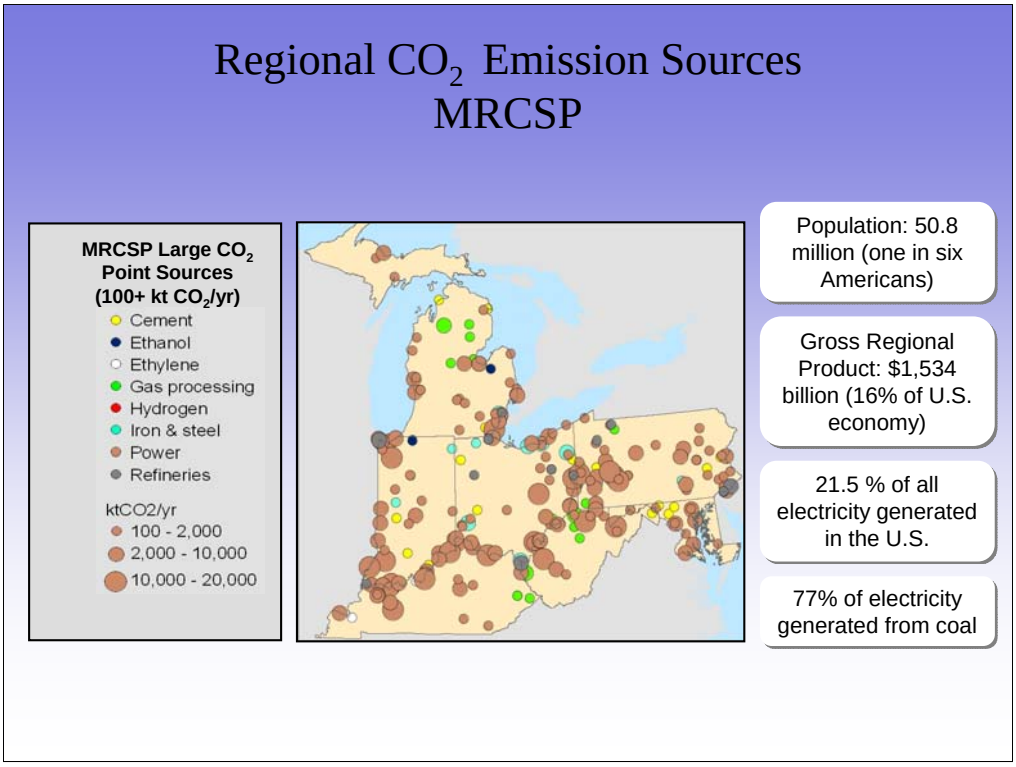
- about 256 million tonnes of CO_2 emitted from utility power plants in 2002

- 20% of the utility emissions from 3 largest plants, 50% from 10 largest plants, and 80% from 24 largest plants

