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Methodology for Phased Development of a Hypothetical Pipeline Network for CO_2 Transport during Carbon Capture, Utilization, and Storage

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ABSTRACT: If implemented on a commercial scale, carbon capture, utilization, and storage (CCUS) has the potential to significantly reduce carbon dioxide (CO_2) emissions. Moving the CO_2 from the point sources to the geologic storage locations will likely require a pipeline network. The Plains CO_2 Reduction (PCOR) Partnership developed a four-step methodology that can be used to estimate the length, cost, and time frame of a hypothetical pipeline network that would be built in phases. The methodology was tested during a case study in which a hypothetical phased pipeline network was estimated for the PCOR Partnership region. The hypothetical pipeline network consisted of trunk lines roughly 10 780 km in total length that could provide an overall CO_2 reduction for the region of about 555.6 Mtonnes of CO_2/year by 2050. The results also indicate that an extensive pipeline network may not be required to transport to storage locations the quantity of CO_2 required to meet the emission reduction targets for the PCOR Partnership region.

INTRODUCTION

Considerable attention is being paid to carbon capture, utilization, and storage (CCUS) as a means of reducing U.S. carbon dioxide (CO_2) emissions. If the concept is deployed on a large scale, substantial capital investment will be necessary for capture, compression, and transport of the CO_2 to the geologic storage targets. Absent regulatory or national policy drivers, early deployment of CCUS is likely to center on the utilization of CO_2 for enhanced oil recovery (EOR) or enhanced coalbed methane (ECBM) recovery, because they could provide a means to cover a significant portion of the large capital cost. Carbon regulation and/or emission standards likely would expand this deployment. Unfortunately, appropriate geologic storage areas, either saline formations or enhanced resource opportunities, are not collocated with many of the large CO_2 sources. It is possible that a regional or even national pipeline network could be needed to transport the CO_2 from the sources to the storage sinks.

According to the International Energy Agency (IEA),[1] long-term transport strategies must be developed that will cluster CO_2 sources and develop pipeline networks that optimize the transport of CO_2 to the storage targets. Regulatory, access, public acceptance, and planning challenges will impact the development of appropriate pipeline routes. Incentives for the creation of CO_2 transport hubs may assist in the pipeline network development, as may regional planning.[1] A methodology was developed by the Plains CO_2 Reduction (PCOR) Partnership to estimate how a hypothetical regional CO_2 pipeline network might look in terms of routing, the time frame over which it might be built, and cost. The PCOR Partnership is one of the United States Department of Energy's (U.S. DOE's) seven Regional Carbon Sequestration Partnerships put in place as part of a national plan to mitigate greenhouse gas emissions. The PCOR Partnership region is expansive, including all or parts of nine states and four Canadian provinces, and its stationary CO_2 emission sources include electricity generators; energy exploration and production activities; agriculture; fuel, chemical, and ethanol production facilities; and various manufacturing and industrial activities.

The pipeline network methodology was tested by applying it to the PCOR Partnership region to estimate the required length and cost of a hypothetical pipeline network that would enable storage of sufficient CO_2 emissions to meet most emission targets. This paper describes the development of the methodology and the results of its application to the PCOR Partnership region.

EXPERIMENTAL SECTION

To arrive at a methodology for estimating how a hypothetical regional CO_2 pipeline network might be devised, various types of pipeline networks and approaches to their design were researched. This information will be presented prior to describing the PCOR Partnership methodology, so that the reader will better understand the logic used in the methodology's development.

Benefits and Challenges Associated with Pipeline Networks. Both benefits and challenges are associated with a CO_2 pipeline network. The Alberta Carbon Capture and Storage Development Council notes many benefits,[2] such as the fact that costs can be reduced through the transport of larger volumes of CO_2 in a given pipeline segment. Pipelines can be consolidated, thereby reducing their total environmental footprint, and their use can allow storage sites to be prioritized according to their geotechnical quality. In a network,

