A PHASED APPROACH TO DESIGNING A HYPOTHETICAL PIPELINE NETWORK FOR CO_2 TRANSPORT DURING CARBON CAPTURE, UTILIZATION, AND STORAGE

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 6 – Deliverable D84

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ABSTRACT

Carbon capture, utilization, and storage (CCUS) continue to receive considerable attention as a way to reduce U.S. carbon dioxide (CO_2) emissions. Substantial capital investment will be required to capture, compress, and transport the CO_2 to storage targets if the concept is deployed on a large scale. Unfortunately, many of the large CO_2 sources are not located near appropriate geologic storage areas, and it is likely that a pipeline network would be needed to transport the CO_2 from the sources to the storage sinks. It is highly unlikely that a pipeline network would be built quickly; rather, it is more likely that a network would be built in stages or phases. An effort was undertaken by the Plains CO_2 Reduction (PCOR) Partnership to estimate how a hypothetical CO_2 pipeline network might be built out in the PCOR Partnership region, over what time frame it might be built, and how much it might cost. It was found that a pipeline network of trunk lines roughly 6700 mi in total length could transport sufficient quantities of CO_2 such that the International Energy Agency (IEA) BLUE Map scenario could be met for the PCOR Partnership region by 2050. The IEA BLUE Map scenario represents a reduction in CO_2 emissions of 50% over 2005 levels by 2050. For the PCOR Partnership, this would be 444.7 Mtons/yr. The overall reduction for the PCOR Partnership region using this approach would be about 612.4 Mtons/yr by 2050.

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LIST OF ACRONYMS AND ABBREVIATIONS

CCUS	carbon capture, utilization, and storage
CEPA	Canadian Energy Pipeline Association
CO_2	carbon dioxide
DSS	decision support system
ECBM	enhanced coalbed methane
EIA	Energy Information Administration
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
IEA	International Energy Agency
IECM	Integrated Environmental Control Model
IOGCC	Interstate Oil and Gas Compact Commission
US$M	million U.S. dollars (in 2009 dollars in this report)
mi	mile
Mtons/yr	million short tons/year
MW	megawatt
NATCARB	National Carbon Sequestration Database and Geographic Information System
NETL	National Energy Technology Laboratory
NG	natural gas
O&M	operations and maintenance
PCOR Partnership	Plains CO_2 Reduction Partnership
ppmv	parts per million by volume
TWh	terawatt-hour; 1 TWh = 10^{12} Wh
U.S.	United States
yr	year

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EXECUTIVE SUMMARY

Carbon capture, utilization, and storage (CCUS) continue to receive considerable attention as an approach to reduce U.S. carbon dioxide (CO_2) emissions. Substantial capital investment will be required to capture, compress, and transport the CO_2 to storage targets if the concept is deployed on a large scale. Absent national policy or regulatory drivers, this huge capital cost means that the utilization of CO_2 for enhanced resource recovery (enhanced oil recovery [EOR] or enhanced coalbed methane [ECBM] recovery) is likely to provide the impetus for the early deployment of CCUS. National carbon management policies (i.e., carbon regulation by Congress and/or emission standards adopted by the U.S. Environmental Protection Agency [EPA]) likely would expand this deployment. Unfortunately, many of the large CO_2 sources are not located near appropriate geologic storage areas, either saline formations or enhanced resource opportunities, and it is possible that a nationwide pipeline network would be needed to transport the CO_2 from the sources to the storage sinks.

Various approaches could be taken to planning a national CO_2 pipeline network that supports CCUS (Bliss and others, 2010). One approach is a nationwide network that would transport CO_2 from the large industrial sources located in geographically diverse areas to large-scale geologic storage sites. A second model consists of a gradual build-out of regional networks in which large CO_2 point sources are connected to existing pipeline infrastructure that serves EOR operations with local storage. A third version considers that shorter pipelines would directly link many large CO_2 power plant sources with nearby storage locations. Because there are only a few thousand utility and industrial CO_2 emission sources and even fewer large geologic storage targets, it is more likely that the third approach will be the one that is implemented. In this scenario, a few very large CO_2 sources would feed dedicated pipelines that carry the gas to a few large EOR injection sites (Bliss and others, 2010). The CO_2 from smaller industrial sources is unlikely to be captured and transported in a pipeline network because the compression of small amounts of CO_2 for pipeline transport would make such a system cost-prohibitive (Bliss and others, 2010).

The cost of a CO_2 pipeline network is the subject of considerable interest, especially with regard to which entities might fund all or parts of a network. A blend of private and public sector involvement may be required to develop CCUS as a viable industry. The choice of which specific approach would be more appropriate would depend on the specific circumstance. For example, if the economics are positive, private funding may be sufficient to construct and operate a pipeline from a particular source or cluster of sources to an enhanced resource opportunity. Other pipelines may need government funding to defray a part of the costs, while still other pipelines may be mandated by the government to meet an emission reduction target without being economically viable, requiring government funding for the life of the project.

It is highly unlikely that a pipeline network would be built quickly as the drivers for rapid implementation of CCUS are not in place. Instead, it is more likely that a network would be built in stages or phases, with the first phase consisting of pipeline segments that connect sources with EOR opportunities, followed by the addition of other sources and sinks as dictated either by the marketplace (in the case of EOR) or national or regional carbon management policy.

An effort was undertaken by the Plains CO_2 Reduction (PCOR) Partnership to estimate how a hypothetical CO_2 pipeline network might be built out in the PCOR Partnership region, over what time frame it might be built, and how much it might cost.

A four-step, phased pipeline planning methodology was developed that can be used to compare hypothetical pipeline routes by relatively quickly estimating the amount of CO_2 that can be stored as well as the length and cost of the trunk pipelines required to store that CO_2. The approach is not intended to provide a method for developing a detailed pipeline network design.

This development methodology was applied to the PCOR Partnership region to estimate a hypothetical pipeline network that could be implemented in phases over the next 40 to 50 years. The volume of CO_2 that would be available from each cluster of sources was determined for three time periods (the present until 2035, from 2035 to 2050, and after 2050), and the most likely storage targets for each source cluster were identified. Hypothetical pipeline routes connecting the sources and sinks were determined. Finally, when viewed as a regional whole, the routes were optimized for each network phase.

It was found that a hypothetical pipeline network of trunk lines roughly 6700 mi in total length could transport sufficient quantities of CO_2 such that the IEA BLUE Map scenario could be met for the PCOR Partnership region by 2050. The IEA BLUE Map scenario represents a reduction in CO_2 emissions of 50% over 2005 levels by 2050 (International Energy Agency, 2010). For the PCOR Partnership, this would be 444.7 Mtons/yr. Meeting this target is dependent upon two major assumptions. The first, put forward by the Energy Research Group at Dalhousie University (Hughes and Chaudhry, 2010), is that the CO_2 output from Canada's electricity generation fleet will increase dramatically until at least 2050. The second assumption is that the Canadian government's goal of a 98% CO_2 emissions capture rate actually would be attained by 2050. These assumptions result in the storage of 369 Mtons/yr of CO_2 in the Canadian portion of the PCOR Partnership. When coupled with the expected U.S. CO_2 storage of 243.4 Mtons/yr, the overall reduction for the PCOR Partnership region is about 612.4 Mtons/yr by 2050.

Dooley and others (2009) estimated that about 28,000 mi of pipeline would be needed in the U.S. to meet the scenario in which the atmospheric CO_2 is stabilized at 450 ppmv by 2050. The pipeline estimates obtained using the PCOR Partnership methodology outlined here indicate that the length required for the U.S. portion of the region totals 3270 mi. At first glance, this seems a bit low, but when the number and distribution of regional storage targets are considered, it is obvious that the average pipeline segment would be shorter in the PCOR Partnership region than in many other areas of the United States.

According to the IEA, long-term strategies are needed to cluster CO_2 sources and develop CO_2 pipeline networks such that source-to-sink transmission of CO_2 is optimized. The preliminary phased hypothetical pipeline routing methodology developed by the PCOR Partnership could help to address this challenge.

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INTRODUCTION

Carbon capture, utilization, and storage (CCUS) continue to receive considerable attention as an approach to reduce U.S. carbon dioxide (CO_2) emissions. Substantial capital investment will be required to capture, compress, and transport the CO_2 to storage targets if the concept is deployed on a large scale. Absent national policy or regulatory drivers, this huge capital cost means that the utilization of CO_2 for enhanced resource recovery (enhanced oil recovery [EOR] or enhanced coalbed methane [ECBM] recovery) is likely to provide the impetus for the early deployment of CCUS. National carbon management policies (i.e., carbon regulation by Congress and/or emission standards adopted by the U.S. Environmental Protection Agency [EPA]) likely would expand this deployment. Unfortunately, many of the large CO_2 sources are not located near appropriate geologic storage areas, either saline formations or enhanced (EOR) opportunities, and it is possible that a national pipeline network would be needed to transport the CO_2 from the sources to the storage sinks.

There are benefits and challenges associated with a CO_2 pipeline network (Alberta Carbon Capture and Storage Development Council, 2009). Some of the cited benefits include:

- Reduction of cost through the transport of larger volumes of CO_2 in a given pipeline segment.
- Consolidation of pipelines, reducing their total environmental footprint.
- Prioritization of storage sites according to geotechnical quality.
- Open access to pipelines, providing fair space allocation to smaller sources. Multiple EOR markets and supply points would provide choice and volume security to all of the participants.

Cited challenges of a network approach include:

- The potential for inefficient development, poor timing, and a lack of private market or competition to minimize costs.

- Common carrier issues regarding the CO_2 quality specification required for EOR, which may be excessively stringent if the CO_2 will be stored in a saline formation.

There are over 4000 miles of CO_2 pipelines in the United States (Bliss and others, 2010). Figure 1 shows the current existing or planned CO_2 pipelines. The map shows that very few large industrial sources are connected by pipeline to a geologic sink, although pipeline networks have been built in the southwest and Gulf Coast portions of the United States to transport CO_2, mostly from natural geologic sources, to EOR opportunities.

Because the timing, severity, and manner of implementation of any future carbon management policies are unknown, it is reasonable to assume that any pipeline infrastructure build-out would be gradual rather than occurring within a short period of time (Bliss and others, 2010). Various approaches could be taken to planning a national CO_2 pipeline network that supports CCUS (Bliss and others, 2010). One approach is a nationwide network that would transport CO_2 from the large industrial sources located in geographically diverse areas to large-scale geologic storage sites. A second model consists of a gradual build-out of regional networks in which large CO_2 point sources are connected to existing pipeline infrastructure that serves EOR operations with local storage. A third version considers that shorter pipelines would directly link many large CO_2 power plant sources with nearby storage locations.

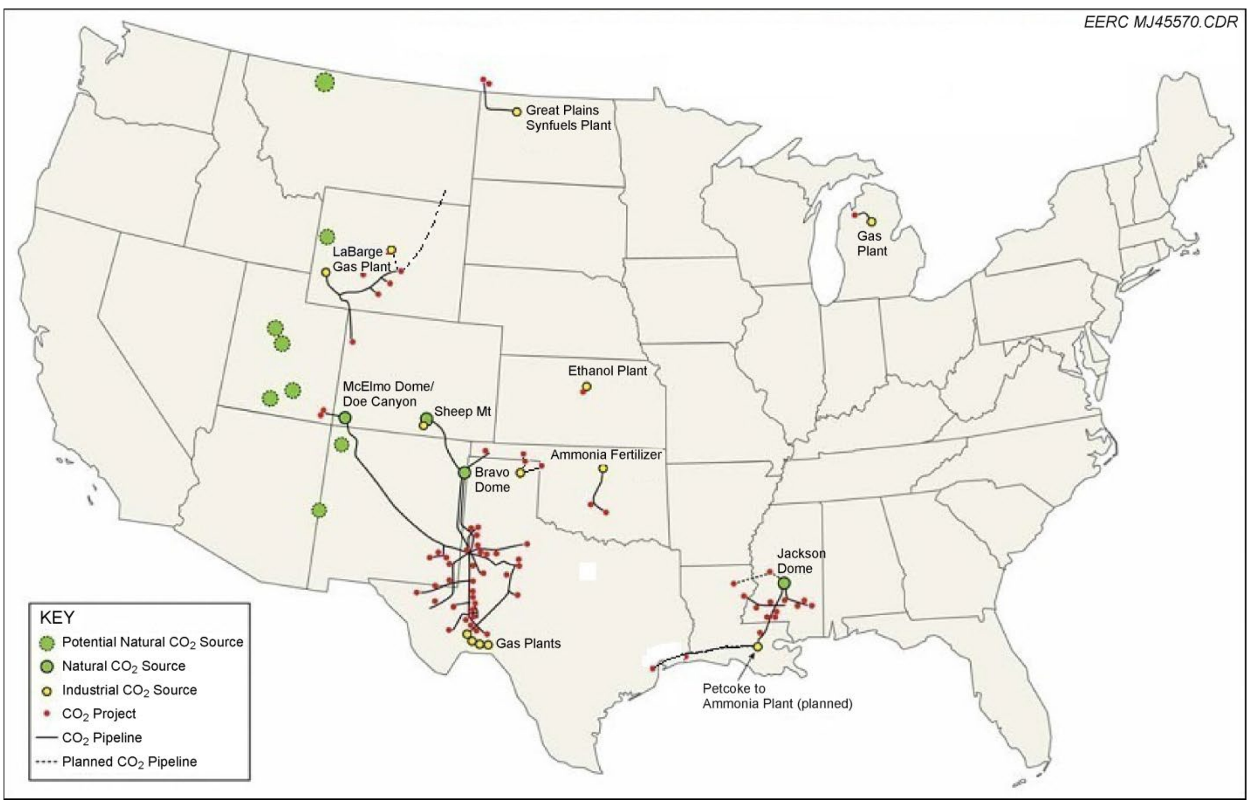

Figure 1. Active U.S. CO_2 pipeline and injection site infrastructure (map courtesy of Steven Melzer, Melzer CO_2nsulting, 2012; used with permission).