- 98% of CO2 emissions from coal-fired power plants

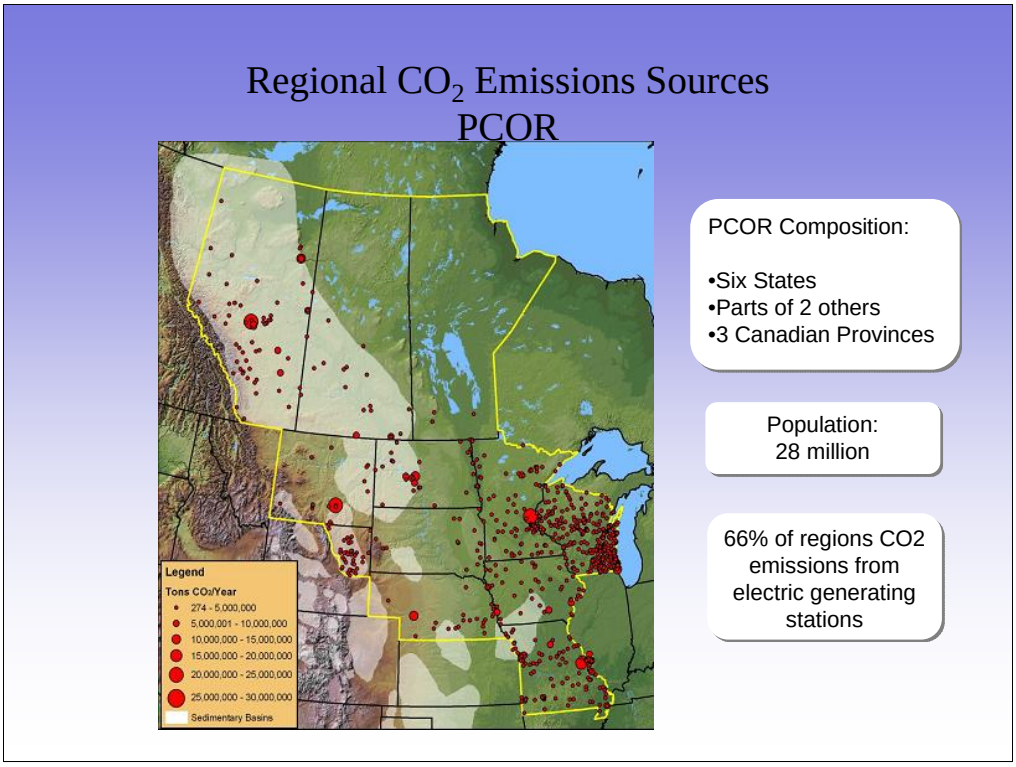
- power plants accounts for 92.2% of point source CO_2 emissions, 7.8% is attributed to other industrial point sources

- Oil refinery, iron& steel, cement and ethanol plants are the major industrial sources and contribute 5.2%, 7.1%, 7.6% and 45.9%, respectively, to the U.S. totals

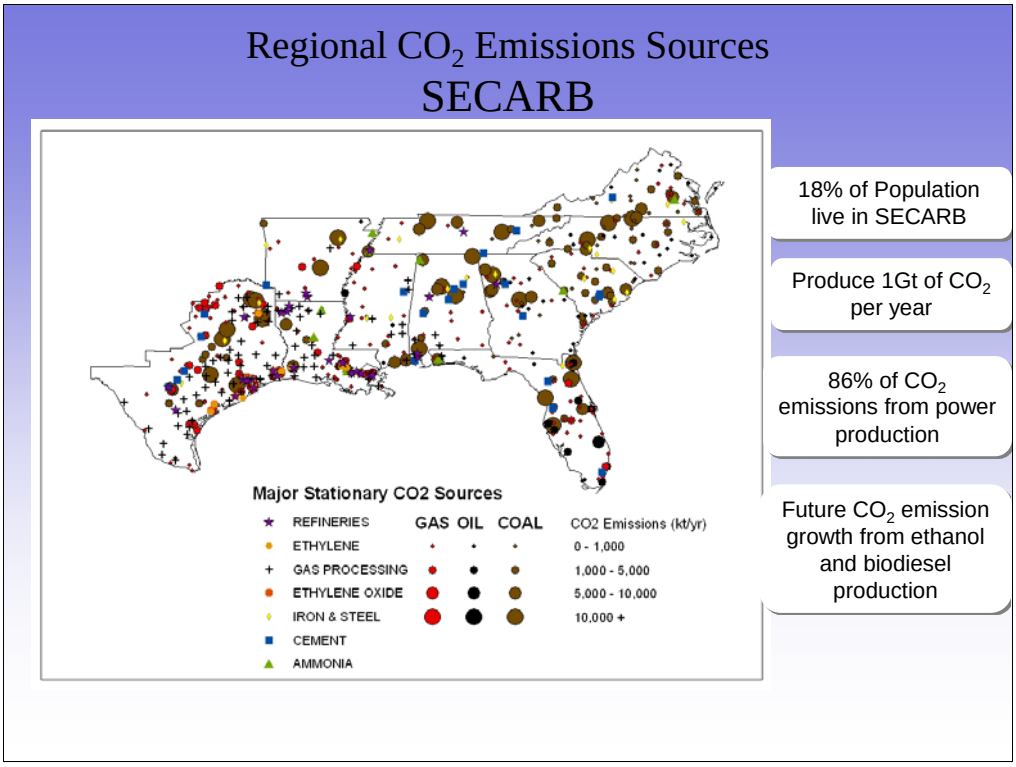


- The Midwest is a populous region, which is home to 1 out of 6 Americans.
- The Midwest is often called "The Nation's Engine Room," because it produces 21.5% of all the electricity generated in the U.S.
- The Midwest is highly dependent on coal for power generation. Approximately 77% of electricity in the region is produced from coal combustion.