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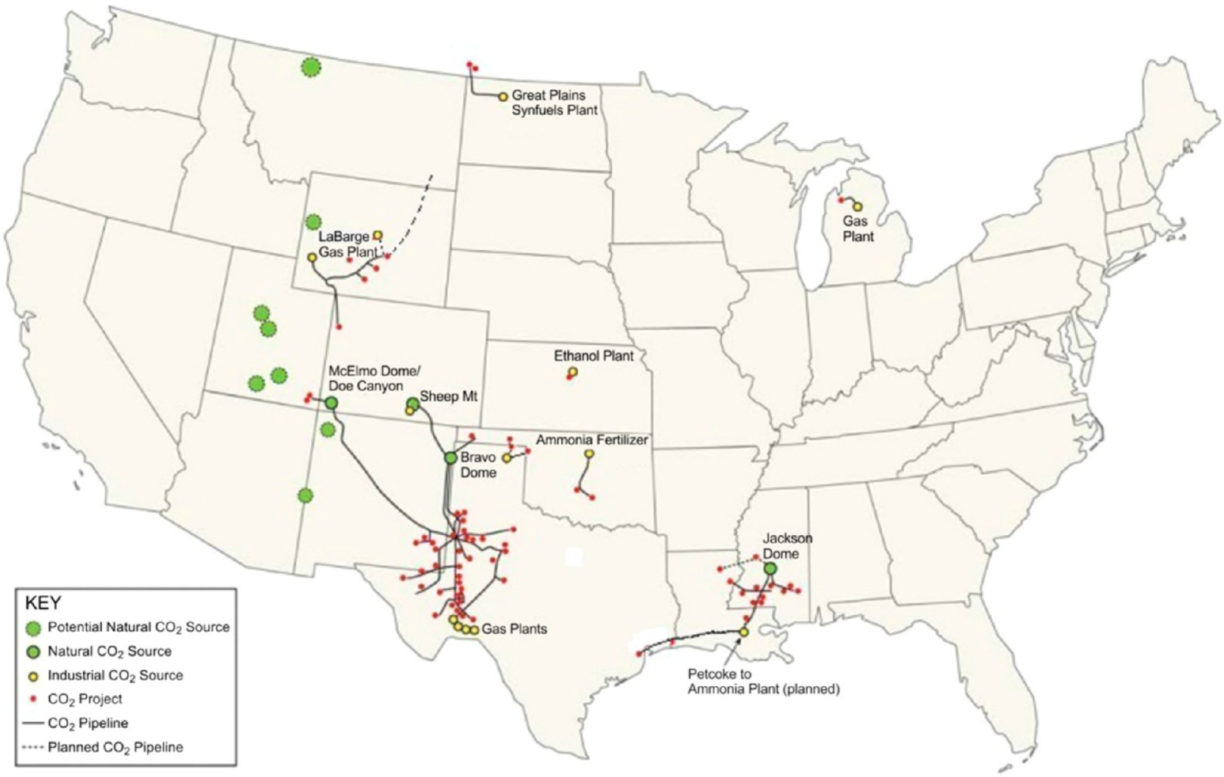

Figure 1. Active U.S. CO_2 pipeline and injection site infrastructure (map courtesy of Steven Melzer[4]).

there might be some form of open access regime to the pipelines intended to ensure that available transport capacity be made available on a not unduly discriminatory basis. Any such regulatory regime would need to ensure the ability of project developers to honor commitments of firm, reliable capacity for the lengthy terms of the investments at both ends of the pipeline (i.e., in CO_2 capture facilities and in EOR production operations). Multiple EOR markets and supply points would provide choice and volume security to all of the participants.

Just as it lists benefits, the Alberta Carbon Capture and Storage Development Council also describes some challenges associated with a network approach,[2] including the fact that the network could be inefficiently developed and/or developed at the wrong time relative to the availability of CO_2 volumes and/or storage sinks. Cost-minimization drivers, such as the development of a private market or competition, could be lacking. CO_2 composition specifications could become problematic in some situations; for example, the CO_2 stream composition required for EOR may be excessively stringent if the CO_2 stream will be stored in a saline formation.

Composition specifications determine compatible materials and operating conditions for pipelines and associated equipment. The onus for compliance with any CO_2 composition specifications would rest with the CO_2 sources and would affect the relative costs of various capture technologies, potentially giving some an advantage over others. If the cost of conforming to a common composition standard exceeds the cost of a separate pipeline, it is not unreasonable to envision the appearance of special-purpose pipelines in niche situations. Individual natural gas, petroleum products, and chemical pipeline operators enforce specifications that are derived from customer requirements and operating and safety considerations. While pipeline specifications do vary across pipelines for the same product, they often are very similar because of similar customer requirements to conform to industry or regulatory standards, as well as similar pipeline equipment. A single standard has obvious advantages, but it is not unreasonable to envision that clusters of sources might exist that produce "off-spec" CO_2 for which economics are more favorable for operating separate pipelines.

