

IDENTIFICATION OF CO₂ SEQUESTRATION STRATEGIES FOR THE PCOR PARTNERSHIP REGION

Melanie D. Jensen, Energy & Environmental Research Center
James A. Sorensen, Energy & Environmental Research Center
Edward N. Steadman, Energy & Environmental Research Center
John A. Harju, Energy & Environmental Research Center

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EXECUTIVE SUMMARY

Phase I efforts focused on identifying and defining the carbon dioxide (CO₂) sources, geologic sinks, and sequestration infrastructure within the Plains CO₂ Reduction (PCOR) Partnership region. The PCOR Partnership has taken a market-based approach that focuses on the development of the information needed to monetize carbon credits from sequestration activities. This information was used to develop both short- and long-range strategies for sequestration of CO₂ in the region.

The PCOR Partnership region contains vast geologic sinks that can be used to sequester CO₂ in a variety of ways. The region contains coal deposits, oil fields, and deep saline formations capable of providing geologically secure, long-term or permanent storage for the CO₂. Approximately two-thirds of CO₂ generated in the region is emitted during electricity generation, while other significant stationary emissions sources include the manufacture of paper and wood products, petroleum and natural gas processing, chemicals and fuels production, ethanol production, petroleum refining, and cement/clinker production. Current sequestration infrastructure such as injection wells; monitoring, mitigation, and verification (MMV) equipment; and pipelines for CO₂ delivery is available to varying degrees in the PCOR Partnership region.

An objective method for matching CO₂ point sources with sinks was used to identify the most promising geologic CO₂ sequestration opportunities in the PCOR Partnership region. A series of spreadsheets containing CO₂ source data, geologic sink types and capacities, CO₂ capture and separation technologies (both those currently in use as well as those still under development) and the source types to which they could be applied, transportation options, and deployment issues (including permitting and MM&V) were generated using data from the PCOR Decision Support System (DSS). The largest CO₂ sources were screened according to their source type (e.g., electrical utility, ethanol production, metals processing) to group sources that produce similar exit gas streams. These source subgroups were sorted by quantity of CO₂ produced, the percentage of the exit stream comprising CO₂, and the presence of SO₂ and/or NO_x or other compounds to better define the CO₂ streams' compositions and potential ease of capture.

The DSS data were used to identify the most promising sequestration scenarios in two categories: short-term, commercially viable (or nearly so) scenarios that can sequester regionally significant amounts of CO₂ within the 2012 time frame outlined in the *Carbon Sequestration Technology Roadmap and Program Plan* and long-term opportunities that can sequester globally significant amounts of CO₂ but require the

technological advances and infrastructural improvements provided by meeting the 2012 Roadmap goals. The outcome of these efforts is the establishment of Phase II field validation tests that provide opportunities for the development of regionally and globally significant demonstrations of sequestration technologies.

The various scenarios were compared, and groups of similar scenarios, called sequestration strategies, were formed. Ultimately, the number of possible strategies was reduced to four that were the most likely to be employed in the region in both the near and long term:

- CO₂ from coal-fired electricity generation facilities used for enhanced oil recovery (EOR), injected into a saline formation, or injected into a coal seam for enhanced coalbed methane (ECBM) production.
- CO₂ produced from natural gas processing and transmission sites injected into a coal bed for ECBM production, a petroleum reservoir for EOR, or a saline formation.
- CO₂ produced during ethanol production used for EOR, injected into a saline formation, or injected into another appropriate sequestration target.
- CO₂ from cement/clinker production used for EOR, injected into a saline formation or injected into a coal seam.

Preliminary economic estimates were made to provide a way to rank these strategies. The economic ranking found that sequestration of CO₂ from power plants during EOR or ECBM activities was probably the most cost-effective. Because of the overall cost reductions possible through the

sale of oil or methane, sequestration that is performed concurrently with EOR or ECBM will likely be the only sequestration performed in the near term.

These results were used to select the following three specific geological sequestration scenarios for demonstration during Phase II activities:

- CO₂ used for simultaneous sequestration and EOR in an oil field in western North Dakota.
- Acid gas (65% CO₂, 35% H₂S) from an Apache Canada Ltd. sour gas plant injected into a field in northwestern Alberta for simultaneous sequestration and EOR.
- CO₂ injected into economically unminable lignite seams to determine the suitability of these strata for both CO₂ sequestration and coalbed methane production.

The PCOR Partnership Phase II demonstrations will provide the detailed information needed for more robust economic analysis and technical development for CO₂ transportation, injection, and monitoring activities needed to directly sequester CO₂ in the near term. The lessons learned during the demonstrations will be directly applicable to sequestration projects elsewhere in the PCOR Partnership region as well as globally.

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BACKGROUND

The Plains CO₂ Reduction (PCOR) Partnership region consists of the states of Iowa, Minnesota, Missouri, Nebraska, North Dakota, South Dakota, Wisconsin, and portions of the states of Montana and Wyoming as well as the Canadian provinces of Alberta, Saskatchewan, and Manitoba. The region was defined in part on the basis of similarities in large stationary carbon dioxide (CO₂) sources as well as its geologic and terrestrial CO₂ sinks. The boundaries of the PCOR Partnership region, as well as the major sinks and stationary sources, are shown in Figure 1. Since September 2003, considerable effort has gone into thoroughly identifying and defining the CO₂ sources, geologic and terrestrial sinks,

and sequestration infrastructure within the region. This information was used in the development of both short- and long-range strategies for sequestration of CO₂ on a regional basis.