1. The Midwest is comprised of 190 "large" power generation facilities (>100 kt/y CO_2), with a total of 418 power generating units and approximately 122 GW of generating capacity.
2. Most power generating units (340 out of 418) fire bituminous coal, accounting for 92% of CO_2 emissions from these facilities
3. Altogether, power generation accounts for 84.5% of CO_2 emitted by large point sources in the Midwest region



The Plains CO_2 Reduction Partnership comprises six states, portions of two others, and three Canadian provinces. The regional population is roughly 28 million and electricity generation, agriculture, energy exploration and production, and manufacturing are the major industries. Nearly 66% of the region's CO_2 emissions are produced by electricity-generating stations.

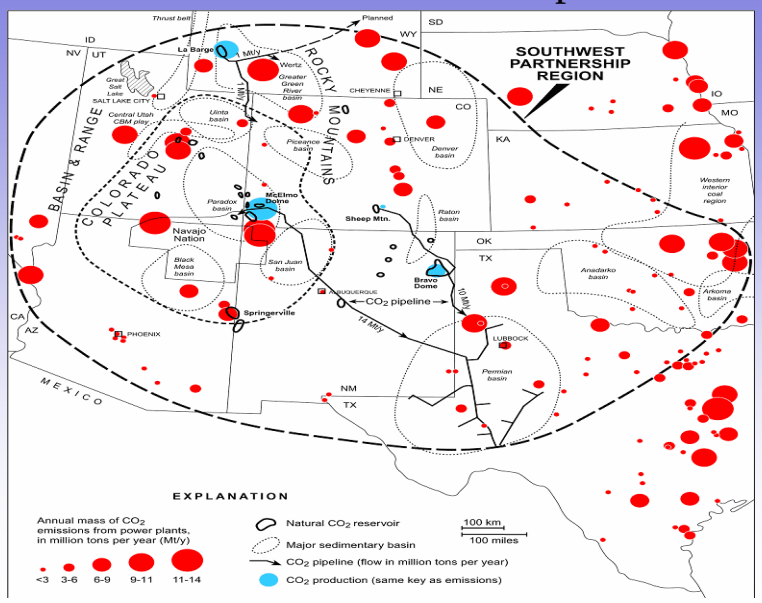


SECARB is made up of the states of Alabama, Arkansas, Florida, Georgia,Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and parts of Virginia and Texas.

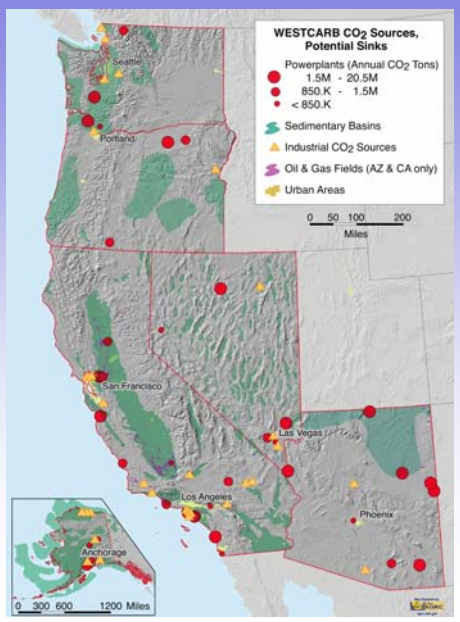
The 18% of the nation's population living in the region produce nearly 1 Gt of CO2 each year, 86% from power production (of this 78% is generated from coal-burning utilities).

Currently the amount produced from production of ethanol or biodiesel is negligible; however, it is expected that the amount of CO2 produced by such facilities will grow rapidly in response to federal and state incentives for ethanol and biodiesel production.