The United States has over 4000 miles of CO_2 pipelines.[3] Figure 1 shows the current existing or planned CO_2 pipelines. The map shows that very few large industrial sources are connected by a 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 for EOR operations, mostly from naturally occurring geologic sources.

CO_2 Pipeline Network Approaches. A national CO_2 pipeline network that supports CCUS could be planned using various approaches.[3] One approach would be to transport CO_2 from geographically diverse large industrial sources to large-scale geologic storage targets via a nationwide pipeline network. In a second model, regional networks would be gradually built out to connect large CO_2 point sources with existing pipeline infrastructure that connects EOR operations with local storage. Finally, shorter pipelines could directly link large CO_2 sources (most likely power plants) with nearby storage locations.

There are currently only a few thousand utility and industrial CO_2 emission sources and even fewer large geologic storage targets; therefore, the third approach likely would be the one that is implemented. In this scenario, a few very large CO_2 sources would feed pipelines carrying the gas to a few large EOR injection sites.[3] CO_2 from smaller industrial sources probably would not be captured and transported in a pipeline network because the cost of compression of small amounts of CO_2 for pipeline transport would be too expensive.[3]

CO_2 Pipeline Network Funding Approaches. Who would fund a CO_2 pipeline network is the subject of considerable interest. Three funding models have been proposed by the Canadian Energy Pipeline Association (CEPA).[2]

(1) 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.

(2) Market Backstop: This approach applies to incremental pipeline network infrastructure that would be uneconomical 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.

(3) Market Franchise: The market franchise approach applies to a pipeline network that is required because of government policy decisions but is not economical. 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.

Market backstop is practiced in the United States when governments at various levels seek to attract industry to operate in certain geographic areas, typically by offering special tax treatment or other incentives. Market franchise is routinely practiced by the government in providing services, such as domestic water lines and sanitary sewers. With public support, it is not unreasonable to envision such government involvement. The choice of which of these approaches would be more appropriate would depend upon the economics of the specific circumstance as well as fundamental political judgments regarding the proper respective roles of private investment and government regulation.

Similar models have been identified by the Interstate Oil and Gas Compact Commission (IOGCC). The IOGCC calls them the Dedicated Pipeline Model (either intra- or interstate), which is roughly similar to the CEPA market approach; the Open Access Model (either intra- or interstate), which is somewhat similar to the CEPA market backstop; and the Government/Public Option Model, which roughly equates to the CEPA market franchise model.[3] Additional details about the IOGCC 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".[3]

Network Development. *Network Analogs.* Various analogs for the phased CO_2 pipeline planning methodology were identified and researched, including the natural gas network, the electricity transmission grid, and the U.S. interstate highway system.[5−11] 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 now 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. In 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.[5] 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.[7] 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, the 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. Pipelines carrying natural gas, petroleum products, and chemicals characteristically have temporary storage and terminals to ensure continuous, reliable operation. Such sites would appear as network nodes. Some entities have studied intermediate storage, such as Gasunie and Vopak, in the design of a CO_2 distribution hub but have not reported economics.[12] 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. Decades of experience with EOR have shown that the operation of CO_2 pipelines does not represent a significant risk in terms of potential for release.[13] Construction costs are impacted by factors associated with the route, including land slope, infrastructure, land use, population density, and property value.[14,15] The final version of the network should have the flexibility to be expanded and modified.

Ideally, comprehensive CCUS infrastructure planning should integrate the cost of CO_2 capture, compression, transfer, injection, and storage to optimize the performance and reduce the cost.[16,17] In reality, each of the components (i.e., capture nodes, EOR sites, and pipelines) depends upon the existence, timing, sizing, economics, and operating characteristics of the other components, making optimization very difficult. However, to estimate how a future system of pipelines might look, a hypothetical pipeline network can be developed. Because the pipelines serve as links in the network, the properties of the nodes (sources and sinks) should be well-understood during 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. The first phase is likely to consist of pipeline segments that connect sources with EOR opportunities, followed by the addition of other sources and sinks as dictated by either the marketplace (in the case of EOR) or national or regional carbon management policy. Because there are significant scale economies to the pipeline throughput that may be sacrificed when several smaller lines are built instead of a single larger line, the hypothetical routes can be drawn to maximize CO_2 transport by incorporating CO_2 from as many sources as possible.[18]