CHARACTERIZATION OF THE PCOR PARTNERSHIP REGION

Federal and provincial greenhouse gas inventories contain summarized data on CO₂ emissions from fossil fuel combustion (U.S. Environmental Protection Agency, 2005a; Environment Canada, 2005a). Figure 2 shows the percentage of these emissions in various sectors for the year 2000 for the states and provinces of the PCOR Partnership region, including the entire states of Montana and Wyoming. The PCOR Partnership source characterization data include only the portion of Montana and

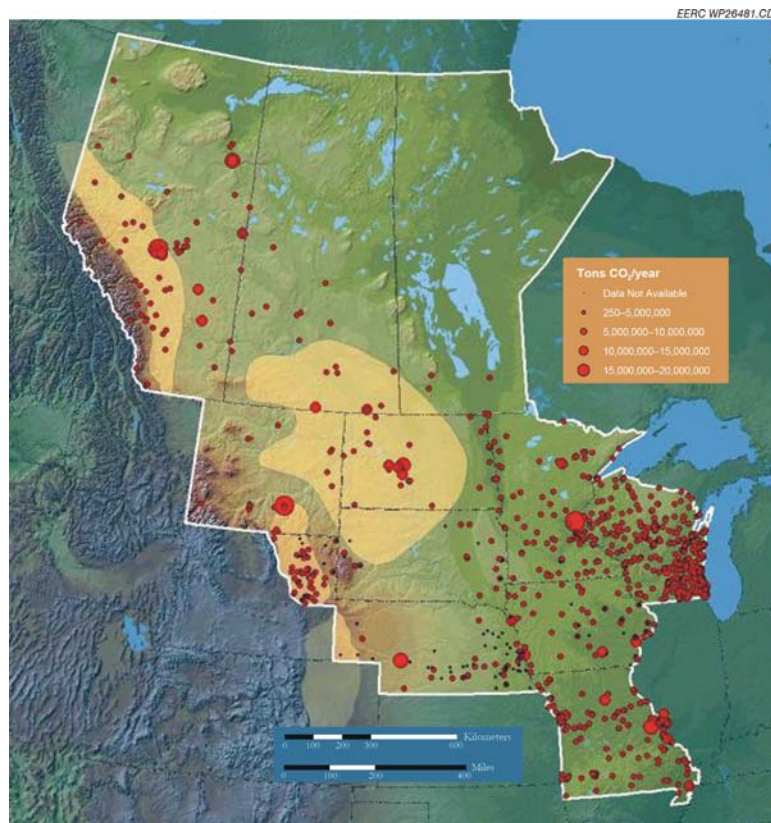


Figure 1. The PCOR Partnership geographic region showing major sinks and stationary sources.

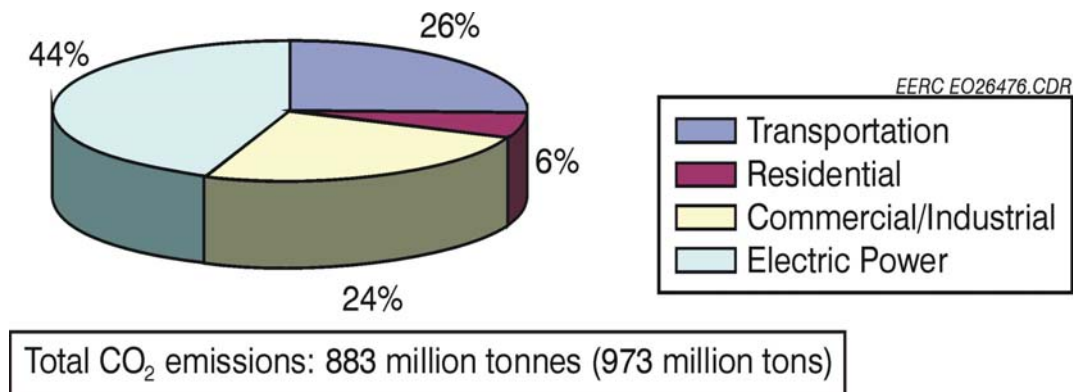


Figure 2. Year 2000 CO₂ emissions from fossil fuel combustion by sector for entire states and provinces within PCOR Partnership region.

Wyoming that are within the region's boundaries. Figure 3 displays these same sectors as compared to the entire CO₂ emissions for the United States and Canada combined.