Regional CO_2 Emissions Sources Southwest Partnership



Regional CO_2 Emissions Sources
WESTCARB

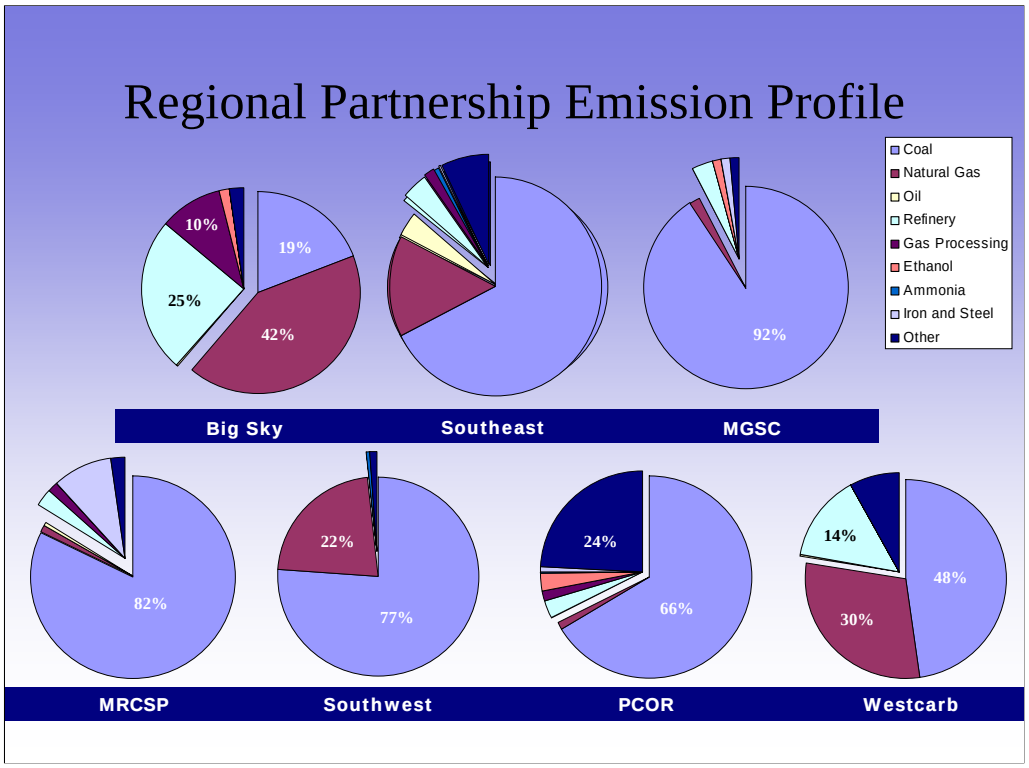


Composition:
- 5 Western States
- Alaska
- British Columbia Province

Opportunities for Enhanced Oil/Gas Recovery are initially in Alaska and California.

Regional power plants:
- Generally fired with natural gas
- Several coal-fired power plants
  - Arizona, Nevada and Washington contribute heavily.

The WESTCARB partnership includes 5 western states and Alaska. The Canadian province of British Columbia is a recent addition to the team. The primary stationary source of CO2 emissions are power generation plants with additional emissions from petroleum refineries, cement and lime plants and other industries. While by numerical count most regional power plants are fueled by natural gas, several large coal-fired plants in Arizona, Nevada and Washington contribute heavily to the total emissions. The region's characterization of geological sequestration options is still evolving, and there appears to a variety of suitable formations and excellent geographical dispersion. Initial opportunities for enhanced oil/gas recovery are also very good, with the primary locations in Alaska and California.