The first two of these models seem to be similar to the existing U.S. natural gas network, although the analogy is not completely accurate. The natural gas pipeline network links hundreds of thousands of individual gas sources with millions of individual delivery points. There are only a few thousand utility and industrial CO_2 emission sources and even fewer large geologic storage targets. Therefore, it is more likely that the third approach will be the one that is implemented, with a few very large CO_2 sources feeding dedicated pipelines that carry the gas to a few large EOR injection sites (Bliss and others, 2010). The CO_2 from smaller industrial sources is unlikely to be captured and transported in a pipeline network because the compression of small amounts of CO_2 for pipeline transport would make such a system cost-prohibitive (Bliss and others, 2010).

The cost of a CO_2 pipeline network is the subject of considerable interest, especially with regard to which entities might fund all or parts of a network. Three funding models have been identified by the Canadian Energy Pipeline Association (CEPA) (Alberta Carbon Capture and Storage Development Council, 2009):

- Market Approach – In this approach, pipelines are constructed as part of an overall project's commercial arrangement and would be built as either a single pipeline or a network, based on the economics and commercial terms of the project. Project economics would be sufficient to result in commercial agreements between parties, which ideally would allow the parties to minimize their capital investment by creating pipeline segments along similar corridors that could be applied to a future network.

- Market Backstop – This approach applies to incremental pipeline network infrastructure that would be uneconomic in the early stages based on initial market supply and demand. In this case, the government would provide financial backstopping. A market backstop model would make sense if the infrastructure would be required long-term and would only need government funds in the early stages of development.

- Market Franchise – The market franchise approach applies to a pipeline network that is required because of government policy decisions but is not economic. In this case, the government would provide all of the funding. If full government funding is provided, then the benefit to the public must equal the government's investment of guarantees.

All of these approaches offer a blend of private and public sector involvement in order to develop CCUS as a viable industry. The choice of which approach would be more appropriate would depend on the economics of the specific circumstance (Alberta Carbon Capture and Storage Development Council, 2009).

Similar models have been identified by the Interstate Oil and Gas Compact Commission (IOGCC). The IOGCC calls them the Dedicated Pipeline Model (either intrastate or interstate), which is roughly analogous to the CEPA market approach; the Open Access Model (either intrastate or interstate), which is similar to the CEPA market backstop; and the Government/Public Option Model, which roughly equates to the CEPA market franchise model (Bliss and others, 2010). Additional details about the IOGCC's models can be found in the IOGCC topical report entitled *A Policy, Legal, and Regulatory Evaluation of the Feasibility of a*

National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide (Bliss and others, 2010).

It is highly unlikely that a pipeline network would be built quickly as the drivers for rapid implementation of CCUS are not in place. Instead, it is more likely that a network would be built in stages or phases, with the first phase consisting of pipeline segments that connect sources with EOR opportunities, followed by the addition of other sources and sinks as dictated either by the marketplace (in the case of EOR) or national or regional carbon management policy.

According to the International Energy Agency (IEA) (2010), long-term transport strategies must be developed that will cluster CO_2 sources. In addition, pipeline networks must be developed that will optimize the transport of CO_2 to the sinks. Regulatory, access, public acceptance, and planning challenges will impact the development of appropriate pipeline routes. Addressing these challenges will require that incentives for the creation of CO_2 transport hubs be developed and that planning be initiated at a regional level (International Energy Agency, 2010). An effort was undertaken by the Plains CO_2 Reduction (PCOR) Partnership to estimate how a hypothetical CO_2 pipeline network might be built out in the PCOR Partnership region, over what time frame it might be built, and how much it might cost. The results of this effort are summarized in this document.

METHODOLOGY

Network Analogs

Various analogs for the hypothetical phased CO_2 pipelines were identified and researched, including the natural gas network, the electricity transmission grid, and the U.S. interstate highway system (Denning, 2004; Edgar and others, 1978; Kabirian and Hemmati, 2007; Kaplan, 2009; Lawrence Berkeley National Laboratory, 2012; Pérez-Arriaga, 2011; U.S. Energy Information Agency, 2009). The primary function of these three systems is the bulk transfer of commodities from the source side to the demand (or destination) side. In most cases, the sources and destinations are geographically scattered, and the transfer system is in the form of a network.

It should be remembered that the natural gas network, the electricity transmission grid, and the highway system are "many-to-many" networks that link hundreds of thousands of sources with hundreds of thousands of end users. By contrast, the CO_2 pipeline network is far more likely to be a "few-to-few" network, with the CO_2 from a few large sources being transported to a few large geologic sinks. The three analog networks were studied because the planning that went into them can inform a well-reasoned CO_2 pipeline network design.

Network Components

The basic components of a network are nodes and links (Denning, 2004). Nodes represent source and destination points or clusters, while links connect pairs of nodes and represent the relationship between them. A network usually consists of the transmission (primary) network and the distribution (secondary) network (Kabirian and Hemmati, 2007). The transmission network includes the nodes and the trunk lines between the nodes. The distribution network includes the branch lines radiating from a node to individual sources and destinations. The electric transmission grid, natural gas transmission pipelines, and interstate highway system are examples of a primary network. Similarly, the electricity distribution system, natural gas distribution system, and local roads make up the secondary network.

The properties of the links (e.g., length and delivery rate) are determined by the characteristics of the nodes that they connect. Key issues in the design procedure consist of locating the nodes and determining the delivery capacity of the routes. A node should be placed in a position where the access cost to it from the individual sources or sinks is lowest. The delivery rate of the trunk line should be sized to be economical yet able to accommodate demand increases in the future. The routes should be selected to minimize both cost and environmental impact. The operation of CO_2 pipelines indicates that they do not represent a significant risk in terms of potential for release (Gale and Davison, 2004). Construction costs are impacted by factors associated with the route, including land slope, infrastructure, land use, population density and property value (Frankel, 2008; Fritze, 2009). The final version of the network should have the flexibility to be expanded and modified.

Comprehensive CCUS infrastructure planning should integrate the cost of CO_2 capture, compression, transfer, injection, and storage in order to optimize the performance and reduce the cost (Marston, 2010; Middleton and Bielicki, 2009). Because the pipelines serve as links in the network, the properties of the nodes (sources and sinks) should be well understood during hypothetical pipeline planning. Any CO_2 pipeline network likely will not be constructed all at once; rather, nodes and trunk lines will be added to the network gradually, and cost-effective performance of the CCUS system may require that the network build-out take place in multiple phases over the course of many years.

Determining the Timing for the Hypothetical Pipeline Phases

The first step in determining the timing of the hypothetical pipeline phases requires a presumption of how aggressively CCUS will be pursued in a region based on various approaches. The IEA's BLUE Map scenario has put forth the concept of a 50% emission reduction (compared to levels from the year 2005) by 2050 (International Energy Agency, 2010). This reduction falls between the two approaches outlined by Dooley and others (2004) when they examined the effects on the U.S. electricity generation assets of stabilizing atmospheric concentrations of CO_2 at 450 ppmv and at 550 ppmv. Their results are summarized in Table 1. The table shows that, as expected, the capture percentages are very different for the two scenarios.

Not only do the emissions vary dramatically within the United States depending on which approach is taken, but there are radical differences between the projected U.S. and Canadian emissions. The Energy Research Group at Dalhousie University projected Canadian electricity generation trends through 2050, as well as the CO_2 capture percentage required to meet the government's goals (Hughes and Chaudhry, 2010). Unlike the relatively stable size of power generation in the United States, electricity production in Canada is predicted to increase

Table 1. Impact of Atmospheric CO_2 Concentration Stabilization on the U.S. Fossil Fuel-Fired Electrical Generation Fleet

450-ppmv Impact on Fossil Fuel-Fired U.S. Electric Generation (TWh)				
	2005	2020	2035	2050
Coal and NG[a] Without CCUS	2377	2170	1194	522
Coal and NG with CCUS	0	472	1130	1,882
Total Coal and NG Generation	2377	2642	2324	2404
Captured and Stored, %	0	18	49	78
550-ppmv Impact on Fossil Fuel-Fired U.S. Electric Generation (TWh)				
	2005	2020	2035	2050
Coal and NG Without CCUS	2377	3370	3819	2800
Coal and NG with CCUS	0	277	339	752
Total Coal and NG Generation	2377	3647	4158	3552
Captured and Stored, %	0	8	8	21

[a] Natural gas.

dramatically through 2050. Even though renewable (hydropower) and nuclear production will increase significantly, the generation capacity based on coal and natural gas are predicted to increase at a rapid rate, as shown in Table 2. In order to meet the Canadian government's greenhouse gas reduction plan, 77% of the CO_2 from the electrical generation sector will have to be captured by 2035. This capture rate increases to 98% by 2050. This is shown in Table 3. It was assumed that the same percentage reduction would be required for large facilities in other emission sectors.

Although the reductions that will stabilize the atmospheric CO_2 concentration at 450 ppm appear to be so stringent as to be nearly unattainable, the timing seems to appropriately delineate the breaks between phases of hypothetical pipeline development and was, therefore, adopted for this study. As a result, Phase I was defined as lasting from about 2015 to 2035, with Phase II running from 2035 to 2050, and Phase III beginning in 2050.

Table 2. Projected Production of Electricity from Coal and Natural Gas in Canada

	2008	2020	2030	2040	2050
Total Coal and NG Generation, TWh	134	200	294	380	467
Percent Increase from 2008		49%	119%	184%	249%

Table 3. Changes in Amount of CO_2 That Must Be Captured and Stored to Meet the Canadian Government's Greenhouse Gas Reduction Goals

	2008	2020	2030	2040	2050
Coal and NG Without CCUS, TWh	134	138	101	52	11
Coal and NG with CCUS, TWh	0	62	193	328	456
Total Coal and NG Generation, TWh	134	200	294	380	467
Percent Captured and Stored	0%	31%	66%	86%	98%

The PCOR Partnership Methodology for Development of Hypothetical Phased CO_2 Pipeline Networks

Other CO_2 pipeline design work by Fritze (2009), Jeffries (2009), Morbee and others (2010), Parfomak and Folger (2008), Parfomak and others (2009), Pershad and others (2010), and Zakkour (2008) was studied. The results were combined with the network design concepts described in the previous text to develop a four-step pipeline planning methodology that features primary and secondary trunk lines as well as source and sink nodes, all implemented in a phased fashion. The four steps are:

1. Selecting, identifying, and clustering the sinks and sources and locating the nodes in the network.

2. Determining the volume of CO_2 to be transported at different phases.

3. Connecting the route between the nodes.

4. Optimizing the network for each phase.

This is not intended to be a detailed CO_2 pipeline network design but is instead a method that can be used to compare routes by relatively quickly estimating the amount of CO_2 that can be stored as well as the length and cost of hypothetical trunk and branch pipelines required to store that CO_2.

Clusters of CO_2 sources are identified by noting which sources are proximally located to each other on the map. The CO_2 emission rate for each of the sources is then taken from one of the many online emission databases such as the EPA e-GRID, the EPA Clean Air Market Data and Maps searchable database, the EPA Greenhouse Gas online data publication tool, or the PCOR Partnership decision support system (DSS) emission data set. An appropriate capture level should be assumed for the emissions from a particular source type. Virtually all of the biogenic CO_2 (i.e., CO_2 from the fermentation process) from an ethanol plant will be captured, but it is likely that only 90% of the CO_2 will be captured from a facility using a solvent scrubbing system to separate the CO_2 from a flue gas stream.

To estimate the future CO_2 emissions of the sources, expected emission trends are determined and applied to the known emission values. The U.S. Energy Information Administration (EIA) publishes CO_2 emissions and emission forecasts from electricity generation in the United States from 2010 to 2035, which allows emission trends to be determined. It was assumed that the emission trends for electricity generation would also apply to CO_2 emission from larger facilities of other industrial sectors. Estimates of CO_2 emission trends through 2050 can be found in the projected data provided by the Rocky Mountain Institute for the Midwest Reliability Council (Rocky Mountain Research Institute, 2012). The CO_2 trends from both data sources are presented in Table 4. As the table shows, it can be assumed that CO_2 emissions will increase by 10% from 2010 to 2035 and by 11% from 2010 to 2050.

The CO_2 storage capacity of each sink or sink cluster must be researched. Some data sets containing this information are available online, including the partners-only PCOR Partnership DSS and the National Energy Technology Laboratory's (NETL's) National Carbon Sequestration Database and Geographic Information System (NATCARB) data set.

Pipeline routes can be determined using a pipeline routing software or can be roughly determined by measuring the distances between the centroid of the cluster of CO_2 sources and the centroid of the sink cluster. Because of the size of the large saline formations, it makes more economic sense to consider a pipeline carrying CO_2 to them to terminate reasonably near the edge of the formation (within roughly 25 mi). The pipeline could be extended later if necessary. Pipeline costs can be estimated using the Carnegie Mellon University Integrated Environmental Control Model (IECM), a free product that is readily available online.

While the easiest sources from which to capture CO_2 are ethanol plants and gas-processing facilities, the earliest storage (i.e., Phase I) likely will be in areas in which the CO_2 can be profitably used, such as during enhanced resource development activities (i.e., EOR or ECBM production). Many gas-processing facilities are situated on or near oil fields, making them ideally located for this type of activity, assuming that the product from several facilities can be gathered to form a large enough stream to supply an EOR project. Ethanol plants, on the other hand, are more widely distributed and may not be located proximally to storage sinks. The majority of the ethanol plants probably will not come into play until late in Phase II or during Phase III hypothetical network development because the value of the CO_2 volumes, even when consolidated, will not exceed the cost to dehydrate, compress, and build a lengthy pipeline to transport the CO_2 to a storage target. In general, the emissions from ethanol- and gas-processing plants are not large and would have to be combined with emissions from other small plants in order to make it worth the expense of laying a pipeline, especially one that could ultimately become a trunk line. It is more likely that the CO_2 emissions from these smaller sources would be stored only if they were located near one another and were close to the storage target(s). Besides larger gas-processing plants and well-situated large ethanol plants, other Phase I sources that would be included in a hypothetical Phase I network would be any power plants having corporate reasons for being an early adopter (e.g., government grants, etc.).