Determining the Timing for the Pipeline Phases. The first step in determining timing for pipeline phases requires an assumption to be made as to how forcefully CCUS will be pursued in a given region. Profitable applications of CO_2 storage, such as EOR, can provide early infrastructure that can be leveraged to reduce the cost of follow-on infrastructure. The rollout of non-profitable follow-on infrastructure will rely ultimately on national or regional carbon management policy. Because government policy cannot be accurately forecast, target CO_2 concentration serves as a surrogate in the following analysis. The IEA's BLUE Map scenario calls for a 50% emission reduction (in comparison to levels from the year 2005) by 2050.[1] This reduction falls between two approaches outlined by Dooley et al.[19] In these approaches, the effects of stabilizing atmospheric concentrations of CO_2 at 450 and 550 ppmv were estimated on the U.S. electricity generation assets. The results indicate that meeting the 450 ppmv target would require that 49% of the CO_2 emissions from the fossil-fuel-fired U.S. electricity-generating fleet would have to be captured and stored by 2035 and that 78% would have to be captured and stored by 2050. In contrast, meeting the 550 ppmv target would only require that 8% of the CO_2 emissions be captured and stored by 2035, while 21% would have to be captured and stored by 2050.

Not only do the emissions vary dramatically within the United States depending upon 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.[20] The Energy Research Group predicts that, unlike the relatively stable size of power generation in the United States, electricity production by coal and natural gas in Canada will increase 249% over 2008 levels by 2050. Even though renewable (hydropower) and nuclear production will increase significantly, the generation capacity based on coal and natural gas is predicted to increase at a rapid rate. According to the study, meeting the Canadian government's greenhouse gas reduction plan will require that 77% of the CO_2 from the electrical generation sector be captured by 2035. This capture rate increases to 98% by 2050. It was assumed that the same percentage reduction would be required for large facilities in other emission sectors.