The Phase I assessment identified, quantified, and characterized over 1000 stationary sources within the PCOR Partnership region (O'Leary et al., 2005). The emissions from these sources totaled nearly

502 million tons (553 million tonnes) of CO₂ annually. CO₂ is emitted from electricity generation; energy exploration and production activities; agricultural; fuel, chemicals, and ethanol production; and various manufacturing and industrial activities. Table 1 shows that the majority of the region's emissions come from just a few source types. About two-thirds of the CO₂ is emitted during electricity generation, followed by industrial sources, petroleum

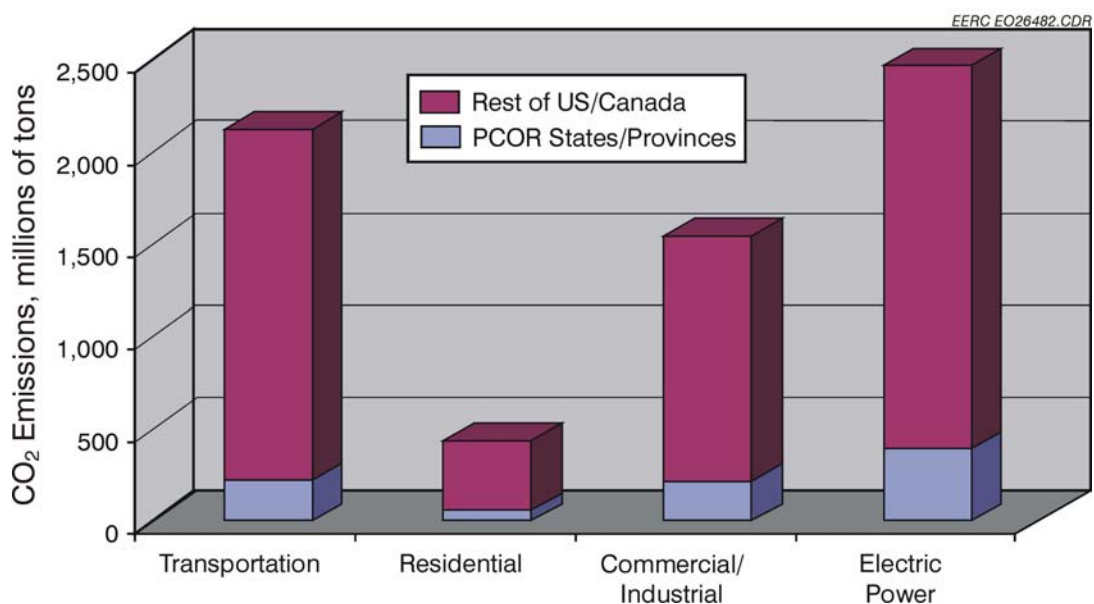


Figure 3. Year 2000 Percentage of CO₂ emissions from fossil fuel combustion by sector for entire states of the PCOR Partnership region relative to combined U.S.–Canada emissions.

Table 1. Summary of CO₂ Point Sources Identified in the PCOR Partnership Region (O’Leary et al., 2005)

Source Type	Quantity	% of All Sources	CO ₂ Emissions (short tons/yr) ^a	% of CO ₂ Emissions
Agricultural Processing	115	10.6	3,647,014	0.7
Ammonia Production	4	0.4	1,780,350	0.3
Animal and Animal By-Product Processing	1	0.1	6,203	0.0
Asphalt Production	23	2.1	1,485,825	0.3
Cement/Clinker Production	13	1.2	12,473,725	2.3
Chemical Production	38	3.5	17,888,288	3.2
CoGeneration	2	0.2	588,559	0.1
Electric Generating	156	14.4	368,397,831	66.6
Ethanol Manufacturing	62	5.7	16,404,839	3.0
Fertilizer Production	2	0.2	38,749	0.0
Foundries/Manufacturing	4	0.4	2,063,867	0.4
Fuels/Chemicals	1	0.1	5,550,057	1.0
Industrial/Institutional Heat and Power	98	9.1	3,070,173	0.6
Iron Ore Processing	6	0.6	2,930,200	0.5
Lime Production	11	1.0	3,974,866	0.7
Manufacturing	205	18.9	10,478,547	1.9
Metals Processing	23	2.1	788,309	0.1
Minerals Processing	9	0.8	509,360	0.1
Mining	9	0.8	122,037	0.0
Miscellaneous	10	0.9	102,966	0.0
Municipal Heat and Power	8	0.7	680,882	0.1
Natural Gas Processing	31	2.9	9,023,148	1.6
Natural Gas Transmission	71	6.6	3,542,082	0.6
Paper and Wood Products	124	11.5	33,937,872	6.1
Petroleum and Natural Gas Processing	14	1.3	28,897,723	5.2
Petroleum Refining	16	1.5	17,717,687	3.2
Sugar Production	10	0.9	4,348,914	0.8
Waste Processing	17	1.6	2,336,808	0.4
TOTAL	1,083	100	552,786,881	100

^a To convert the short tons in the table to metric tons, multiply by 0.9072.

refining and natural gas processing, ethanol production, and agricultural processing.

The emissions profile (i.e., the percentage of CO₂ emissions from various source types) for the Canadian portion of the PCOR Partnership is virtually identical to

that of Canada as a whole (Figure 4). On the other hand, when compared to the total U.S. CO₂ emissions, the states in the PCOR Partnership region emit relatively more CO₂ from electric utilities and less from industries and transportation. For the most part, the distribution of the sources with the largest CO₂ output is coincident