MRCSP			
Power Generation		**Metric Ton**	**kt**
	Coal	625,900,000	625,900
	Natural Gas	9,900,000	9,900
	Oil	4,137,000	4,137
Non-Power Generation			
	Refinery	19,863,000	19,863
	Gas Processing	13,607,000	13,607
	Ethanol	446,000	446
	Ammonia	21,000	21
	Iron and Steel	70,327,000	70,327
	Other	17,704,000	17,704

WESTCARB			
Power Generation		**Metric Ton**	**kt**
	Coal	83,400,000	83,400
	Natural Gas	52,200,000	52,200
	Oil	300,000	300
Non-Power Generation			
	Refinery	25,000,000	25,000
	Gas Processing	0	0
	Ethanol	0	0
	Ammonia	0	0
	Iron and Steel	0	0
	Other	14,000,000	14,000

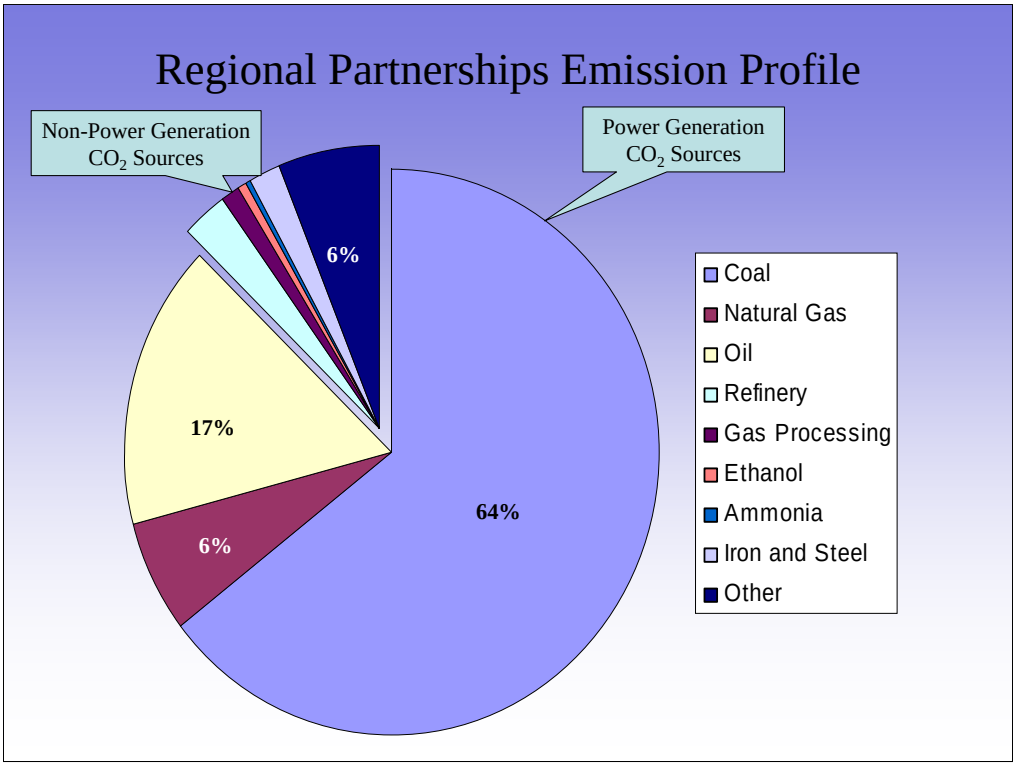
SOUTHWEST			
Power Generation		**Metric Ton**	**kt**
	Coal	455,253,000	455,253
	Natural Gas	133,764,000	133,764
	Oil	99,000	99
Non-Power Generation			
	Refinery	0	0
	Gas Processing	0	0
	Ethanol	0	0
	Ammonia	2,825,000	2,825
	Iron and Steel	0	0
	Other	6,600,000	6,600

MGSC			
Power Generation		**Metric Ton**	**kt**
	Coal	256,256,000	265,256
	Natural Gas	5,006,000	5,006
	Oil	48,000	48
Non-Power Generation			
	Refinery	9,703,000	9,703
	Gas Processing	0	0
	Ethanol	3,848,000	3,848
	Ammonia	214,000	214
	Iron and Steel	3,857,000	3,857
	Other	4,338,000	4,338

BIG SKY			
Power Generation		**Metric Ton**	**kt**
	Coal	5,542,745	5,543
	Natural Gas	12,188,863	12,189
	Oil	24,293	24
Non-Power Generation			
	Refinery	7,238,348	7,238
	Gas Processing	2,880,187	2,880
	Ethanol	434,635	435
	Ammonia	0	0
	Iron and Steel	0	0
	Other	677,283	677