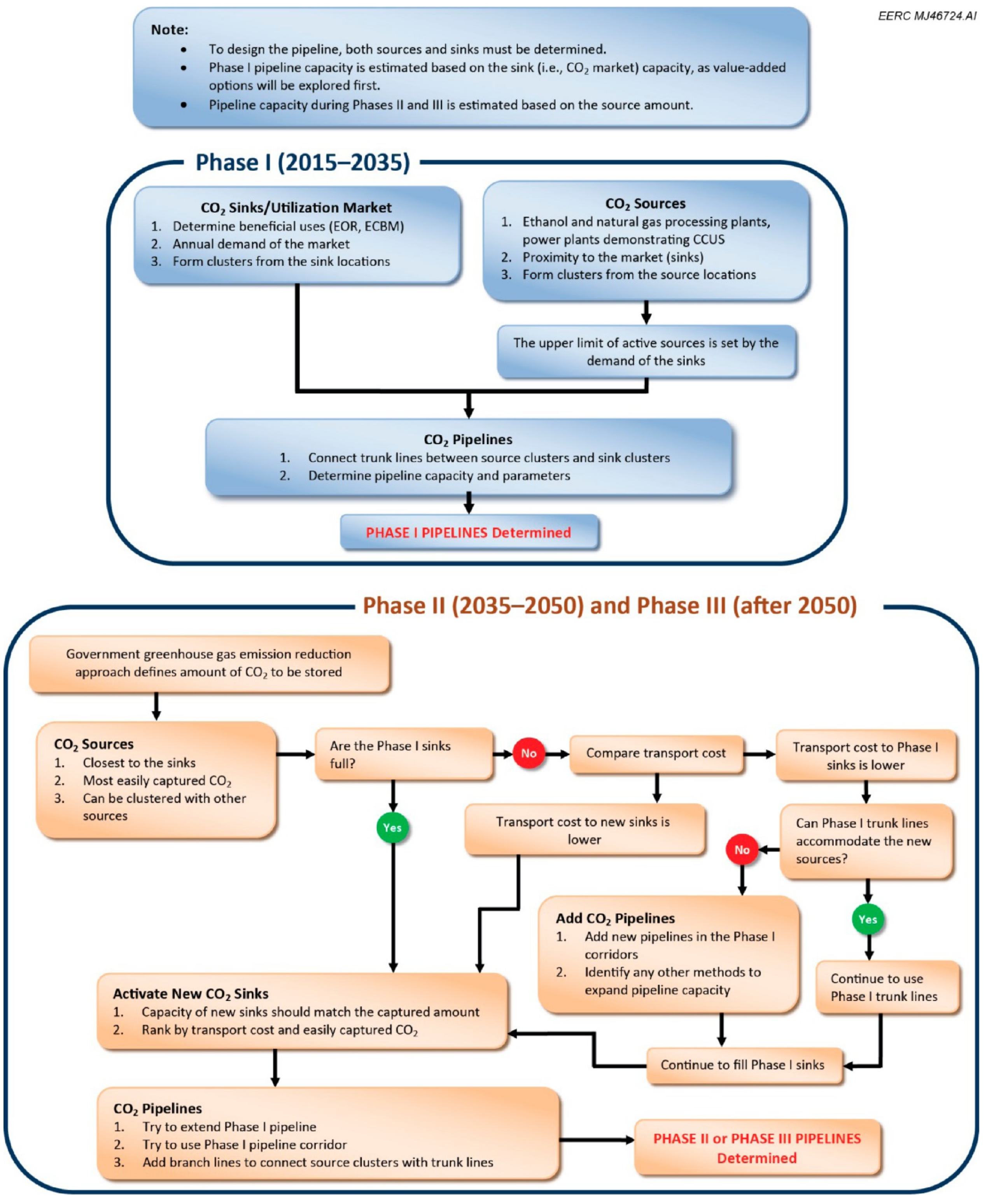

Figure 2. Flow diagram of the PCOR Partnership hypothetical phased pipeline development.

The timing noted in both the Dooley and Dalhousie University studies delineated appropriate breaks that could be applied to pipeline development and were, therefore, adopted for this study. Phase I is defined as covering the time period from about 2015 to 2035; phase II covers from 2035 to 2050; and phase III begins in 2050.

The PCOR Partnership Methodology for Preliminary Development of Phased CO_2 Pipeline Networks. Additional CO_2 pipeline design work was studied, notably that by Fritze,[15] Jeffries,[21] Morbee et al.,[22] Parfomak and Folger,[23] Parfomak et al.,[24] Pershad et al.,[25] and Zakkour.[26] The results were combined with the network design concepts described earlier 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 nodes, thereby determining a route, and (4) optimizing the network for each phase (to the extent possible).