Some of the hypothetical Phase I pipelines may be "one-to-one" pipelines that connect a particular source to a specific nearby sink. The most noticable example of this is the connection of a gas processing facility with local oil fields where the CO_2 will be used for EOR. It is expected that hypothetical Phase I pipelines will be a combination of judiciously sited pipelines

Table 4. CO_2 Emission Trends over Time

Total CO_2 Emission by Power Generation		2010	2020	2035	2050
United States	Million tons	2538	2452	2784	2800
Midwest Reliability Council Region	Million tons	213	197	235	NA
United States	Increase % from 2010		−3.39%	9.67%	10.31%
Midwest Reliability Council Region	Increase % from 2010		−7.79%	10.10%	NA

linking several sources (i.e., a source cluster) to a sink (or a cluster of sinks in a localized area) and one-to-one pipelines transporting CO_2 between one specific CO_2 source to a specific storage target. If possible, existing pipelines could be incorporated into a hypothetical pipeline network.

Some of the Phase I pipelines may be “one-to-one” pipelines that connect a particular source to a specific nearby sink. The most noticable example of this is the connection of a gas processing facility with local oil fields where the CO_2 will be used for EOR. It is expected that Phase I pipelines will be a combination of judiciously sited pipelines linking several sources (i.e., a source cluster) to a sink (or a cluster of sinks in a localized area) and one-to-one pipelines transporting CO_2 between one specific CO_2 source to a specific storage target. If possible, existing pipelines could be incorporated into a preliminary pipeline network.

Phase II of a hypothetical network would incorporate more power plants, some of the larger industrial facilities (particularly cement kilns), and the rest of the ethanol and gas-processing facilities. Target geologic sinks would include the rest of the EOR opportunities as well as nearby saline formations. Some of the hypothetical pipelines in this phase would be the branch lines as well as trunk lines.

Phase III of a network will come into play if sufficiently stringent climate policy and regulations have been put into place so as to force more widespread adoption of CCUS. This phase will include the remainder of the larger coal-fired power plants that must capture CO_2 as well as larger industrial facilities. Target geologic sinks added to the hypothetical network at this point would consist primarily of saline formations. During this phase, the trunk lines could be connected to other trunk lines in the network, and feeder lines could be added from large facilities to hook them up with the branch lines. It is also possible that it might not make economic sense to connect all of the pipeline segments together to form a single hypothetical network during Phase III. In this case, there might be multiple pipeline segments connecting specific source and sink clusters as well as smaller hypothetical pipeline networks serving specific areas.

A flow diagram of the methodology that was developed for determining the routes for a CO_2 transmission network is summarized in Figure 2. The flowchart shows that, in Phase I, clusters of sinks and sources are formed. Because this phase is driven by economics, emission sources would be selected based on their proximity to the EOR sinks. This methodology assumes that the life of an EOR project is 20 years (Tzimas and others, 2005). Therefore, the annual CO_2 injection rate was calculated by dividing its EOR CO_2 capacity by 20. It can be expected that the CO_2 demand by the oil fields would be much greater than the amount captured during Phase I; therefore, the hypothetical pipelines built during Phase I should have large enough capacities to be able to transport additional CO_2 in the ensuing phases.

Some of the sinks used in Phase I would not be completely filled at the end of Phase I. If the transport cost to the older sinks is lower than the cost of transport to new sinks, the old sinks will continue to be used in Phase II. As more sources are included in Phase II, new sinks will be opened, and the hypothetical pipeline network will be expanded. Expansion will be based on the existing Phase I pipelines so as to minimize cost. Possible expansion methods include using the same hypothetical Phase I pipeline corridor and adding branch lines to the old trunk line. The

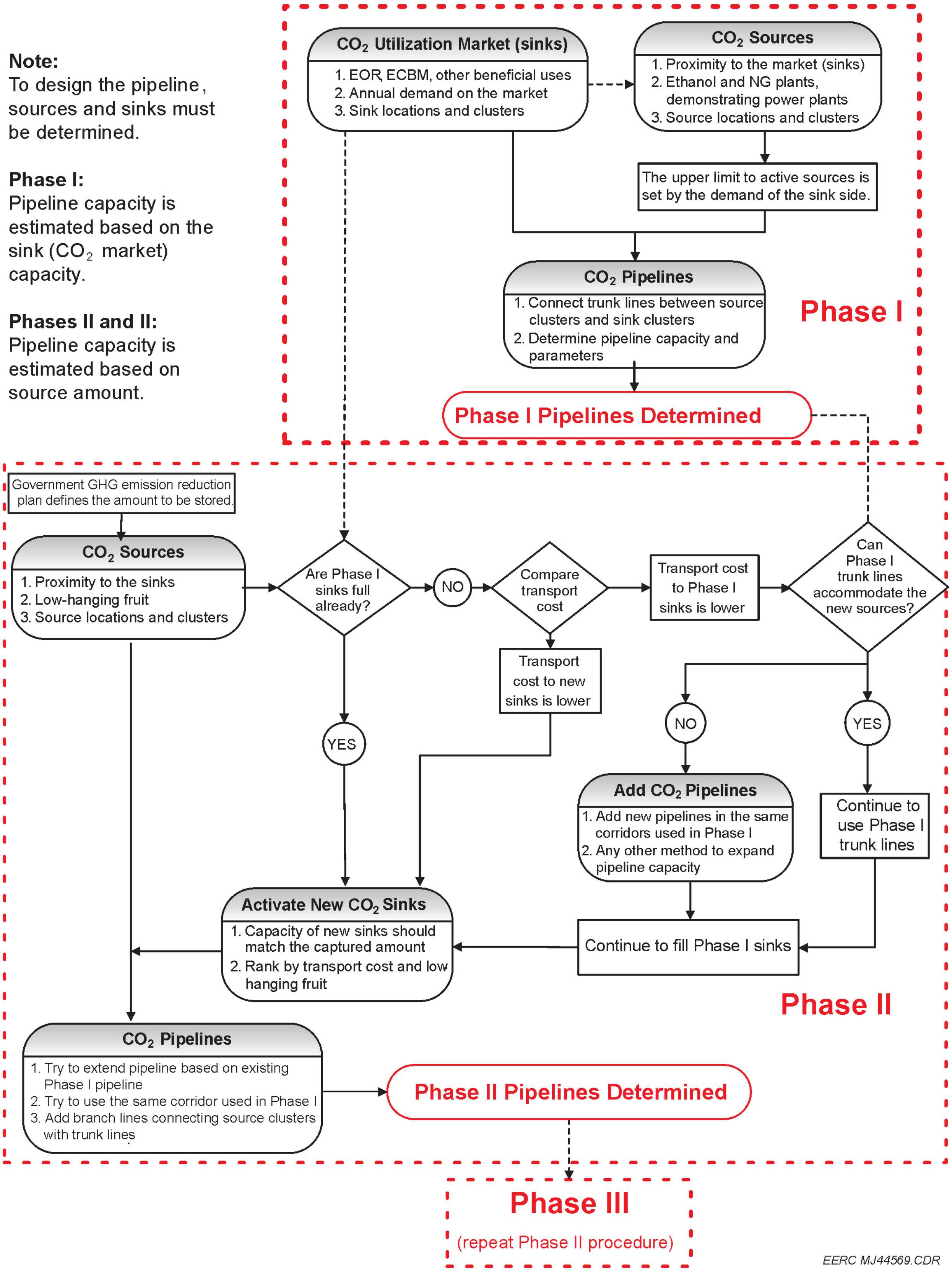

Figure 2. Flowchart summarizing the pipeline network development methodology.

goal of Phase II would be a 50% reduction in CO_2 emissions by 2050, when Phase III would go into effect as a “maintenance” phase in which some hypothetical pipelines would be extended to allow CO_2 to reach different storage targets if the first ones have been filled.

RESULTS – A CASE STUDY OF A HYPOTHETICAL PIPELINE NETWORK FOR THE PCOR PARTNERSHIP REGION

The pipeline network development methodology described earlier in this document was applied to the PCOR Partnership region to estimate a hypothetical pipeline network that could be implemented in phases over the next 40 to 50 years. The oil fields, coal seams, and saline formations that are available for CO_2 storage in the PCOR Partnership region are shown in Figure 3, while the CO_2 emission sources are shown in Figure 4. For each state or province, clusters of CO_2 emission sources and geologic sinks were identified. The volume of CO_2 that would be available from each cluster of sources was determined for three time periods (the present until 2035, from 2035 to 2050, and after 2050), and the most likely storage targets for each source cluster were identified. Hypothetical pipeline routes connecting the sources and sinks were determined. Finally, when viewed as a regional whole, the routes were optimized for each network phase. The following text describes the results of this case study, beginning with the Canadian provinces.

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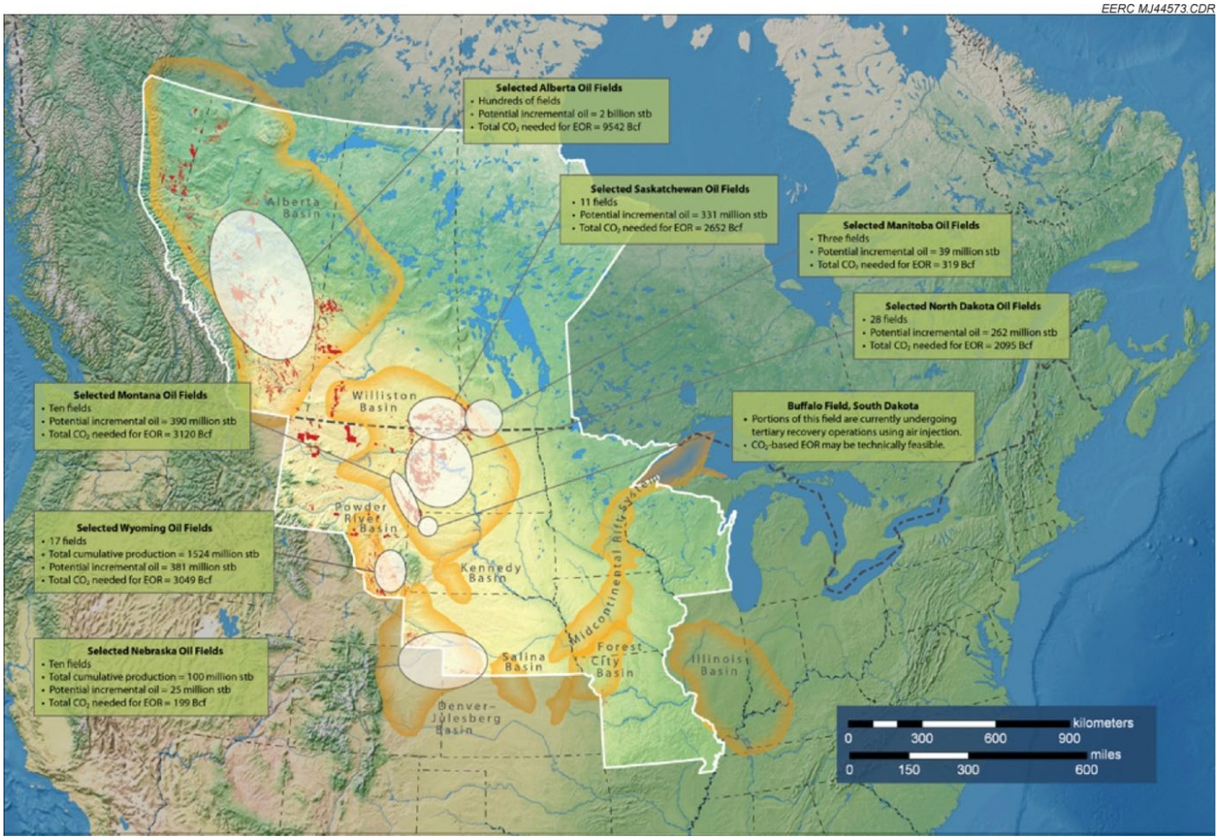

Figure 3. Geologic sinks available for CO_2 storage within the PCOR Partnership region.

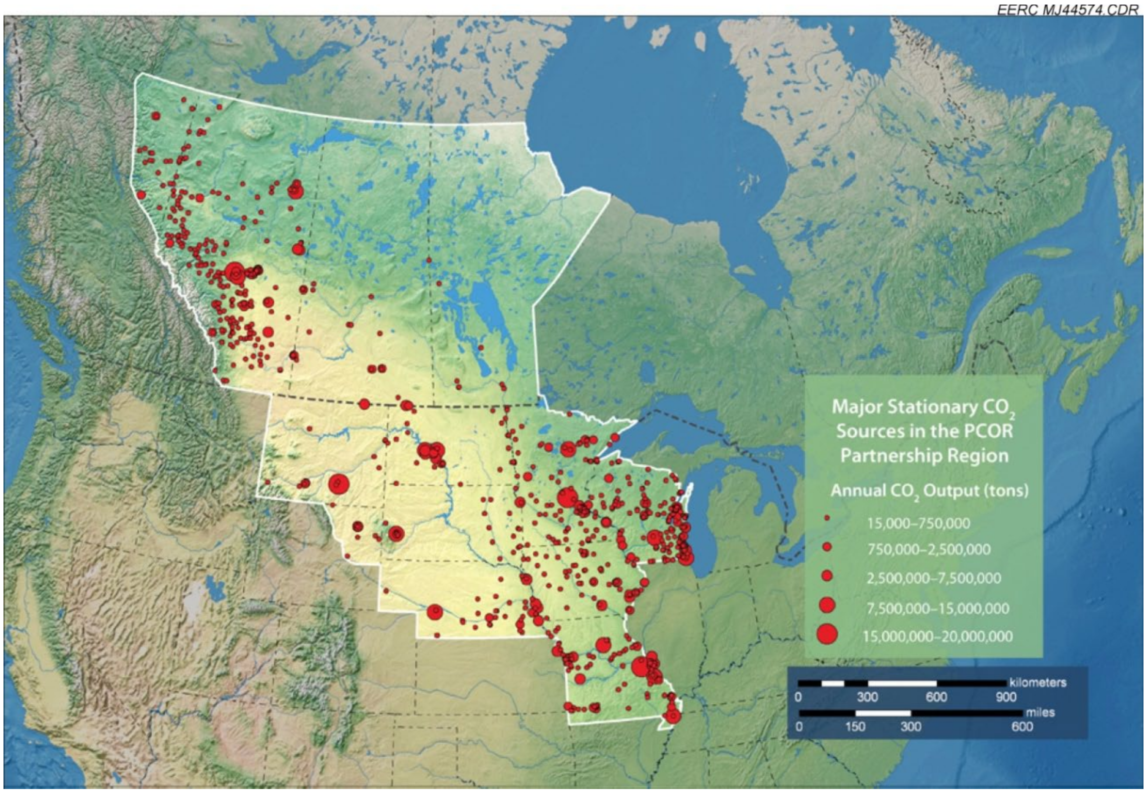

Figure 4. CO_2 emission sources in the PCOR Partnership region.