PCOR			
Power Generation		**Metric Ton**	**kt**
	Coal	358,897,602	358,898
	Natural Gas	7,064,040	7,064
	Oil	43,237	43
Non-Power Generation			
	Refinery	14,522,653	14,523
	Gas Processing	8,708,521	8,719
	Ethanol	17,908,028	14,908
	Ammonia	2,041,710	2,042
	Iron and Steel	4,530,541	4,531
	Other	130,905,902	130,906

SOUTHEAST			
Power Generation		**Metric Ton**	**kt**
	Coal	671,195,000	671,195
	Natural Gas	150,541,000	150,541
	Oil	35,067,000	35,067
Non-Power Generation			
	Refinery	39,452,000	39,452
	Gas Processing	15,862,000	15,862
	Ethanol	0	0
	Ammonia	9,443,000	9,443
	Iron and Steel	2,560,000	2,560
	Other	71,326,000	71,326



Total			
Utility		**Metric Ton**	**kt**
	Coal	2,642,053,347	2,642,053
	Natural Gas	255,189,903	255,190
	Oil	675,846,530	675,847
Non-Utility			
	Refinery	115,779,001	115,779
	Gas Processing	41,057,708	41,058
	Ethanol	22,636,663	22,637
	Ammonia	14,330,710	14,331
	Iron and Steel	81,274,541	81,275
	Other	245,551,185	245,551

This slide is a summation of the 7 Regional Partnerships carbon dioxide emission profile. The utility sector is the dominant source of carbon dioxide emission with coal overshadowing the combined emissions from oil and gas power generation. Ammonia production equals the remaining non-utility sector carbon dioxide emission. Hence the interest in developing carbon dioxide capture and separation technologies should there be a need to install these systems.

Techno-Economic Results from Phase I

Preliminary Matrix Assessment
Candidate CO_2 Capture Technologies for Example Sources

Source Type	Point of Capture	Amine Scrubbing	Ammonia Scrubbing	Physical Absorption	Gas Separation Membrane	Gas Absorption Membrane	Oxyfuel + Drying/ Compression	Simple Drying /Compression
Power Plants Post Combustion	Flue Gas	1	2	--	2	2	2	--
Power Plants Pre-Combustion	Shifted Syngas	--	--	1	2	--	--	--
Iron / Steel Facilities	Blast Furnace Gas	1	--	1	2	3	--	--
Refineries	Heater/Boiler Flue Gas	1	3	--	2	3	2	--
Cement Plants	Kiln Flue Gas	1	3	--	3	3	3	--
Gas Processing Plants	Vented CO_2	--	--	--	--	--	--	1

1 —Commercially available; 2 —Actively being developed; 3 —Very early stage of R&D

Source: Midwest Partnership

The MRCSP reviewed candidate technologies for capturing CO_2 from large industrial point sources against technical and economic considerations regarding the application of these capture technologies to the large CO_2 point sources found in the Midwest region.