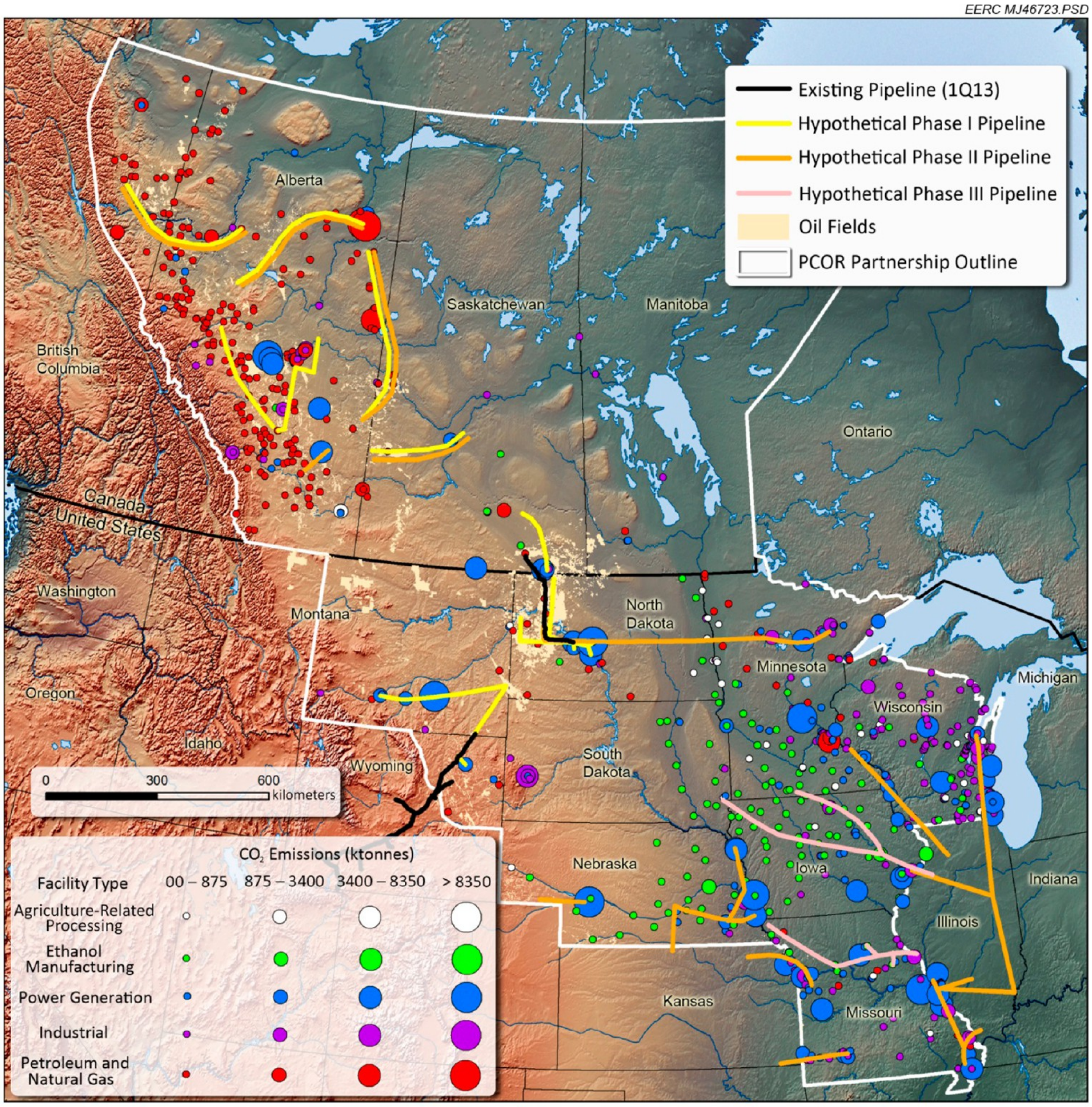

Figure 3. Hypothetical phased pipeline network for the PCOR Partnership region.

This approach is not intended as a method for the development of a detailed CO_2 pipeline network design. Instead, it can be used to estimate the amount of CO_2 that ultimately can be transported and stored as well as the length and cost of the trunk and branch pipelines required to store that CO_2.

Clusters of CO_2 sources would be identified first. Sources that are proximally located to each other are noted, keeping in mind the economics of capturing the CO_2 at the various facilities within a potential cluster. The CO_2 emission rate for each source is then taken from an online emission database, such as the United States Environmental Protection Agency (U.S. EPA) e-GRID, the EPA Clean Air Market Data and Maps searchable database, the U.S. EPA Greenhouse Gas online data publication tool, the Environment Canada greenhouse gas search engine, or the partners-only 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 would 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. On the basis of the EIA forecasts, a range of potential future emission trends may be estimated. It was assumed that the emission trends for electricity generation would also apply to CO_2 emission from larger facilities in 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.[27] The CO_2 trends from both data sources projected that U.S. CO_2 emissions will likely increase by 10% from 2010 to 2035 and by 11% from 2010 to 2050. The Dalhousie University study mentioned earlier[20] is a source for estimating CO_2 emission trends from point sources in Canada. It is important to recognize that each of these projections have inherent limitations and uncertainties. Such trends should only be used for rough estimations in hypothetical future situations, as is the case here.

The CO_2 storage capacity of each sink or sink cluster should be researched or estimated using porosity and permeability data. There are some online data sets that contain this information, including the partners-only PCOR Partnership DSS and the U.S. DOE National Energy Technology Laboratory's (NETL's) National Carbon

Table 1. Summary of the Preliminary Phased Pipeline Network for the PCOR Partnership Region

	km of new hypothetical pipeline	CO_2 transported by new hypothetical pipeline (Mtonnes/year)	capital cost of new hypothetical pipeline ($M, 2009 US$)	O&M[a] cost of new hypothetical pipeline ($M, 2009 US$)	levelized annual cost of new hypothetical pipeline ($M, 2009 US$)
United States					
phase I	1078	53	676	3	80
phase II	4184	168	2966	14	348
phase III	0	0	0	0	0
total, phases I and II	5262	221	3642	17	428
total, all phases	12135	633	7916	38	928
Canada					
phase I	2520	146	1251	8	146
phase II	2969	184	1887	9	222
phase III	1384	82	1136	4	132
total, phases I and II	5489	330	3138	17	368
total, all phases	6873	412	4274	21	500
grand total, phases I and II	10751	551	6780	34	795
grand total, all phases	12135	633	7916	38	928

[a]Operating and maintenance.