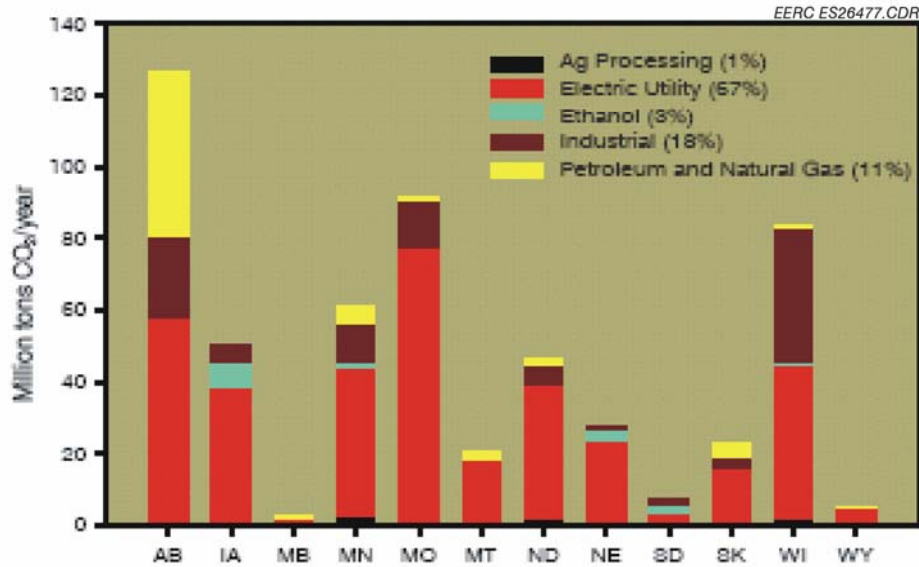


Figure 4. Emissions profile of the PCOR Partnership region.

with the availability of fossil fuel resources, namely coal, natural gas, and oil. This relationship is significant with respect to geologic sequestration opportunities. Many of the smaller sources are concentrated around more heavily industrialized metropolitan regions in southeastern Minnesota and southeastern Wisconsin.

Geologic and Terrestrial Sinks

The PCOR Partnership region contains vast geologic sinks that can be used to sequester CO₂ in a variety of ways. The region contains coal deposits, oil fields, and deep saline aquifers capable of providing geologically secure, long-term or permanent storage for CO₂. These geologic features and their CO₂ storage capabilities have been detailed in other documents (Nelson et al., 2005a, b; Smith et al., 2005; Fischer et al., 2005; Stewart and Bachu, 2000; Bachu et al., 2005); details will not be repeated here.

In addition to its significant geologic sinks, the PCOR Partnership region also contains many opportunities for terrestrial sequestration of CO₂. Terrestrial sinks include agricultural lands (e.g., croplands,

grasslands, and range lands), forest lands, and wetlands and peat bogs. Forested areas within the PCOR Partnership region total more than 303 million acres (National Association of State Foresters, 2002; University of British Columbia 2005; University of Colorado at Boulder Institute of Cognitive Science, 2005; Coleytown Middle School, 2005), agricultural lands (both farm- and rangeland) total more than 402 million acres (U.S. Department of Agriculture, 2005; Statistics Canada, 2001), the Prairie Pothole Region includes 30.8 million acres of wetlands (U.S. Fish & Wildlife Service, 2005; Wiken et al., 2003), and the region contains more than 106 million acres of peat bogs (Minnesota Shoreland Management, 2005; Campbell et al., 2000).

Sequestration Infrastructure

Current sequestration infrastructure such as injection wells; monitoring, mitigation, and verification (MMV) equipment; and pipelines for CO₂ delivery is available to varying degrees in the PCOR Partnership region. Analysis to date has indicated that the oil and gas fields in the Williston Basin region contain approximately 1100 fields

that could be utilized during CO₂ sequestration (Smith et al., 2005), especially as part of enhanced oil recovery (EOR) activities. A 12-in.-diameter CO₂ pipeline stretches for 204 miles from the Dakota Gasification Company (DGC) plant in Beulah, North Dakota, to the CO₂ sequestration demonstration at Weyburn, Saskatchewan. The pipeline passes through some of the region's best geologic sinks (e.g., North Dakota and Saskatchewan oil and coal fields, the Madison Saline Formation, and other suitable saline formations) and could potentially transport CO₂ for sequestration into these formations.

CO₂ Storage Capacity of the PCOR Partnership Region

The sequestration options available in the PCOR Partnership region offer value-added benefit in terms of EOR and enhanced coalbed methane (ECBM) recovery, and terrestrial sequestration options offer positive ecosystem effects. An estimated 261 million barrels of oil could be recovered during EOR activities in western North Dakota alone (Smith et al., 2005). At a price of \$56/bbl, carbon sequestration as part of EOR could produce a salable product worth \$14.6 billion in North Dakota. The Wyodak–Anderson coal field in Wyoming and Montana could produce as much as 15.8 Tcf of methane during ECBM (Nelson et al., 2005a). At the predicted 2006 average Henry Hub natural gas price of \$7.34/mcf (Energy Information Administration, 2005), the methane resulting from sequestration activities in the Wyodak–Anderson coals could bring nearly \$116 billion while sequestering almost 7 billion tons of CO₂.