Canadian Provinces

The PCOR Partnership contains the Canadian provinces of Manitoba, Saskatchewan, and Alberta, as well as the northeastern corner of British Columbia. In this area of the PCOR Partnership, a significant portion of the CO_2 emission sources are close to injection sites because of the wide distribution of oil fields. Twenty-six storage target clusters were identified based on the distribution of oil fields and coal deposits with ECBM potential; these are shown in Figure 5.

Twenty-seven emission clusters were noted for the region and are shown in Figure 6. The future CO_2 emissions of these clusters were estimated based on the Government of Canada's aggressive greenhouse gas emission reduction plan developed in 2007 that was discussed earlier in this document.

The Alberta Basin holds great potential for CO_2 EOR opportunities, and almost all of the CO_2 injected in Phase I would be used in the oil fields, significantly offsetting the cost associated with the CCUS process. The sink–source pairs identified for Phase I were determined by the EOR capacity of the oil fields and their proximity to the emission clusters. The delivery capacity of the pipelines was defined by both the estimated emission level in 2035 and the injection rate of the EOR sinks. The cumulative amount of CO_2 injected during Phase I was calculated and compared with the total EOR capacity of the sinks. If any EOR capacity remained at the end of Phase I, that capacity was utilized in Phase II.

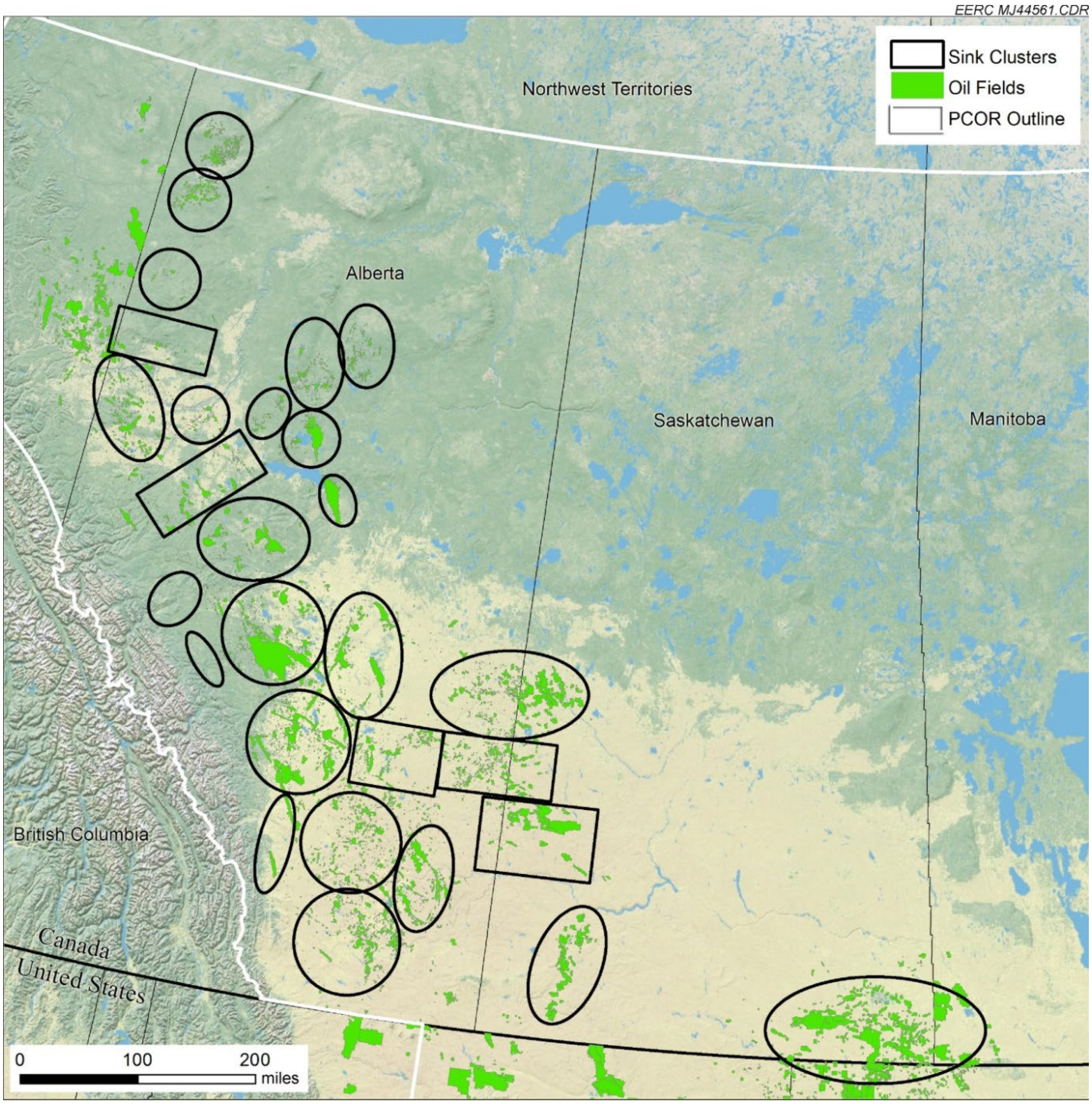

Figure 5. Storage target clusters identified for the Canadian provinces in the PCOR Partnership region.

After the CO_2 injection no longer results in incremental oil production, the CO_2 could be injected into the depleted oil fields for permanent, although nonbeneficial, storage. New hypothetical pipelines had to be developed for Phase II as the number of emission clusters, and therefore the amount of CO_2, increased. Because the geologic locations of the sink and emission clusters did not change, the new hypothetical pipelines would be expected to be constructed along the corridor of the Phase I pipelines. The delivery capacity of the new pipelines in Phase II was determined by the mass of CO_2 estimated to be produced in 2050. Occasionally, rather than

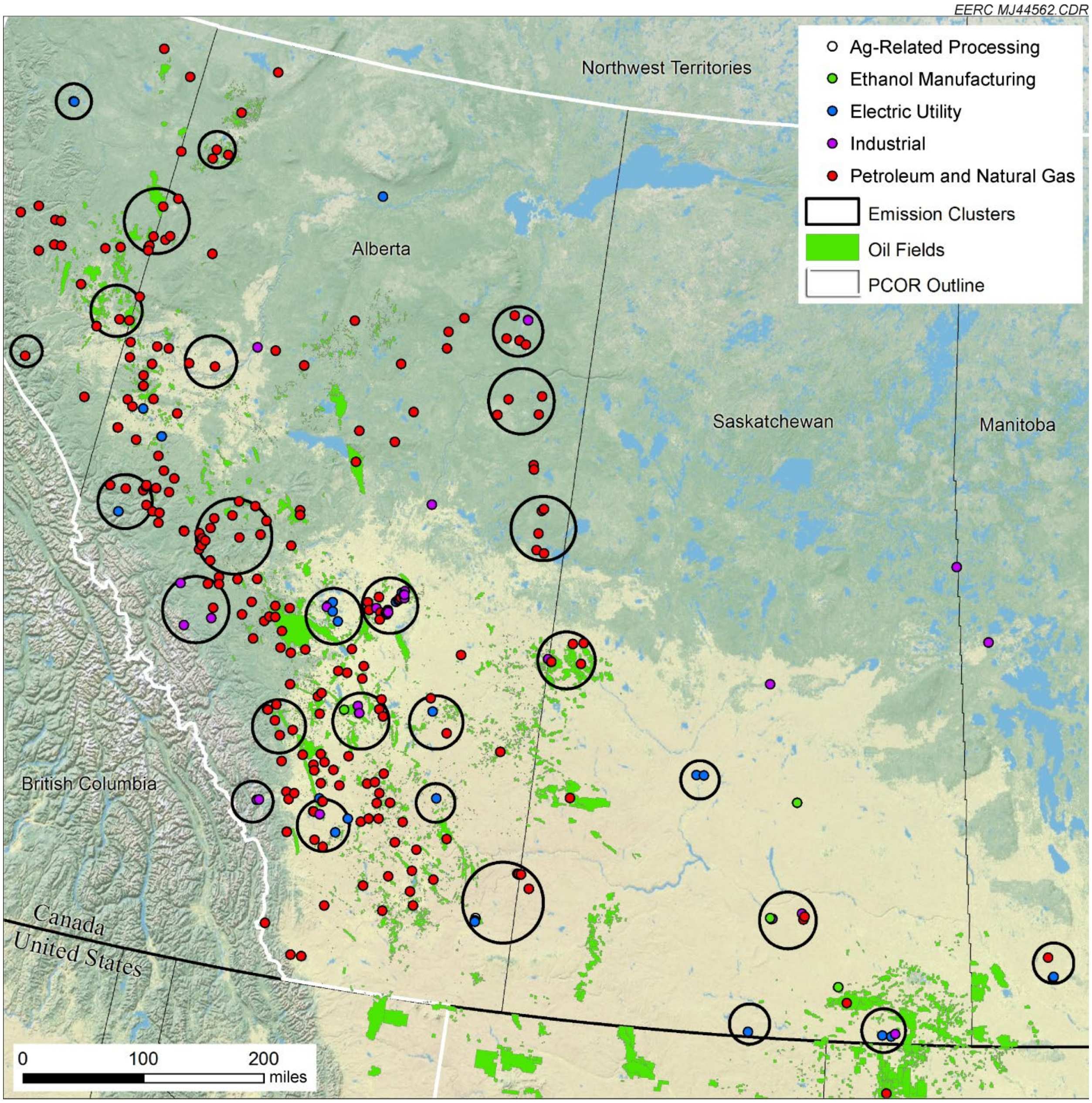

Figure 6. CO_2 emission clusters identified for the Canadian provinces in the PCOR Partnership region.

sending the CO_2 to the previously activated oil fields for nonbeneficial storage, opportunities were found for transport of the CO_2 to other oil fields for EOR utilization even though the distance was longer. The capital cost of the new hypothetical pipeline connecting the emission clusters with the new EOR site was higher than that of the pipeline to the old storage site. Therefore, this additional cost was compared with the revenue gained by selling the CO_2 during the EOR project life. If the revenues were higher than the additional cost, then the new EOR site was chosen as the target sink.

By the time Phase III begins, some sink clusters will be at capacity and no longer able to accept additional CO_2, so the CO_2 will be transported to a saline formation for injection. Additional new hypothetical pipelines would have to be constructed to connect the emission clusters in northeastern Alberta with the saline injection sites in the western Alberta Basin.

Table 5 summarizes the length of new pipeline required and associated costs for each phase of hypothetical network development in the Canadian provinces of the PCOR Partnership region. Table 6 shows the total length of pipelines that would be in use during each phase of the hypothetical network. The Phase I values include the Alberta trunk line that is currently being planned.

Wyoming, Montana, and South Dakota

The western states in the PCOR Partnership region contain ample sinks but relatively few CO_2 sources. In the portion of northeastern Wyoming that is a part of the PCOR Partnership region, a cluster of six power plants located proximally to each other could provide a total of roughly 6 Mtons/yr of CO_2 to a hypothetical pipeline network and would serve as the primary source cluster for this portion of Wyoming. This source cluster is roughly 30 mi from the Denbury Greencore Pipeline that is being built to the Bell Creek Field in extreme southeastern Montana. Additional, smaller facilities in Wyoming (a power plant, a petroleum refinery, and a natural gas-processing facility) are located next to oil fields that could potentially serve as sinks for their CO_2, negating a reason to build a pipeline to connect with the Greencore Pipeline.

Table 5. New Pipelines Constructed in the Canadian Provinces During Each Phase of Hypothetical Network Development

Phase (last year of phase)	Length, mi	CO_2 Delivery Capacity, Mtons/yr	Capital Cost, M$	O&M* Cost, $M/yr	Levelized Cost, $M/yr
Phase I (2035)	1566	160.5	1251	8.1	146
Phase II (2050)	1845	203.5	1887	9	222
Phase III (after 2050)	860	90.8	1136	4	132

* Operations and maintenance.

Table 6. Total Length of Hypothetical Pipelines Operated in the Canadian Provinces During Each Phase of Network Development

Phase (last year)	Total Length, mi
Phase I (2035)	1566
Phase II (2050)	3421
Phase III (after 2050)	4281

In Montana, the larger sources are power plants, and with one exception located near an oil field in extreme eastern Montana, they are located in a reasonably straight line such that a pipeline could be easily routed between them and the Cedar Creek Anticline, an oil-rich area of southwestern North Dakota and eastern Montana. The Denbury pipeline that reaches the Bell Creek oil field could also be extended to the Cedar Creek Anticline to provide additional storage targets for the Wyoming CO_2.

Given the need for CO_2 in the region for EOR opportunities, all of the pipelines in Montana and Wyoming that have been discussed in this section would probably be good candidates for inclusion in Phase I of a hypothetical CO_2 pipeline network.

Figure 7 shows the source clusters and potential future pipeline routes for Montana and Wyoming. Table 7 presents the length of pipelines suggested for Phase I of a hypothetical pipeline network as well as the cost estimates associated with those pipelines.

There are very few sources of CO_2 in western South Dakota, and none that is large enough to make it cost-effective to link with a pipeline. For example, a power plant located on the northeastern edge of the Black Hills produces less than 200,000 short tons of CO_2 each year. This amount is not large enough to make it worth the cost of capturing the CO_2, compressing it, and constructing a pipeline to connect the source with either the Denbury Greencore pipeline or the oil fields of the Cedar Creek Anticline.

North Dakota

North Dakota contains many extensive CO_2 sinks and, like Montana and Wyoming, relatively few CO_2 sources. Regional oil fields have provided ample opportunity for CO_2 use in EOR. The total estimated EOR capacity is approximately 859 Mtons. Not only are oil fields a potential sink for CO_2, but a large saline aquifer in western North Dakota is also available for CO_2 storage after the depleted oil fields' storage capacities have been filled. The CO_2 storage capacity far exceeds the available CO_2 from sources in this area.