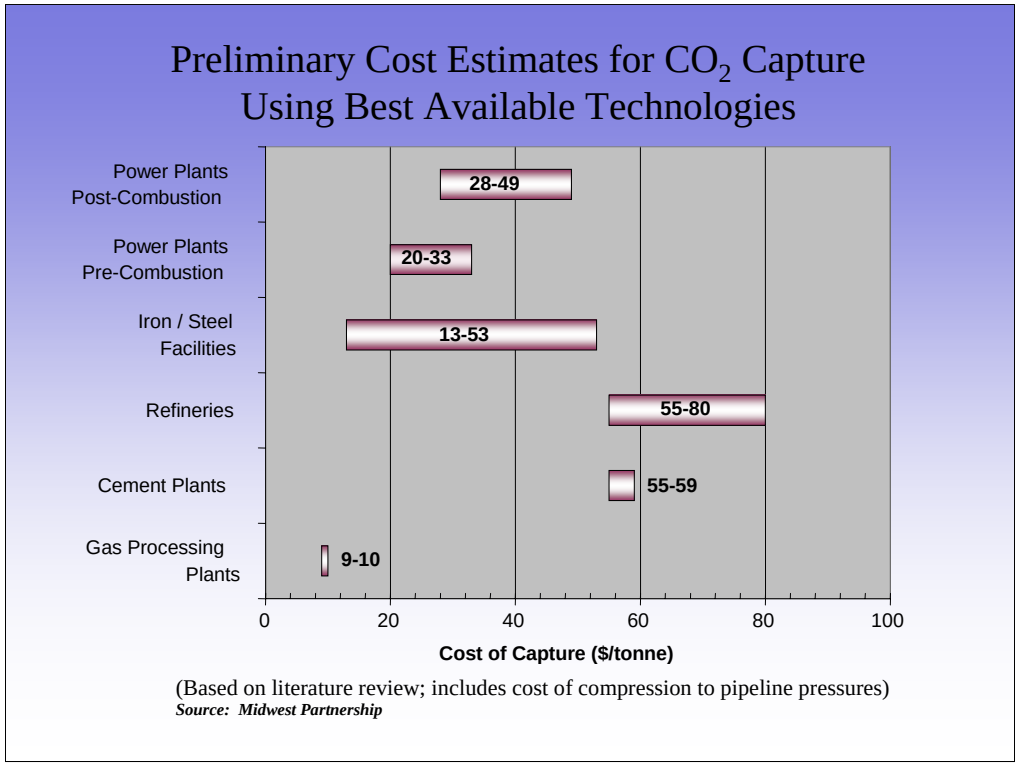
This table integrates these technical and economic considerations, and shows how the candidate capture technologies might best be matched to the MRCSP region's diverse array of large CO_2 point sources. Because many of the candidate technologies are still being researched and developed, multiple candidates are identified for some of the source types. Also, the ranking for a particular capture technology may be different depending on the CO_2 source, due to the complexity of integrating the capture technology with the source type.

A preliminary assessment of these candidates are ranked in numerical order to provide some indication of their potential applicability. The terms used to rate the technologies are defined as follows:

1 – Commercially available and therefore the most likely candidate for capturing CO_2 among currently available, demonstrated technologies.

2 – Technology that is being actively developed and shows clear potential for economic or technical improvement over the current best-available commercial technologies.

3 – Includes technologies that are either in the very early stages of research and development, or are being developed but requires major breakthroughs to become advantageous.



This slide compares the economics of carbon capture for various types of point source CO_2 emissions.

- Amine scrubbing is regarded as the best available commercial technology (BACT) for capturing CO_2 from post combustion streams, such as conventional power plant flue gas, off-gas from furnaces used in iron/steel manufacturing, refinery flue gas, and cement kiln flue gas.
- Physical absorption is the BACT for pre-combustion capture of CO_2 from high-pressure shifted syngas in oxygen-fired IGCC plants and natural gas steam reforming or partial oxidation plants, as well as from pressurized, shifted blast furnace off-gas in integrated steel mills. Both of these processes are commercially available, and have been used for CO_2 capture.
- CO_2 capture from high-purity streams produced by gas processing plants (as well as ethylene, ethanol, and hydrogen plants) requires only dehydration and compression, which lowers the cost considerably compared to streams that require gas separation.
- The cost distribution, shown by the bar length, is due to differences in information sources, and to differences in the technology that is applied. For example, amine scrubbing and physical absorption are both currently the leading candidates for capturing CO_2 from blast furnace off-gas (both received a '1' in the assessment table). Amine scrubbing is potentially attractive for capture because the off-gas contains a higher concentration of CO_2 than power plant flue gas; therefore the cost of using amine technologies are comparable in both cases. In addition, physical absorption may result in even lower costs because the flue gas also contains an appreciable concentration of CO, which could be shifted to increase the CO_2 concentration even further (hence, the lower-cost end of the bar).
- Unlike power plants, CO_2 emitted by a typical refinery is produced by an array of small heaters, boilers, and furnaces that are scattered throughout the facility. Moreover, most refineries (and cement plants) do not have the infrastructure (e.g., sufficient sources of low-grade heat) required to support CO_2 capture via amine scrubbing; hence, significant enhancements to the plants would likely be needed. Thus, retrofitting refineries (and cement plants to some extent) for CO_2 capture will likely be more complex and site-specific than retrofitting power plants for capture. This is reflected in the CO_2 capture costs shown in the bar chart.