The PCOR Partnership region's geologic sinks are capable of sequestering significant quantities of CO₂. Phase I efforts of the PCOR Partnership have provided idealized reconnaissance-level estimates for major potential CO₂ sinks in the region. The Mississippian Madison and

Lower Cretaceous saline formations have estimated sequestration capacities of 60 billion tons of CO₂ and more than 160,000 million tons of CO₂, respectively (Fischer et al., 2005). Powder River Basin coal seams in southeastern Montana and northeastern Wyoming are capable of sequestering about 6.9 billion tons of CO₂ during coalbed methane production activities (Nelson et al., 2005a), while coal beds in western North Dakota have an estimated sequestration capacity of 380 million tons of CO₂ (Nelson et al., 2005b). Selected oil fields in the Williston Basin, Powder River Basin, and part of the Denver–Julesburg Basin could be used for EOR and have a maximum sequestration capacity of more than 10 billion tons of CO₂ (Smith et al., 2005). Practical CO₂ storage capacities were calculated for oil and gas reservoirs in Alberta, Saskatchewan, and Manitoba by Bachu and Shaw (2004) to be 3.2 billion tons of CO₂. These sequestration capacities are summarized in Table 3, which shows that the region's geologic sinks can sequester roughly 241 billion tons of CO₂. This idealized capacity could sequester all of the characterized PCOR Partnership region's stationary CO₂ emissions for 437 years.

While the amount of carbon that can be sequestered terrestrially is species- and location-dependent, gross estimates of sequestration capacity can be made by applying average sequestration rates to the available acreages. Such estimates indicate that croplands in the PCOR Partnership region can sequester approximately 68 million tons of CO₂ per year for the next 50 years (National Association of State Foresters, 2002; Statistics Canada, 2001; N.D. Farmers Union and U.S. Geological Survey, 2003a, Bangsund et al., 2005), and the forested areas of the PCOR Partnership states can sequester approximately 1044 million tons of CO₂ per year for the next 50 years (McDougall, 1986; Manitoba Geography, 2005;

Table 3. Estimated Idealized Geologic Sequestration Capacities of the PCOR Partnership Region for Geologic Sinks That Have Been Characterized Thus Far

Geologic Sink	Sequestration Capacity, million tons CO ₂
Mississippian Madison saline aquifer system	60,000
Lower Cretaceous saline aquifer system	161,000
Powder River Basin coal seams	6,800
North Dakota lignite deposits	380
EOR in selected oil fields	10,000
Oil and gas fields in Alberta, Manitoba, and Saskatchewan	3,200
Total	241,380

Coleytown Middle School, 2005; IEA Greenhouse Gas R&D Programme, 2005). It is estimated that wetland restoration in the Prairie Pothole Region (PPR) has the potential to sequester approximately 55 million tons of CO₂ per year over the next 10 years (Gleason et al.; 2005); however, Euliss et al. (2005) have indicated that levels of accumulated carbon could be as much as 153 million tons of CO₂ per year over the same time frame. Peat lands are expected to store approximately 49 million tons of CO₂ per year (N.D. Farmers Union and U.S. Geological Survey, 2003b; Iowa State University, 2005; U.S. Fish & Wildlife Service, 2005a), and grasslands in this region have the potential of sequestering approximately 193 million tons of CO₂ per year (National Association of State Foresters, 2002; European Commission Joint Research Centre, 2003; Brenner et al., 2001).

Table 4 shows that the region's terrestrial sinks can sequester about 1409 million tons of CO₂ per year for at least the next 50 years, which is more than six times the region's annual transportation-related CO₂ emissions.

Terrestrial sequestration results from land management practices that promote carbon buildup in biomass and soils. These practices also have positive environmental effects and include adopting conservation tillage, reducing soil erosion, and minimizing soil disturbance; using buffer strips along

waterways; enrolling land in conservation programs; restoring and better managing wetlands; restoring degraded lands; converting marginal croplands to wetlands or grasslands; eliminating summer fallow (Lal et al., 1999; Cihacek and Ulmer, 2002) using perennial grasses and winter cover crops; and fostering an increase in forests (Peterson et al., 1999).

Based on carbon data on wetlands in cropland collected during 1997 by the U.S. Geological Survey (USGS) and the 1997 National Resources Inventory, restoration of cropland wetlands would result in the sequestration of more than 70 million tons of soil organic carbon in the U.S. PPR. This preliminary estimate is conservative and does not account for carbon stores in wetland vegetative communities or for other greenhouse gas (GHG) offsets associated with reduction in methane and nitrous oxide; both GHG benefits are expected to be significant.

IDENTIFYING THE MOST PROMISING OPPORTUNITIES FOR GEOLOGIC CO₂ SEQUESTRATION IN THE PCOR PARTNERSHIP REGION

Method Used to Match Geologic Sinks and CO₂ Point Sources

The PCOR Partnership's CO₂ source and sink data are housed in the PCOR Partnership Decision Support System (DSS), which is an interactive, Web-based

Table 4. Estimated Terrestrial Sequestration Capacities of the PCOR Partnership Region for Terrestrial Sinks That Have Been Characterized Thus Far

Terrestrial Sink	Sequestration Potential, million tons CO ₂ /yr
Forests	1044
Wetlands	55
Agricultural Lands (crop-, range-, and grasslands)	261
Peat Bogs	49
Total	1409

geographic information system (GIS) database designed to facilitate CO₂ sequestration scenario development. The DSS is used to identify the character and spatial relationships of sources, sinks, and infrastructure. The DSS has also been used to locate areas that may present challenges with regard to deployment, such as national wildlife refuges, national parks, and national forests and grasslands. The DSS provided the data used during the CO₂ source-sink matching activity.