A CO_2 pipeline already exists in the state, having a capacity of 3.5 Mtons/yr CO_2 and stretching from the Great Plains Synfuels Plant to the Weyburn–Midale oil fields in southeastern Saskatchewan (Dakota Gasification Company, 2012). This existing CO_2 pipeline can serve as the starting point for a hypothetical pipeline network. A concentration of lignite-fired power plants would be the main source of CO_2 during Phase I development in North Dakota. Assuming a 90% capture rate, over 31 Mtons of CO_2 would be available for EOR each year. This is more CO_2 than can be carried by the existing pipeline's excess capacity, making new pipelines necessary. Because 31 Mtons/yr is too large for a reasonably sized CO_2 pipeline, two hypothetical pipelines having the same diameter would be required to deliver this quantity of CO_2. A new pipeline could also connect the power plant source cluster with new pipelines that reach into additional oil-bearing areas that would serve as CO_2 sinks. The existing pipeline is well situated for supplying CO_2 to regional oil fields for EOR, and it would make sense that one pipeline would roughly follow the 200-mile- long existing CO_2 pipeline corridor for that purpose. The other pipeline could be routed to provide CO_2 to oil fields near the border with Montana. The oil and

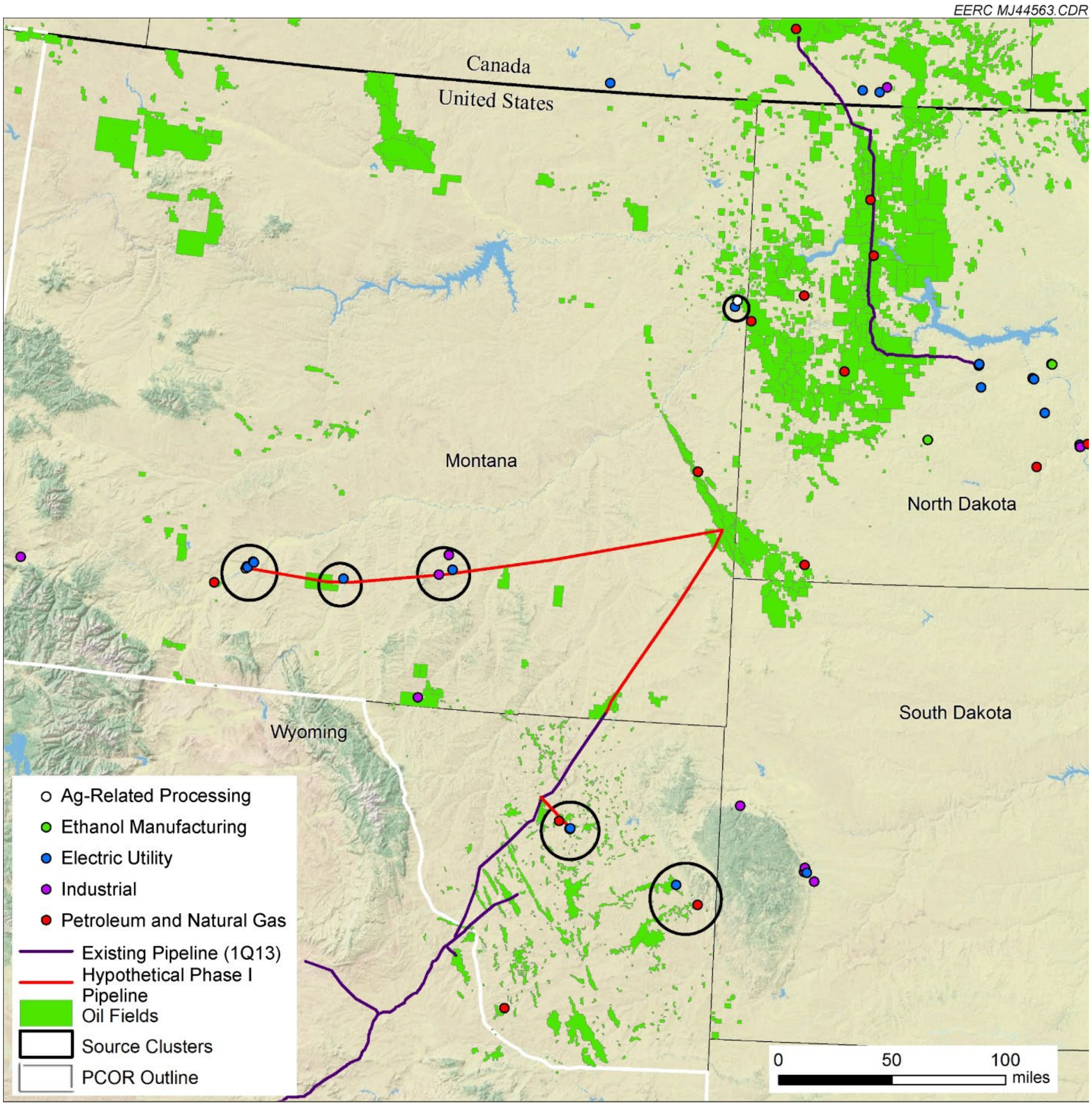

Figure 7. Clusters of CO_2 sources and potential hypothetical Phase I pipeline routes in Montana, Wyoming, and South Dakota (1Q13 means first quarter 2013).

Table 7. Hypothetical New Pipelines Constructed in Montana and Wyoming During Phase I

Phase (last year of phase)	Length, miles	CO_2 Stored, Mtons/yr	Capital Cost, $M	O&M Cost, $M/yr	Total Levelized Cost, $M/yr
Phase I (2035)	370	26.0	360.64	1.85	42.45

gas exploration in western North Dakota has resulted in the construction of new gas-processing facilities. These are located proximally to likely injection sites and would, therefore, be best served by a short, dedicated pipeline rather than connection with a pipeline network. Possible hypothetical pipeline network routes are shown in Figure 8. Table 8 provides the costs associated with the new hypothetical pipelines that could be constructed for large-scale CO_2 storage activities during Phase I.

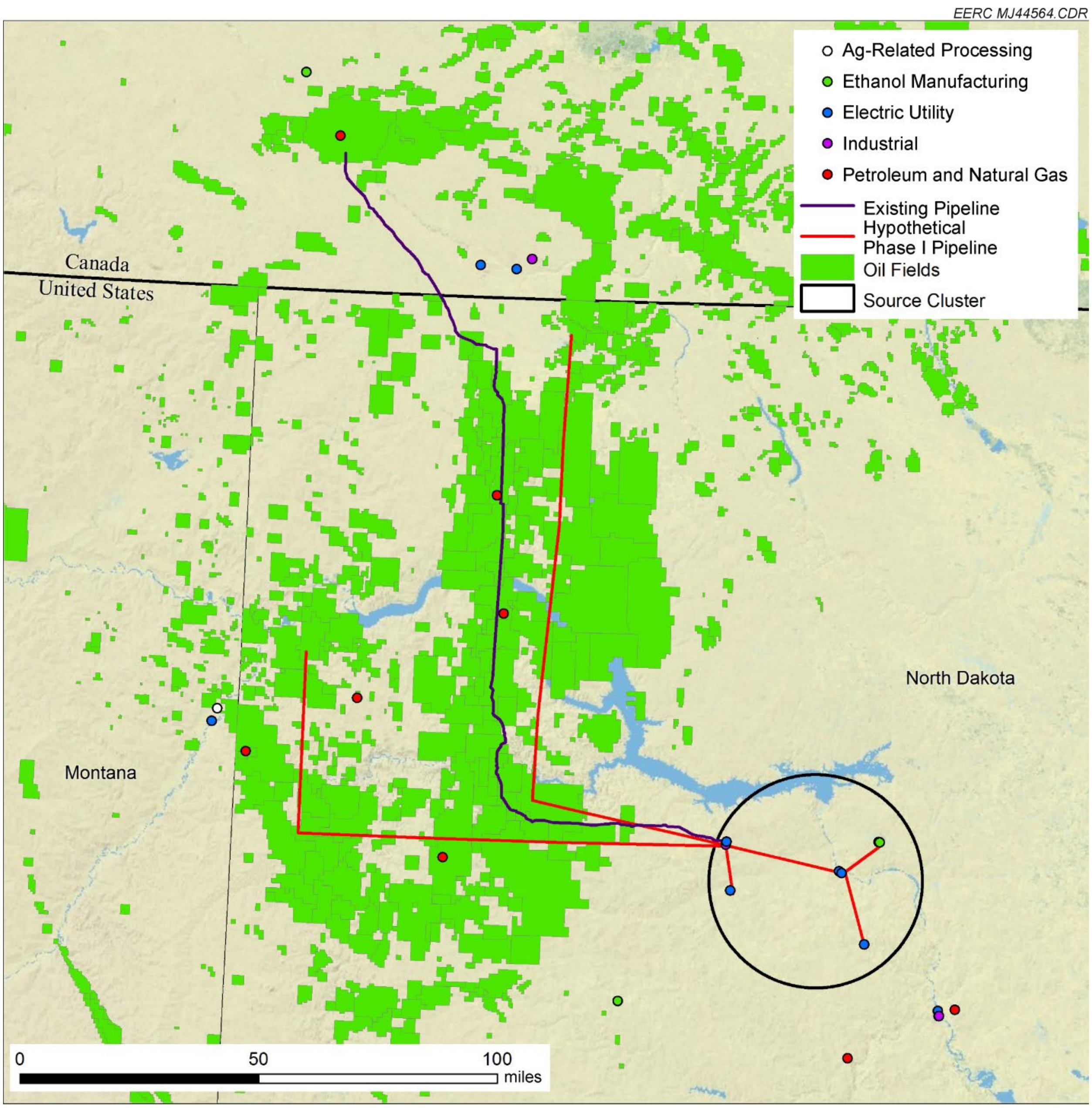

Figure 8. Cluster of power plant CO_2 sources and hypothetical Phase I pipeline routes in western North Dakota.

Table 8. Hypothetical New Pipelines Constructed in North Dakota During Phase I

Pipeline	CO_2 Stored, Mtons/yr	Length, mi	Capital Cost, M$	O&M Cost, $M/year	Total Levelized Cost, $M/year
Northern Route	16	140	146.09	0.70	17.2
Western Route	16	160	169.8	0.80	19.9

Minnesota

Development of the hypothetical pipeline network in North Dakota after Phase I would be limited as most of the pipelines would be constructed to take advantage of the EOR opportunities offered during Phase I. However, it is possible that about 10.5 Mtons/yr of CO_2 from power and iron-processing plants in northern Minnesota could be connected via a pipeline that would extend to western North Dakota. The hypothetical pipeline would be approximately 500 miles in length and is illustrated in Figure 9. Because of the long distance to the Williston Basin in western North Dakota and the carrying capacity required, the pipeline would most likely have to be split into two parallel pipelines (designated A and B in Table 9) having the same diameter.

The cost of the two hypothetical pipelines is shown in Table 9. The total levelized cost is roughly $105 million/yr. Sale of the CO_2 to the oil fields for EOR at a price of $20/ton would result in an annual revenue of $220 million. While this looks promising, a more rigorous cost–benefit analysis would be required to determine if this option is economically viable when the cost associated with capturing and compressing the CO_2 is considered.

Ethanol Plants in Southern Minnesota, Iowa, and Missouri

Iowa and southern Minnesota present a challenge for developing a hypothetical pipeline network to gather CO_2 as most of the emitters are ethanol plants, which are small, scattered throughout the area, and only produce about 9 Mtons of CO_2 annually. Because there are virtually no options near these sources that would offer an economic incentive for storage, it is most likely that this pipeline segment would be implemented only during Phase III, if at all. The hypothetical pipeline system that was developed is shown in Figure 10. Only biogenic CO_2 was considered as it would likely be impractical to separate and capture CO_2 from the flue gas of small natural gas- or coal-fired boilers. Over 550 miles of pipeline would be required to gather the biogenic CO_2 from the ethanol plants at a total levelized cost of more than $46 million/yr. This is a substantial investment for a relatively meager 9 Mtons per year of CO_2, especially when considering that almost half of this total comes from a single large ethanol plant located 22 mi from the end of the pipeline route. While it may be considerably cheaper to capture, dehydrate, and compress biogenic CO_2 from ethanol plants than from a flue gas stream, it is not worth the expense to develop an expensive, distributed pipeline network to collect it in this instance.