- The uncertainty in CO2 capture costs are probably greater than what is shown by the bars on this chart. This is to be expected, since the available data is limited and may vary in quality for each industry. These cost ranges are not absolutes due to the variability in the assumptions of the economic analysis performed between studies.

Regional Partnership
Capture Working Group Workshop

Conclusions

Capture Working Group Workshop

- March 30, 2005:
  - Hosted by Illinois Basin RCSP, ISGS, and University of Illinois
- Presentations on Phase I capture activities from all 7 Regional Partnerships
- Participation from technology developers, utilities, and a climate change expert
  - UOP, Ameren, ConocoPhillips, and University of Illinois
- Analysis of CO_2 capture technologies costs and rankings
- Developed proposed Phase II capture and separation action items for NETL consideration

Capture Working Group Workshop Conclusions

- Few commercial capture technologies currently available
- Capture is major part of total sequestration costs
- Impacts of Developing Technologies in Capture and Separation – Technologies Examined:
  - Amine Scrubbing, Alkaline Salt Scrubbing, Ammonia Scrubbing, Physical Absorption, Hybrid Absorption, Gas Separation Membrane, Gas Absorption Membrane, Physical Adsorption, Solid Chemical Absorption, Cryogenic, Hydrate Formation, Electrochemical Separation, Biochemical Separation, Oxyfuel, Chemical Looping Combustion
- Action Items for Phase II

Regional Partnership
Capture Working Group Workshop

Proposed Phase II Action Items

Proposed
Phase II Action Items

1) Identify potential regional impacts for various levels of implementation of capture and separation technologies:
   - Replacement power (quantity and generation types)
   - Other emissions reductions (SO_2, NO_x, PM, Hg, etc.)
   - Resource Availability (e.g. water, land)
   - Consider new sources with capture

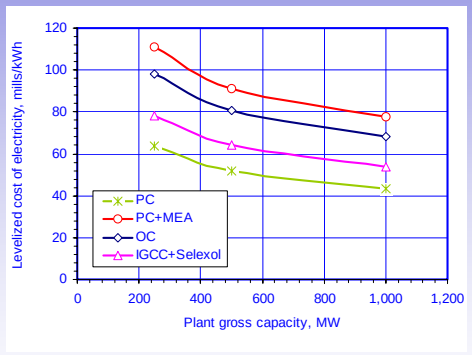
Proposed
Phase II Action Items

2) Development of a common database of point source types matched with possible commercial and emerging capture technologies that each point source type can utilize
   - Identify cost of each technology per point source type
   - Identify sub-total capital cost for each technology and total CO_2 capture per point source type (by region, state, industry)

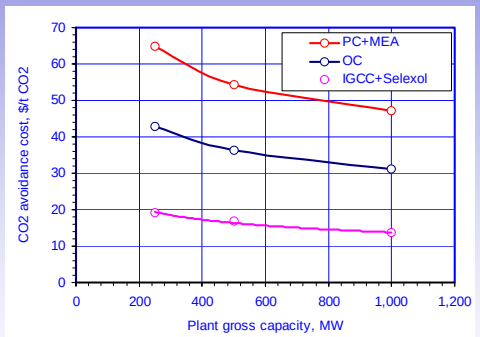
Proposed
Phase II Action Items

3) Use of NETL sponsored Carnegie Mellon University's IECM-CS model, if applicable, by all Partnerships
4) Carbon capture case study with inputs from industrial partners
   - Rolled into final Regional Implementation Plans
   - Identify Technology Portfolio
     - Techno-economic studies of
       - Super-critical PC
       - Ultra-critical PC
       - Advanced MEA
       - Other technologies

Techno-Economic Analysis
Illinois Basin Partnership
New power plants (IL coal)



Cost of electricity



CO_2 avoidance cost

Source: Illinois Basin Partnership

This slide illustrates two of the type of scaling curves that will be developed by NETL awarded projects in the future. The Regional Partnership Phase II solicitation was the first to have the Carbon Capture and Sequestration Systems Analysis Guidelines – April 2005.

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