An objective method for matching CO₂ point sources with sinks was used to identify the most promising geologic CO₂ sequestration opportunities in the PCOR Partnership region. A series of Excel™ spreadsheets containing the CO₂ source data, geologic sink types and capacities, CO₂ capture and separation technologies (both those currently in use as well as those still under development) and the source types to which they could be applied, transportation options, and deployment issues (including permitting and MMV) were generated using data from the DSS. The largest CO₂ sources were screened according to their source type (e.g., electrical utility, ethanol production, metals processing) to group sources that produce similar exit streams. These source subgroups were sorted by quantity of CO₂ produced, the percentage of the exit stream comprised of CO₂, and the presence of SO₂ and/or NO_x or other compounds to better define the CO₂ streams' compositions and potential means of capture.

To match a source to a sink, the DSS was used to locate the individual CO₂ sources. Sources having similar physical properties and located in relatively close proximity to each other were consolidated into a single source. A buffer of a desired distance (125 miles) was drawn around the center of the consolidated source, and any viable geologic sinks located within that buffer were identified. The type of sequestration that could be performed in those sinks (e.g., EOR, injection into a saline formation) was determined from the data in the DSS. For each match of geologic sink and consolidated CO₂ source, called a scenario, the types of technologies that might be used to separate and capture the CO₂ for sequestration were identified, if possible. It should be noted that current capture and separation technologies are too expensive under current market conditions for many of the streams generated in the PCOR Partnership region, either because the types or quantities of impurities present in the stream would prevent effective separation and capture or because the operating pressures of a particular stream composition are not appropriate for the technology.

Identification of Potential Sequestration Strategies

The data from the DSS were used to identify the most promising sequestration scenarios in two categories: short-term, commercially viable (or nearly so) scenarios that can sequester regionally significant amounts of CO₂ within the 2012 time frame outlined in the *Carbon Sequestration*

Technology Roadmap and Program Plan and long-term opportunities that can sequester globally significant amounts of CO₂ but require the technological advances and infrastructural improvements provided by meeting the 2012 Roadmap goals.

The various scenarios were compared and groups of similar scenarios, called sequestration strategies, were formed. Based primarily on source types and major geologic sinks, the sequestration strategies that were identified were:

- CO₂ from coal-fired electricity generation facilities used for EOR, injected into a saline formation, or injected into a coal seam for ECBM production.
- CO₂ produced from natural gas processing and transmission sites injected into a coal bed for ECBM production, a petroleum reservoir for EOR, or a saline formation.
- CO₂ produced during ethanol production used for EOR, injected into a saline formation, or injected into another appropriate sequestration target.
- CO₂ from paper and wood product factories used for EOR, injected into a saline formation, or injected into a coal seam.
- CO₂ from cement/clinker production used for EOR, injected into a saline formation, or injected into a coal seam.

While these strategies include both the PCOR Partnership region's major point source and sink types, some of them are more likely to be employed than others. The region contains several major electricity-generating facilities in the immediate vicinity of coal beds, oil fields, and saline formations. Natural gas

production often occurs in conjunction with oil production or in unminable coal seams; both areas are amenable to sequestration opportunities. Ethanol facilities produce significant quantities of very pure CO₂ streams but are often not located near the major sinks; the location of future ethanol facilities may be influenced by opportunities for EOR or ECBM. At least one ethanol facility is planned for western North Dakota, which would be in the immediate vicinity of some of the region's best sinks.

Paper and wood products are produced in Wisconsin and northern Minnesota. While these sources are not located in close proximity to any oil fields, coal fields, or saline formations, future oil and gas prices may be sufficient to support the construction of pipelines from these areas to oil or coal fields in the Williston Basin or Illinois Basin. Finally, there are only 16 cement/clinker facilities in the region, and they are widely dispersed. Their exit gas streams have a higher concentration of CO₂ than coal-fired power plants (roughly 35% to 15%, respectively), potentially making them a regionally important source.

Our analysis identified four strategies that are most likely to be employed in the region in the long term:

- CO₂ from coal-fired electricity generation facilities used for EOR, injected into a saline formation, or injected into a coal seam for ECBM production.
- CO₂ produced during ethanol production used for EOR, injected into a saline formation, or injected into another appropriate sequestration target.
- Acid gas produced from oil and gas-processing activities injected into an oil field for EOR.

- CO₂ from cement/clinker production used for EOR, injected into a saline formation, or injected into a coal seam.

Relative Economics of the Strategies

One of the most expensive aspects of CO₂ sequestration is the capture and separation of the CO₂ from the source's exit stream. CO₂ produced during ethanol manufacture requires only dehydration and compression. The cost of capture and separation for the CO₂ produced by the power plants and cement/clinker production was estimated using a spreadsheet tool prepared by PCOR Partnership project personnel. The spreadsheet calculates performance and cost estimates for various CO₂ separation and capture scenarios for power generation, petroleum refining, and cement production. An effort was made to provide consistent estimates across all of the options; therefore, the results are best used for screening and comparison. Because performance and cost for many components within the systems are variable, plant-, site-, or technology-specific evaluations require additional process design and engineering for each specific case. Costs and other impacts of replacement power are not currently considered in the spreadsheet tool. All of the spreadsheets calculate costs for the production of the CO₂ stream at pressures ranging from 1500 to 2800 psi, the appropriate pressure for pipeline transport and sequestration. The spreadsheet was developed using the guidelines prescribed in the *Carbon Capture and Sequestration Systems Analysis Guidelines* prepared by the U.S. Department of Energy National Energy Technology Laboratory and dated April 2005.