Six ethanol plants are located in northern and central Missouri that produce about 660,000 tons of CO_2 annually. These plants could be connected with a 245-mile-long pipeline as shown in Figure 11. The total levelized cost of this hypothetical pipeline is about $16.2 million/yr. Assuming that the CO_2 could be sold for $20/ton, the annual revenue of

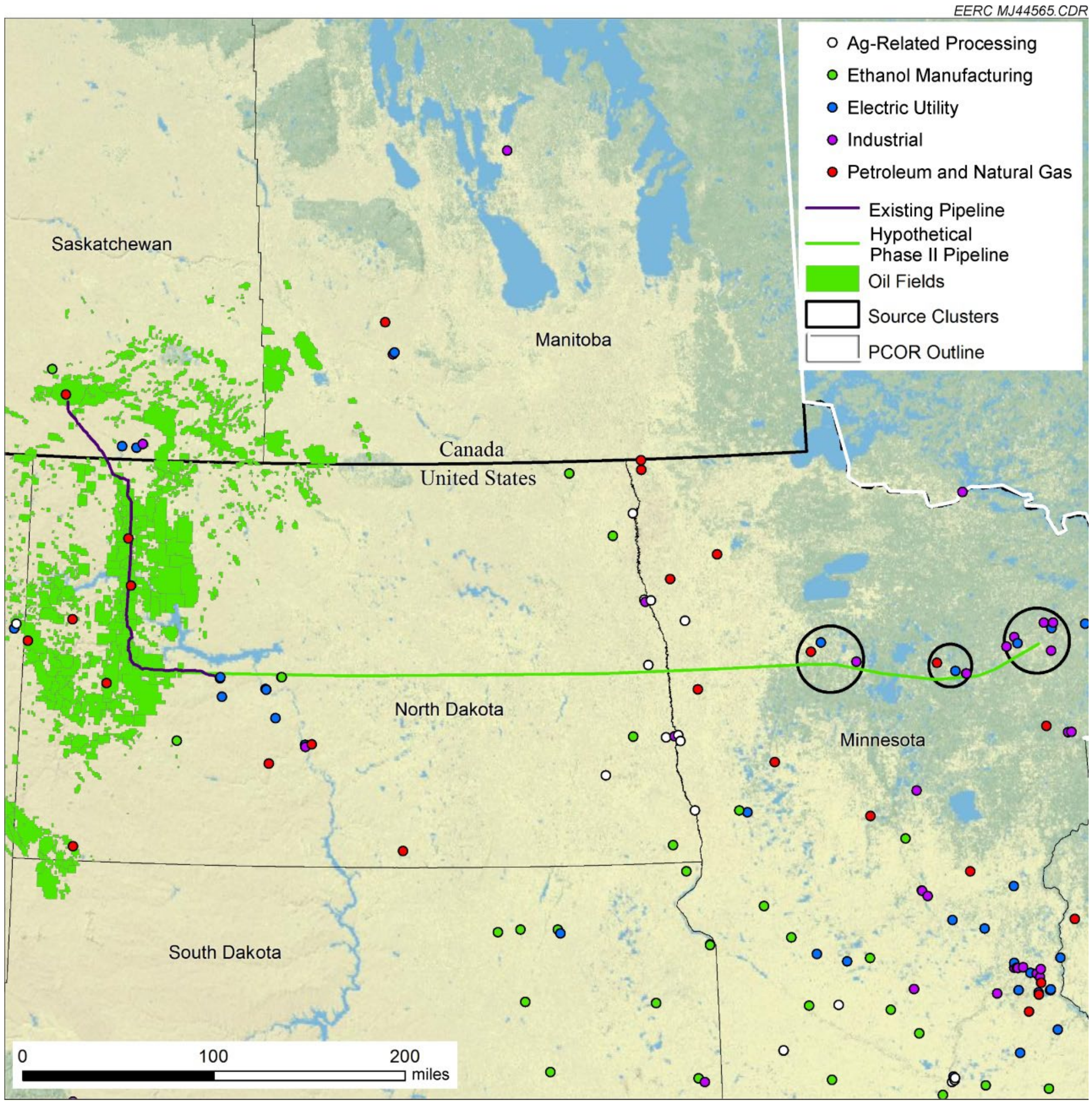

Figure 9. Hypothetical pipelines connecting northern Minnesota's sources with the oil fields in western North Dakota.

660,000 tons of CO_2 would be $13.2 million/yr. Obviously, the cost of constructing that long of a pipeline for such a small amount of CO_2 is prohibitively expensive for the minimal emission reduction that storage would produce. As is the case with the ethanol plants in Iowa, it is unlikely that the emissions from these facilities would ever be stored.

Six ethanol plants are located in northern and central Missouri that produce about 660,000 tons of CO_2 annually. These plants could be connected with a 245-mile-long pipeline as shown in Figure 11. The total levelized cost of this hypothetical pipeline is about $16.2 million/yr. Assuming that the CO_2 could be sold for $20/ton, the annual revenue of 660,000 tons of CO_2 would be $13.2 million/yr. Obviously, the cost of constructing that long of a

Table 9. Optional Hypothetical Pipelines Constructed in Northern Minnesota During Phase II or III

Pipelines	CO_2 Stored, Mtons/year	Length, mile	Capital Cost, \$M	O&M Cost, \$M/year	Total Levelized Cost, \$M/year
Pipeline A	5.5	500	442.1	2.5	52.3
Pipeline B	5.5	500	442.1	2.5	52.3

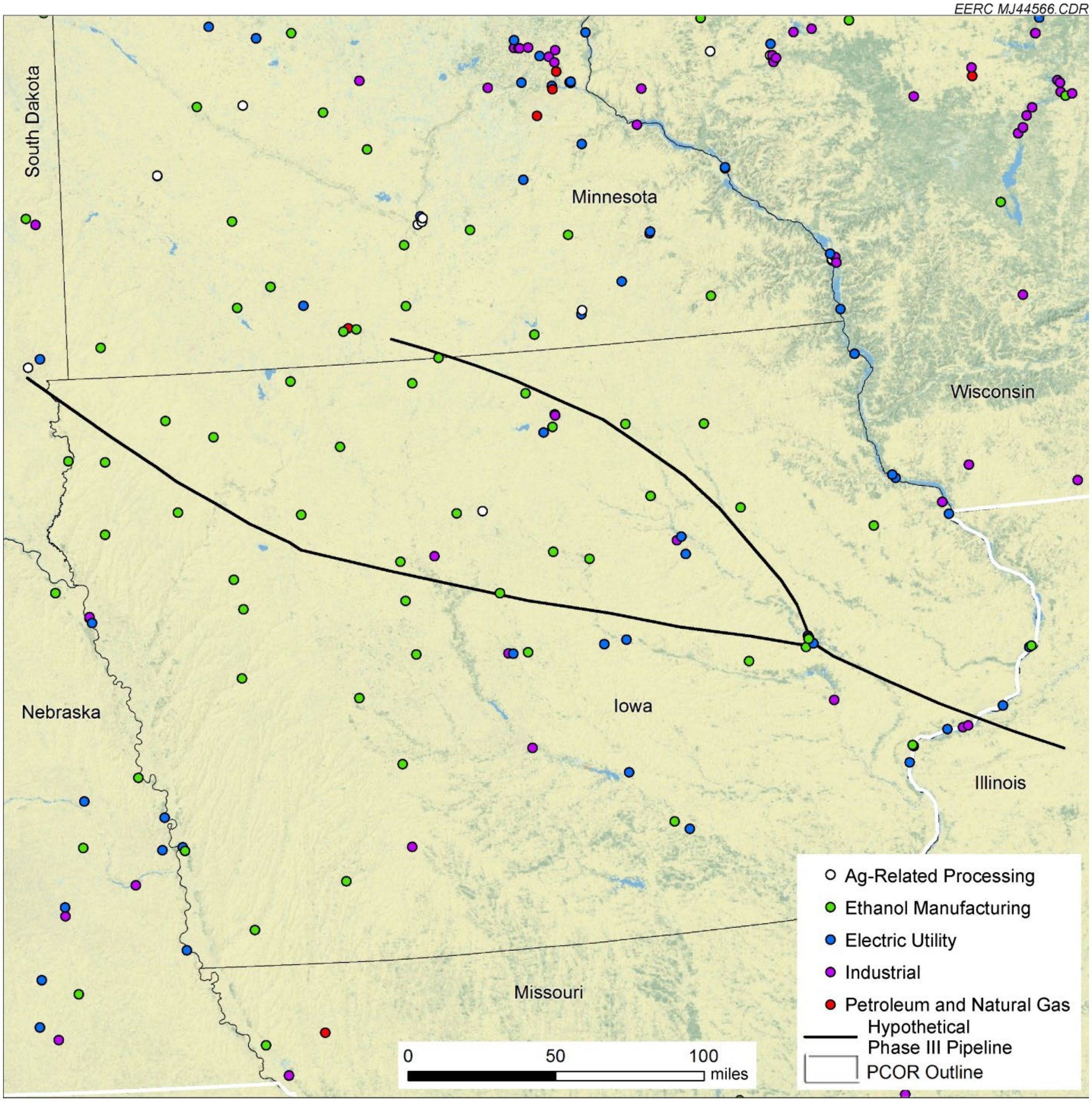

Figure 10. Hypothetical Phase III pipeline network for transporting CO_2 from ethanol plants in Iowa and southern Minnesota.

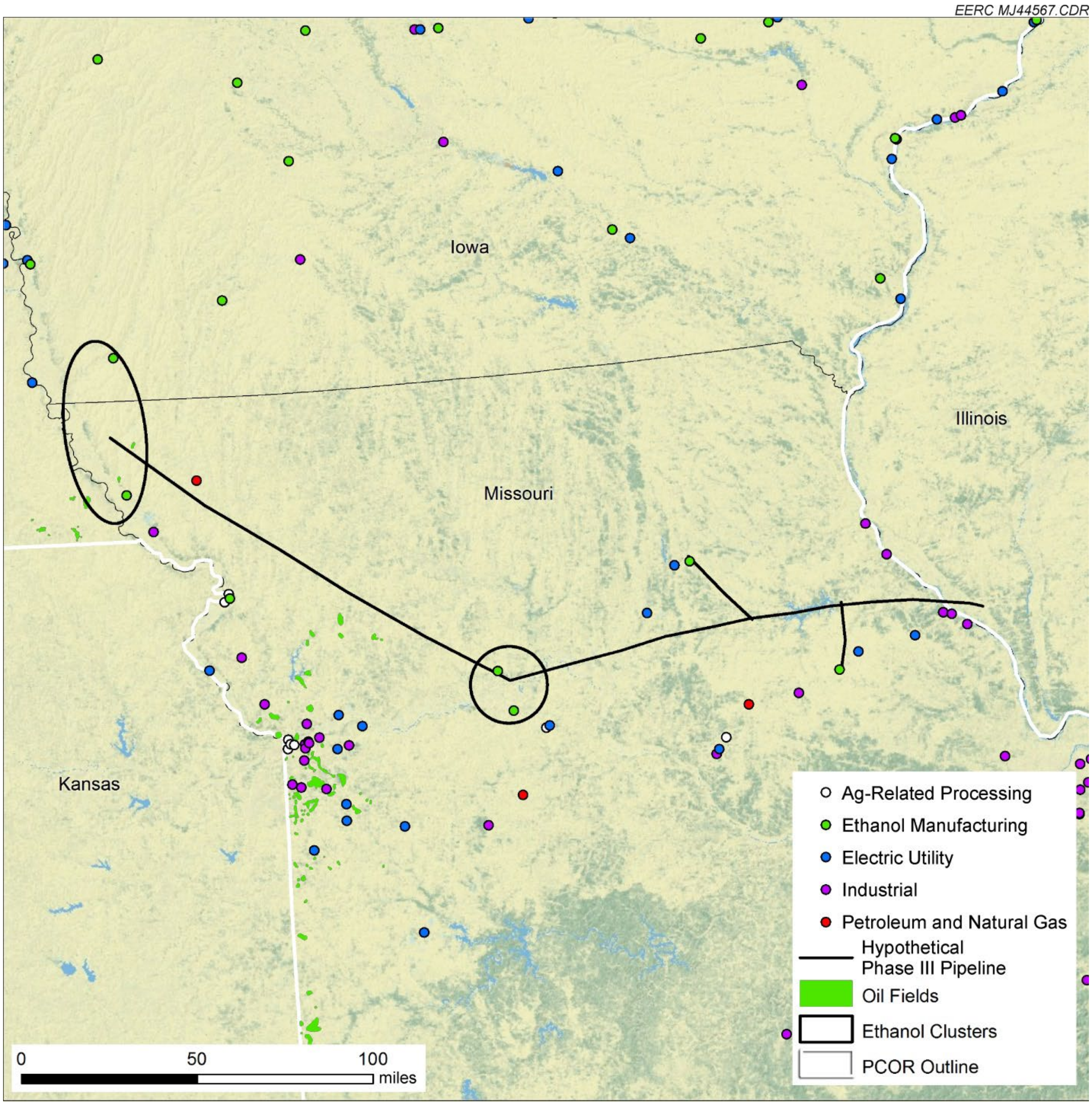

Figure 11. Hypothetical CO_2 pipeline connecting ethanol plants in northern Missouri. This pipeline system would probably not be economical.

pipeline for such a small amount of CO_2 is prohibitively expensive for the minimal emission reduction that storage would produce. As is the case with the ethanol plants in Iowa, it is unlikely that the emissions from these facilities would ever be stored.

Missouri

Missouri does not have any appropriate geologic sinks that have been identified so captured CO_2 streams must be sent to the saline formations in Illinois and/or Kansas. Therefore, hypothetical pipeline construction would occur during Phase II. Fortunately, most of the emission sources are located on the eastern and western edges of Missouri, especially the St. Louis and Kansas City metropolitan areas. In fact, at 69.5 Mtons/yr of CO_2, these sources emit about 70% of the total CO_2 emitted in Missouri. Concentration of the emissions and proximity to the potential storage sites offer cost-reduction advantages when planning a pipeline network. As shown in Figure 12, seven source clusters were identified. The CO_2 from the emission clusters near Kansas City were combined and sent to a saline formation in Kansas. Similarly, the CO_2 from the emission clusters in the southwest part of the state were also merged and sent to Kansas for storage in a saline formation. CO_2 from the emission clusters in the southeast corner of the state were combined and sent a short distance into Illinois for storage in the saline formation there. The CO_2 from the emission cluster near St. Louis was sent to southern Illinois for storage in the saline formation. Table 10 presents the pipeline length and cost information for this part of the hypothetical Phase II network.

Nebraska

Huge saline storage potential exists in southwestern Nebraska; however, most of the emission sources are located in the central and eastern reaches of the state. The saline formation in central Kansas may provide a second storage option, and pipelines can be built to western Nebraska and central Kansas. Six emission clusters were identified in Nebraska. Three of them straddle the Iowa border and contain several of Iowa's large emission sources. The CO_2 from these clusters is sent southward to Kansas for storage, merging with the CO_2 from two other emission clusters on the way. CO_2 from the emission cluster identified in the western part of the state would be sent to the saline formation in western Nebraska for storage. All of these would be considered to be hypothetical Phase II pipelines. A map of the source clusters is shown in Figure 13, and hypothetical pipeline length and cost information is given in Table 11.

Wisconsin

Wisconsin contains many large CO_2 sources but has no storage sinks. About 24.15 Mtons/yr of CO_2 from a few power plants and large manufacturing facilities could be stored in the saline formation in Illinois. Because this method of storage would not be a beneficial use of the CO_2, it would likely be implemented during Phase II. Transport of the CO_2 to Illinois would require two identical hypothetical pipelines that are 250 mi long, as shown in Figure 14. Table 12 presents the costs incurred to construct this pipeline segment.

A cluster of large CO_2 sources exists in the Minneapolis–St. Paul, Minnesota, area, which is adjacent to Wisconsin. The EOR capacity in western North Dakota would be filled by the sources in North Dakota. Therefore, the CO_2 from the Minneapolis cluster would most likely be transported across southeastern Minnesota and southern Wisconsin to the saline formations in Illinois. The annual CO_2 delivery rate from this cluster is 32 Mtons/yr. Because of the large amount transported, two parallel hypothetical pipelines having the same capacity would have to be built. Table 13 shows that the estimated cost of each of the twin hypothetical pipelines (A and B) would be $41.7 million.