Using the spreadsheets, the capture and separation cost using amine scrubbing was estimated for the largest CO₂ source in the region, the Coal Creek Station in western North Dakota, as well as for a

cement/clinker plant in Edmonton, Alberta. This cost includes the cost of compression to pipeline pressures. It was assumed that the pipeline costs, actual injection, instrumentation, and monitoring costs would be similar, irrespective of strategy. The estimated costs for each strategy are shown in Table 5. As the table shows, the cost estimates indicate that, when an ethanol plant of sufficient capacity is located in the vicinity of EOR or ECBM opportunities, this type of strategy is the most cost-effective. While the coal-fired power plants that are currently on line in the PCOR Partnership region are by far the largest producers of CO₂, and the spreadsheet results suggest that the use of CO₂ from these plants for EOR activities may be economically viable, the reality is that most of these plants have fundamental design characteristics that significantly impede the addition of large-scale capture technologies. The parasitic power loads that are necessary to run amine-based capture technologies and compressors are also factors that work against the use of CO₂ from existing coal-fired power plants in the region for EOR and/or ECBM activities. However, CO₂ capture and compression from power plants that utilize integrated gasification combined cycle (IGCC) technology may be economical. Depending on the future location of IGCC power plants and the future of oil and gas prices, IGCC power plants in the PCOR Partnership region will likely be significant providers of CO₂ to tertiary oil recovery projects in the region.

Selection of Phase II Demonstration Projects

The strategies that were identified during sink-source matching offer the most promising long-term opportunities for large-scale geologic sequestration in the PCOR Partnership region. However, because current capture and separation technologies are not applied to many of the streams either because of volume or impurity type/concentration, they are not

Table 5. Estimated Costs for Various CO₂ Sequestration Strategies

Strategy/Source Type	CO ₂ Emissions, tons CO ₂ /yr (assuming an 80% capacity factor)	Approximate Distance from Sinks, mi	Capture or Avoided Cost (for power plant), \$/ton CO ₂	Value of By-Products, \$/ton CO ₂	Cost of the Strategy (not including actual injection, MMV, etc.) ^a , \$/ton CO ₂
Power Plant/EOR	8,469,638	75	26.69	114.24 ^b	-87.55
Power Plant/ECBM	8,469,638	100	26.69	0.10 ^c	26.59
Power Plant/Saline Aquifer	8,469,638	25	26.69	0.00	26.69
Ethanol Plant/EOR	53,536	150	9.00 ^d	114.24	-105.24
Ethanol Plant/ECBM	53,536	175	9.00	0.10	13.40
Ethanol Plant/Saline Aquifer	53,536	120	9.00	0.00	13.50
Cement Plant/EOR	777,086	170	43.07	114.24	-71.17
Cement Plant/ECBM	777,086	580	43.07	0.10	42.97
Cement Plant/Saline Aquifer	777,086	550	43.07	0.00	43.07

^a Negative costs indicate a profit made on the sequestration activity through sale of the by-products.

^b Calculated as follows: from Table 1 in Smith et al., 2005, it can be calculated that 2.04 bbl oil are recovered for each ton of CO₂ injected. At a fairly conservative cost of \$56/bbl, the value of the oil recovered would be \$56/bbl * 2.04 bbl/ton CO₂ = \$114.24/ton CO₂.

^c Calculated as follows: from the PCOR Partnership Phase II proposal, p. 8, total coalbed methane in the Harmon Seam is estimated to be 4.4 Tcf, and the effective CO₂ storage capacity is 328 million tons. At the current Henry Hub price of natural gas of \$7.34/mcf, the value of the methane recovered would be (\$7.34/1000 ft³) * (4.4 × 10⁹ ft³/328 × 10⁶ tons CO₂) = \$0.10/ton CO₂.

^d From Figueroa, 2005.

considered near-term approaches for CO₂ sequestration. Technology validation tests were therefore selected for Phase II that employ sequestration while generating offsetting revenue during the production of either oil or coalbed methane. This approach is likely to be the one taken while new capture and separation technologies are developed and the cost of existing technologies is decreased to a point where

simple sequestration is no longer cost-prohibitive. The selected demonstrations will provide the opportunity to test and evaluate various methods of sequestration that are short-term in nature as well as to provide additional data that may permit better definition of some of the long-term strategies. Many factors were considered when selecting specific scenarios for demonstration, including:

- The potential to provide the information needed to advance the long-term, large-scale sequestration opportunities for the region.
- The applicability of the technology to the PCOR Partnership region as well as elsewhere globally.
- The likelihood of sequestration permanence.
- Total sink (or similar sink) capacity.
- Economic considerations that could offset some sequestration costs with sales from products such as oil or methane.
- The logistics of performing the demonstration, such as construction and permitting requirements.
- Public acceptance.
- Buy-in by groups needed for injection operations.
- The ability of the scenarios to help meet the 2012 goals of the *Carbon Sequestration Technology Roadmap and Program Plan*.

Taking all of these factors into account, the geologic sequestration scenarios that will be demonstrated during Phase II are:

- CO₂ from the Dakota Gasification Company gasification plant used for simultaneous sequestration and EOR in an Amerada Hess oil field in western North Dakota.
- Acid gas (65% CO₂, 35% H₂S) from an Apache Canada Ltd. sour gas plant injected into a field in northwestern Alberta for simultaneous sequestration and EOR.

- CO₂ injected into economically unminable lignite seams to determine the suitability of these strata for both CO₂ sequestration and coalbed methane production.

These demonstrations make use of CO₂ produced either on-site (as in the case of the sour gas) or at the Great Plains gasification facility. Performing the planned demonstrations will provide detailed information needed for more robust economic analysis of CO₂ transportation, injection, and monitoring activities for direct sequestration of these CO₂ stream types.

Development of a PCOR Partnership Regional Carbon Management Strategy

The results of PCOR Partnership Phase I have pointed toward the need to develop a long-term vision for carbon management in our region. This vision requires consideration of the regional and world economic and socioeconomic trends. As the world and region contemplate a carbon-managed future, it is critical that both short-term and long-term strategies are developed to deal with carbon management issues. The eventuality of carbon management should have a marked effect on the types and locations of new energy production and industrial facilities that are built in the future and the development of infrastructure that facilitates carbon management. Advanced power production facilities, ethanol plants, cement/clinker production plants, and other stationary CO₂ sources should be located in a manner that considers the further development of the existing CO₂ pipeline. The expansion of regional CO₂ pipeline(s) should be planned to efficiently aggregate and transport CO₂ from existing and planned stationary sources. This pipeline would be initially employed for the dual purposes of enhanced resource recovery and sequestration and, eventually, for sequestration alone.

Table 6 provides estimates of the potential CO₂ available from selected existing CO₂ sources, while Table 7 provides estimates for future CO₂ sources. The CO₂ sources listed in Table 6 were selected on the basis of relative ease and economics of CO₂ capture and their proximity to enhanced resource recovery opportunities. Tables 6 and 7 also provide estimates of the resource recovery potential if the CO₂ from the selected sources and potential future sources were employed. Future work should contemplate the development of a regional CO₂ transportation pipeline that facilitates the use of CO₂ from selected stationary sources for enhanced resource recovery and sequestration. Although this concept is highly speculative, it provides a notion of the type of regional planning and coordination that will be required to facilitate carbon management in the future.

CONCLUSIONS

The exercise of identifying feasible sequestration strategies for the PCOR Partnership region showed that:

- CO₂ capture and separation technologies that can be economically applied to the majority of the large stationary sources (i.e., coal-fired power plants, cement kilns) in the PCOR Partnership region are needed before widespread CO₂ sequestration can be employed in our region. Amine scrubbing is probably the nearest to being commercially applied to these facilities, but development of emerging techniques that show promise should continue with these types of sources in mind.

Table 6. Williston Basin CO₂ Sources – Readily Capturable CO₂

Company	mcf/day
DGC	247,977
Grasslands	3,679
Lignite	909
Red Trail	7,700
Total	260,296*

* Enough CO₂ to produce 32,000 bb/day incremental oil.

Table 7. Williston Basin CO₂ Sources – Speculations on Future CO₂

Source	mcf/day (approximate year)
North Dakota & Saskatchewan Refineries	1000,000 (2010)
Minnesota Refineries	1000,000 (2015)
Excelsior, MN, IGCC ¹	150,000 (2010)
Leland Olds IGCC	150,000 (2015)
Estevan, SK IGCC	150,000 (2012)
ND Coal-to-Liquid	100,000 (2015)
New Ethanol	15,000 (2010)
Total New CO ₂	765,000 mcf/day ²

¹ Interstate Oil and Gas Compact Commission

² Has the potential to incrementally produce 95,600 bbl/day by the year 2015.

- CO₂ produced from sources in the southeastern portions of the PCOR Partnership region may not be able to be economically sequestered in PCOR Partnership geologic sinks. As a national program, it will be important that all sequestration options be investigated and infrastructure developed to enable the most cost-effective sequestration to be performed. This may require sequestration in other regions.
- Because of the overall cost reductions possible through the sale of oil or methane, sequestration that is performed concurrently with EOR or ECBM will likely be the only sequestration performed in the near term, absent other economic stimuli.
- It is imperative that regional carbon management strategies that coordinate the development and location of major stationary CO₂ sources be established in a manner that allows for the development of regional pipelines and aggregation facilities. In regions that are rich in fossil fuel resources (such as the PCOR Partnership region), the cost of developing much of this infrastructure may be offset by the economic benefits provided by enhanced resource recovery operations.

The PCOR Partnership Phase II field validation tests will provide the detailed information needed for more robust economic analysis and technical development for CO₂ transportation, injection, and monitoring activities needed to directly sequester CO₂ in the near term. The lessons learned during the demonstrations will be directly applicable to sequestration projects elsewhere in the PCOR Partnership region as well as globally.

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For more information on this topic, contact:

Melanie D. Jensen, EERC Research Engineer
(701) 777-5115; mjensen@undeerc.org

James A. Sorensen, EERC Senior Research Advisor
(701) 777-5287; jsorensen@undeerc.org

Edward N. Steadman, EERC Senior Research Advisor
(701) 777-5279; esteadman@undeerc.org

John A. Harju, EERC Associate Director for Research
(701) 777-5157; jharju@undeerc.org

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