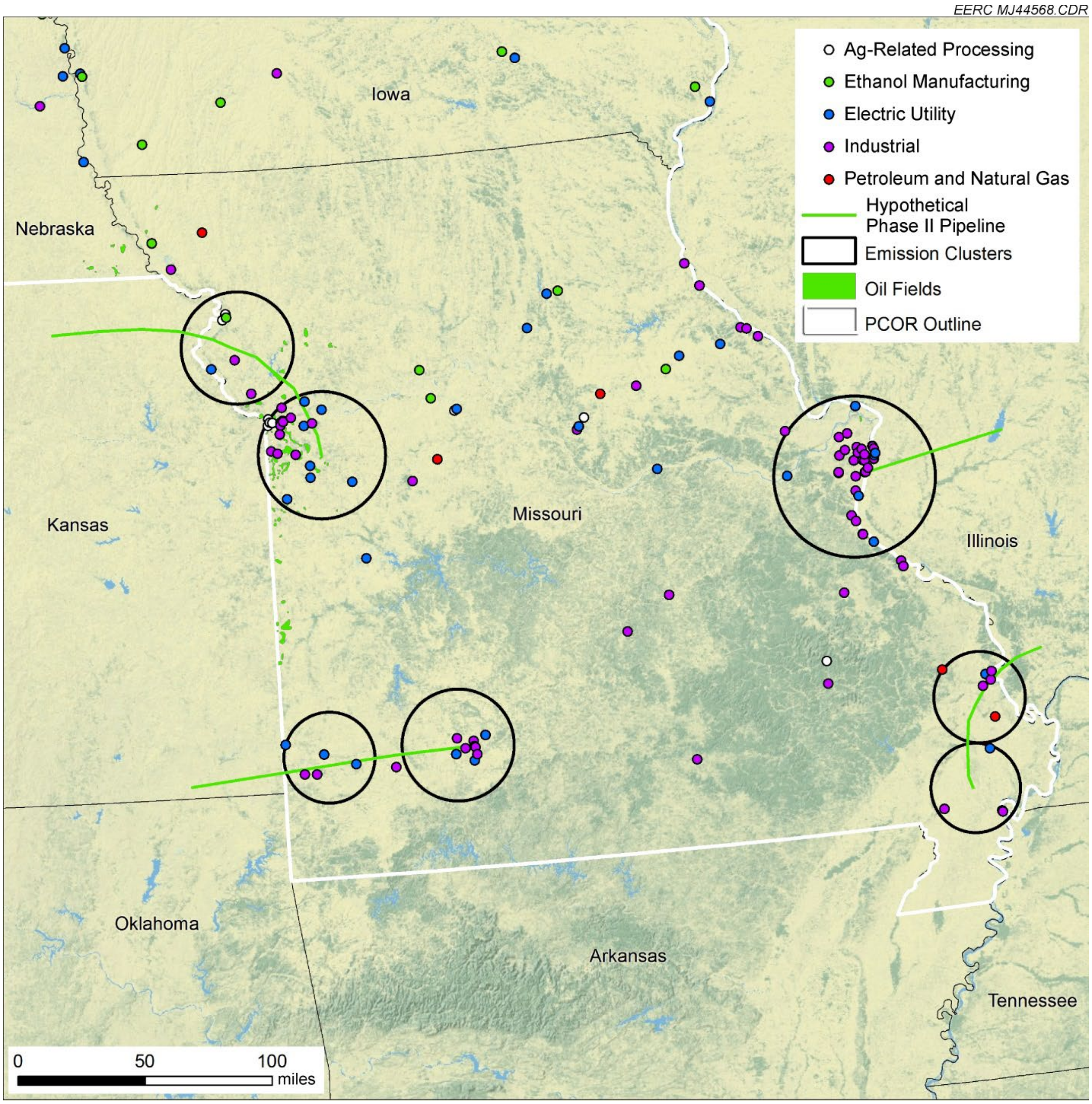

Figure 12. CO_2 emission clusters in Missouri and hypothetical Phase II pipeline routes.

Table 10. Hypothetical New Pipelines Constructed in Missouri, All During Phase II

Phase (last year of phase)	Length, mile	CO_2 Stored, Mtons/yr	Capital Cost, $M	O&M Cost, $M/yr	Total Levelized Cost, $M/yr
Phase II (2050)	220	62.5	194.6	1.14	23.1

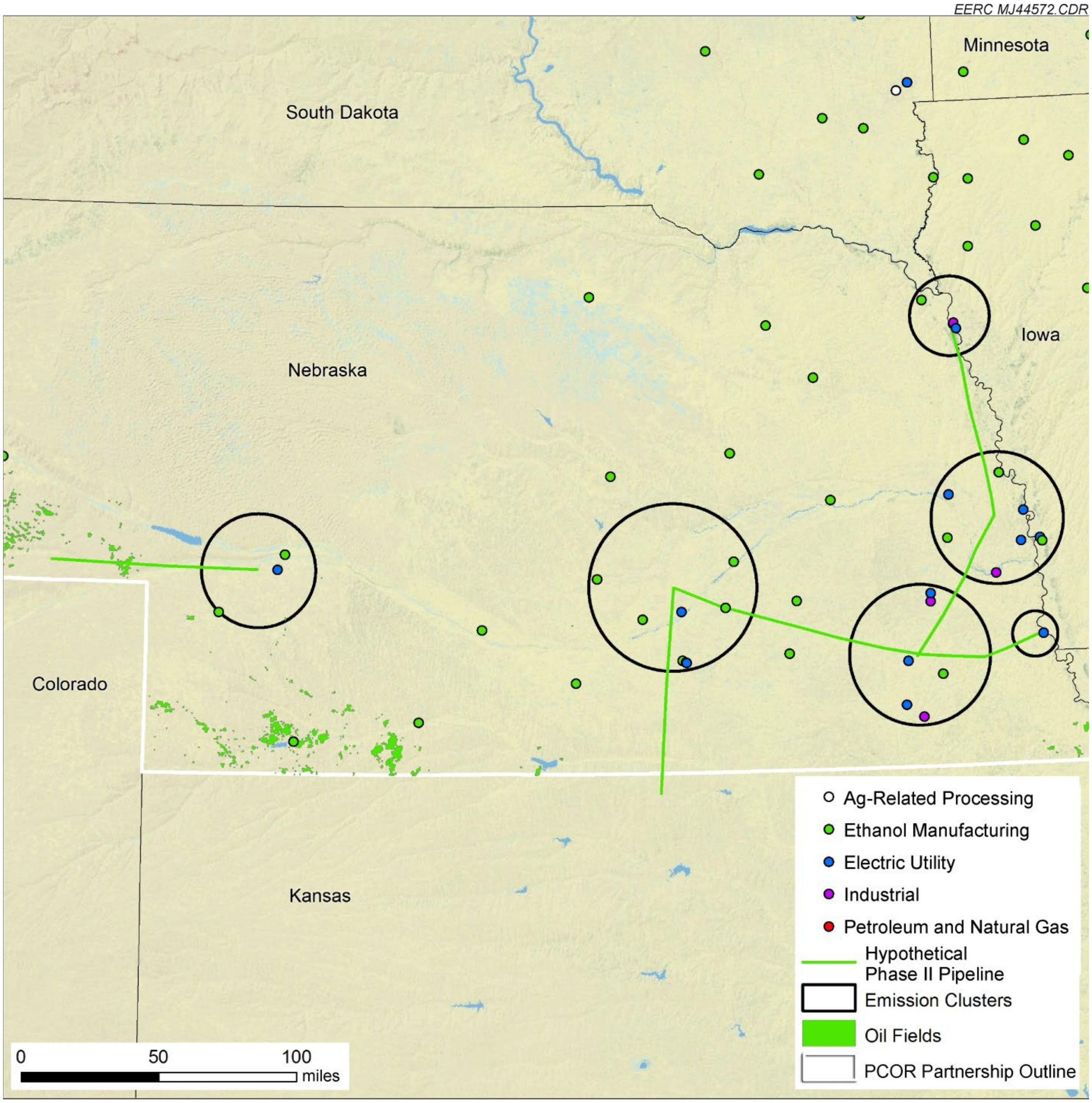

Figure 13. CO_2 emission clusters in Nebraska and hypothetical Phase II pipeline routes.

Table 11. Hypothetical New Pipelines Constructed in Nebraska, All During Phase II

Phase (last year of phase)	Length, miles	CO_2 Stored, Mtons/yr	Capital Cost, $M	O&M Cost, $M/yr	Total Levelized Cost, $M/yr
Phase II (2050)	380	54.65	570	2.45	66.8

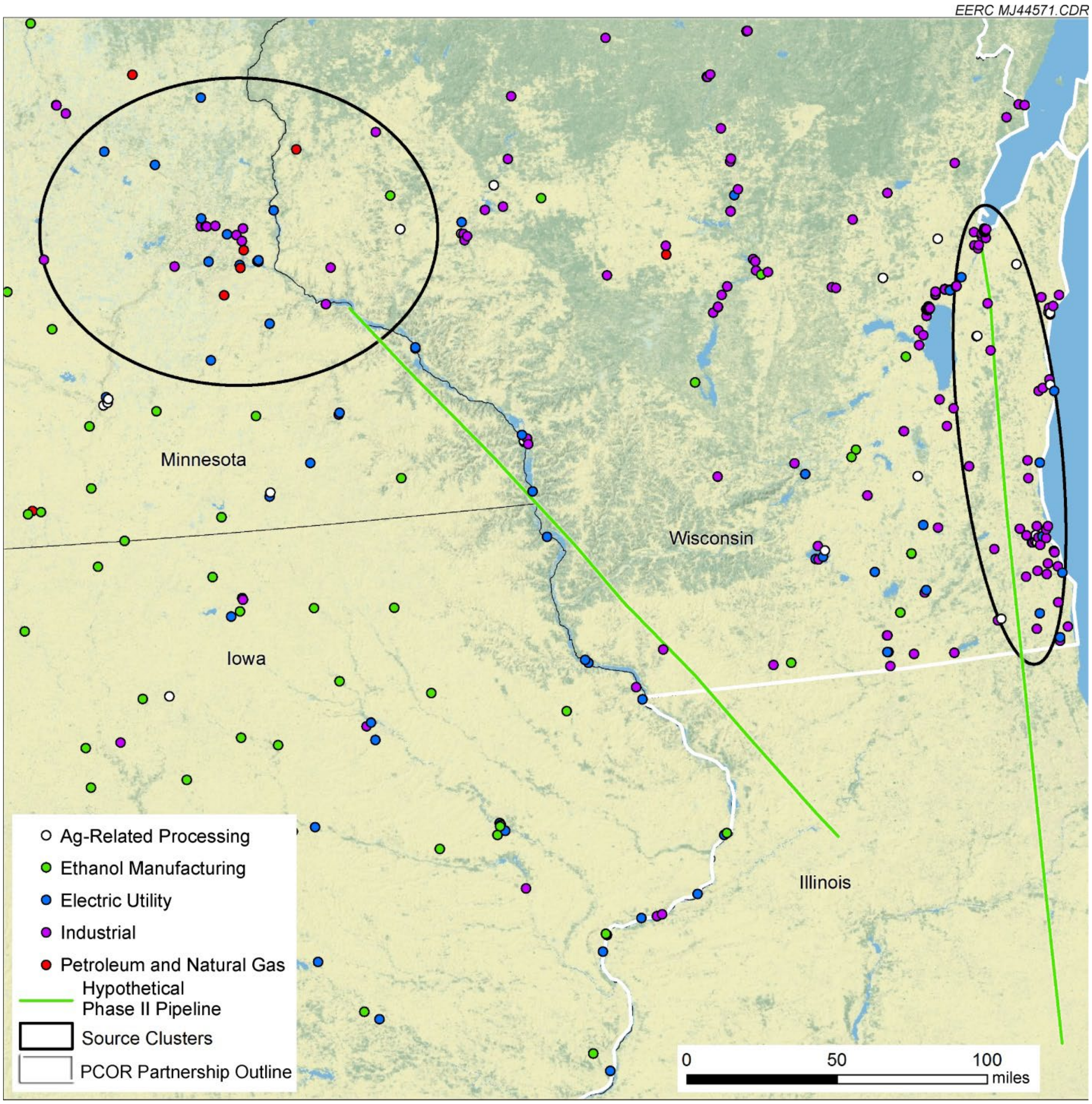

Figure 14. CO_2 emission cluster in Minnesota and Wisconsin and their associated pipeline routes.

Table 12. Hypothetical New Pipeline Constructed to Transport CO_2 from Wisconsin to a Saline Formation in Illinois

Phase (last year of phase)	Length, miles	CO_2 Stored, Mtons/yr	Capital Cost, $M	O&M Cost, $M/yr	Total Levelized Cost, $M/yr
Phase II (2050) – Pipeline A	250	12.1	299.7	1.25	35.1
Phase II (2050) – Pipeline B	250	12.1	299.7	1.25	35.1

Table 13. Hypothetical New Pipeline Constructed to Transport CO_2 from the Minneapolis Cluster to Saline Formations in Illinois

Phase (last year of phase)	Length, miles	CO_2 Stored, Mtons/yr	Capital Cost, $M	O&M Cost, $M/yr	Total Levelized Cost, $M/yr
Phase II (2050) – Pipeline A	250	16	358.7	1.25	41.7
Phase II (2050) – Pipeline B	250	16	358.7	1.25	41.7

SUMMARY AND CONCLUSIONS

Today's CO_2 market is driven by demand for EOR and other uses and is influenced by oil prices and efficiencies in capture technologies (Bliss and others, 2010). Federal mandates to reduce CO_2 emissions may promote strategies to capture and store CO_2 but may not provide for funding for the construction of required infrastructure. If this is the case, public resources might be required (Bliss and others, 2010). If CO_2 is not used for EOR or ECBM recovery, the pipeline would be moving a noneconomic commodity to a saline formation, and this might be viewed less favorably by the public than transport of CO_2 as a positive-value commodity (Bliss and others, 2010).

These concepts formed the basis for the PCOR Partnership's hypothetical pipeline network development methodology. In the methodology, the development of hypothetical regional pipeline hubs and limited networks will begin by building out the hypothetical infrastructure needed for enhanced resource recovery (particularly EOR). As long as EOR continues to be economically attractive, this approach will drive pipeline network development. Transport of CO_2 to saline formations would likely not take place before EOR opportunities have been exhausted.

The PCOR Partnership approach was applied in a case study. Table 14 summarizes the results of the case study, while Figures 15–17 present the hypothetical pipeline network routes as they would appear at the end of Phases I, II, and III, respectively. It was found that a hypothetical pipeline network roughly 6700 mi in total length (for the trunk lines) could transport sufficient quantities of CO_2 such that it appears that the IEA BLUE Map scenario could be met for the PCOR Partnership region by 2050. The IEA BLUE Map scenario is a reduction in CO_2 emissions of 50% over 2005 levels by 2050. Meeting this target is dependent upon two major assumptions. The first, put forward by the Energy Research Group at Dalhousie University, is that the CO_2 output from Canada's electricity generation fleet will increase dramatically until at least 2050. The second assumption is that the Canadian government's goal of a 98% CO_2 emission capture rate actually would be attained by 2050. These assumptions result in the storage of 369 Mtons/yr of CO_2 in the Canadian portion of the PCOR Partnership. When coupled with the expected U.S. CO_2 storage of 243.4 Mtons/yr, the overall reduction for the PCOR Partnership region is about 612.4 Mtons/yr by 2050. The BLUE Map scenario target was 444.7 Mtons/yr, based on a total CO_2 emission for the region in 2005 estimated from various EPA and Environment Canada data sets.

Table 14. Summary of the Hypothetical Phased Pipeline Network for the PCOR Partnership Region

Phase	U.S. I	U.S. II	U.S. III	Canada I	Canada II	Canada III	Total of Phases I and II by 2050	Total, Including Phase III
Miles of Hypothetical New Pipeline	670	2600	0	1566	1845	860	6681	7541
CO_2 Transported by Hypothetical New Pipeline, Mtons/yr	58	185.4	0	160.5	203.5	90.85	607.4	698.2
Capital Cost of Hypothetical New Pipeline, $M (2009 US$)	676.5	2965.6	0	1251	1887	1136	6780.1	7916.1
O&M Cost of Hypothetical New Pipeline, $M (2009 US$)	3.4	13.6	0	8.1	9	4	34.0	38.0
Levelized Annual Cost of Hypothetical New Pipeline, $M (2009 US$)	79.6	348.0	0	145.6	222	132	795.2	927.2

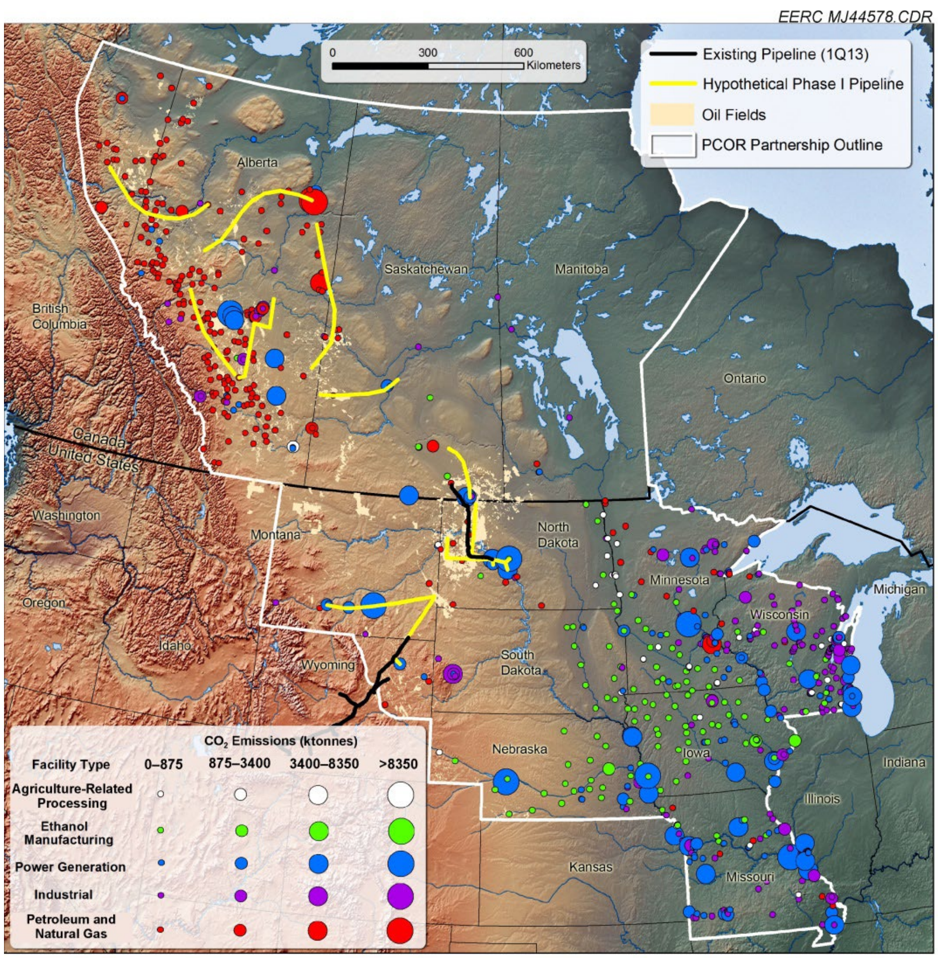

Figure 15. The hypothetical Phase I pipeline network as determined for the PCOR Partnership region.

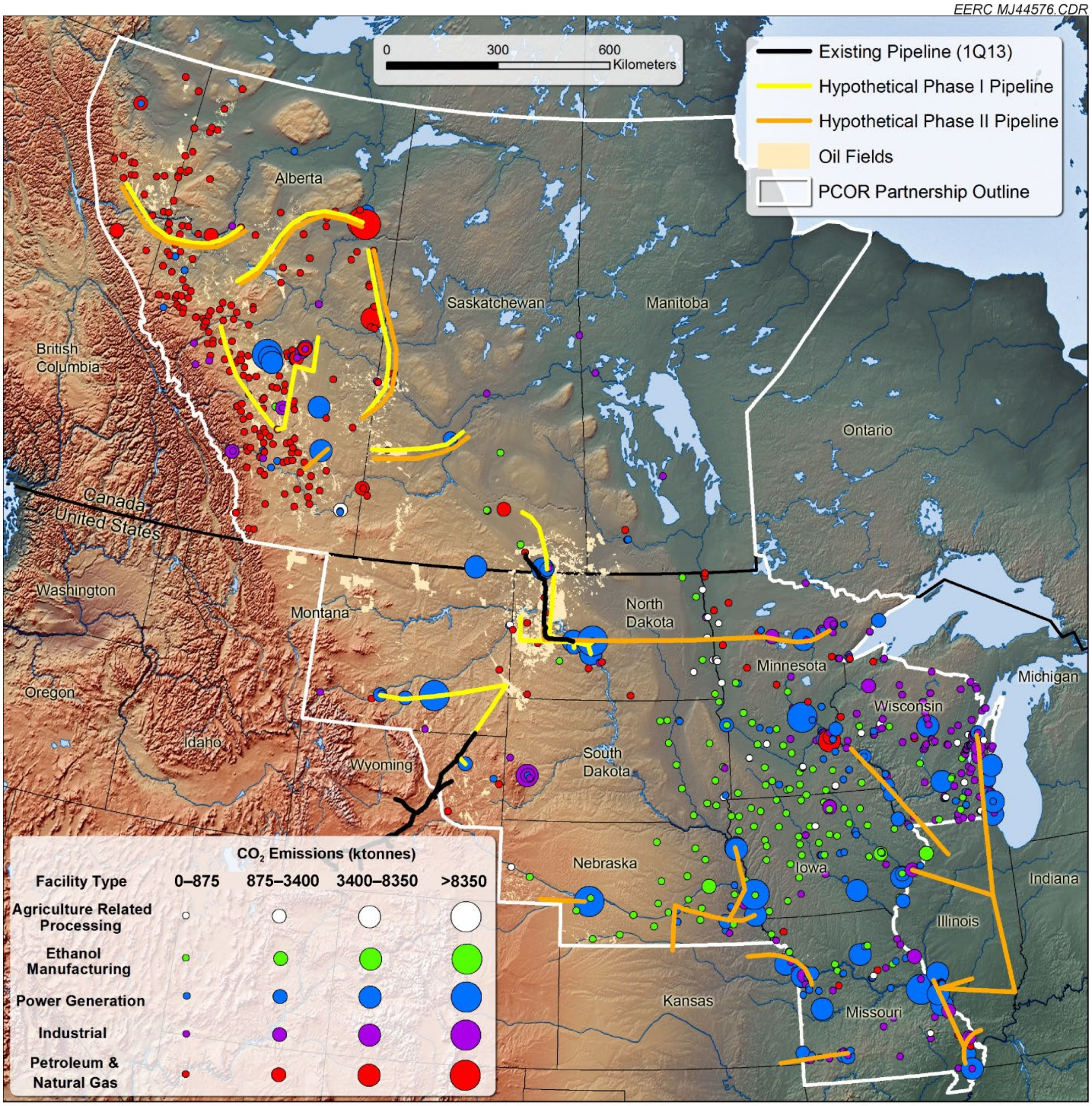

Figure 16. The hypothetical Phase II pipeline network as determined for the PCOR Partnership region.

Dooley and others (2009) estimated that about 28,000 mi of pipeline would be needed in the United States to meet the scenario in which the atmospheric CO_2 is stabilized at 450 ppmv by 2050. The hypothetical pipeline estimates obtained using the PCOR Partnership methodology outlined here indicate that the length required for the U.S. portion of the region totals 3270 mi. At first glance, this seems a bit low, but when the number and distribution of regional storage targets are considered, it is obvious that the average hypothetical pipeline segment would be shorter in the PCOR Partnership region than in many other areas of the United States.

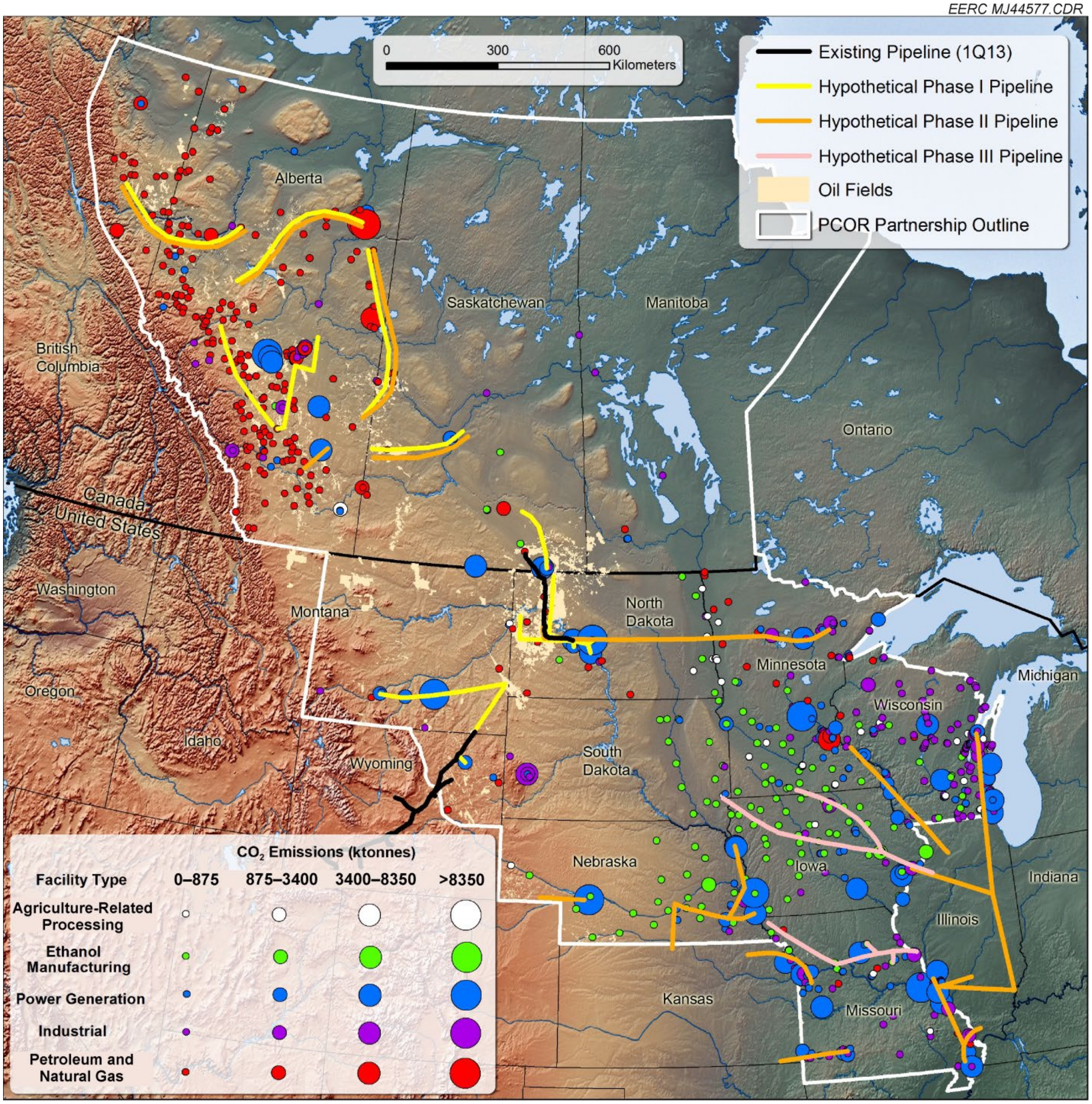

Figure 17. The hypothetical Phase III pipeline network as determined for the PCOR Partnership region.

According to the IEA, "the challenge for the future of transport technology is to develop long-term strategies to cluster CO_2 sources and develop CO_2 pipeline networks that will optimize the source-to-sink transmission of CO_2. The development of appropriate pipeline routes presents a number of regulatory, access, public acceptance and planning challenges. To address these, governments will need to initiate planning at a regional level and develop incentives for the creation of CO_2 transport hubs" (International Energy Agency, 2010). The hypothetical phased pipeline routing methodology developed by the PCOR Partnership could help to address this challenge.

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