Sequestration Database and Geographic Information System (NATCARB) data set.

Pipeline routes should be determined next. They can be determined using pipeline routing software, or they can be very roughly estimated by measuring the distance between the centroid of a cluster of CO_2 sources and the centroid of a 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 miles) and extending the pipeline later if necessary. The Carnegie Mellon University Integrated Environmental Control Model (IECM), a free product that is readily available online,[28] can be used to estimate pipeline costs.

The easiest sources from which to capture CO_2 are ethanol plants and gas-processing facilities because the CO_2 that they produce as part of their processing is relatively pure. However, the earliest storage (i.e., phase I) is most likely to be in areas in which the CO_2 can be profitably used, such as during EOR or ECBM production. Many gas-processing facilities are situated on or near oil fields; therefore, they are ideally located for this purpose. It is assumed that the product from several smaller gas-processing facilities would be gathered to form a large enough stream to supply an EOR project. Ethanol plants are more widely distributed and may not be located near storage sinks. Therefore, the majority of the ethanol plants probably will not come into play until late in network development (i.e., during phases II or III), because the value of the CO_2 volumes, even when combined, will not exceed the cost to dehydrate, compress, and build a pipeline to transport the CO_2 to a storage target. In addition to the well-situated facilities from which CO_2 is easier to capture (i.e., larger gas-processing and ethanol plants), other sources that would be included in a phase I network would be any power plants having corporate reasons for being an early adopter (e.g., government grants, etc.). Phase I pipelines likely will be a combination of judiciously sited pipelines that link a source cluster to a sink/cluster of sinks in a localized area and one-to-one pipelines that transport CO_2 between one specific CO_2 source and a specific storage target. When possible, existing pipelines could be incorporated into a preliminary pipeline network.

More power plants would be incorporated during phase II of a network, along with some of the larger industrial facilities, such as cement kilns, and the rest of the gas-processing and ethanol facilities. Target geologic sinks would include the remaining EOR opportunities as well as saline formations. This phase would include both branch and trunk lines.

Phase III would come into play if sufficiently stringent climate policy and regulations force more widespread adoption of CCUS. Sources in this phase include the remainder of the larger coal-fired power plants and industrial facilities that are required to capture CO_2. Geologic sinks added to the network during phase III would consist primarily of saline formations. During this phase, the trunk lines could be connected with other trunk and branch lines in the network. Feeder lines could be added from large facilities to hook them up with the branch lines. If it does not make economic sense to connect all of the pipeline segments together to form a single network during phase III, there may be smaller pipeline networks serving specific areas consisting of multiple pipeline segments connecting specific source and sink clusters.

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 on the basis of their proximity to the EOR sinks. This methodology assumes that the life of an EOR project is 20 years.[29] 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 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 pipeline network will be expanded. Expansion will be based on the existing phase I network to minimize cost. Possible expansion methods include using the same methodology.

Phase I is the pipeline corridor for trunk lines and adding branch lines to the old trunk line. The goal of phase II would be a 50% reduction in CO_2 emissions by 2050, when phase III would go into effect. Phase III would be a "maintenance" phase, in which some pipelines would be extended to allow CO_2 to reach different storage targets if the first ones have been filled.

■ RESULTS AND DISCUSSION

In a case study, the PCOR Partnership pipeline network development methodology was applied to the PCOR Partnership region. The case study produced a hypothetical pipeline network that could be implemented in three phases over the next 40−50 years (from the present until 2035, from 2035 to 2050, and after 2050). Clusters of CO_2 emission sources and geologic sinks were identified for each of the states and provinces in the PCOR Partnership region. The volume of CO_2 that would be available from each cluster of sources was estimated, and the most likely storage targets for each source cluster were identified. Hypothetical pipeline routes that connected the sources and sinks were determined. Costs were estimated for those pipeline routes using the Carnegie Melion IECM software.[28] Finally, when viewed as a regional whole, the routes were optimized for each network phase to the extent possible. Figure 3 shows the hypothetical pipeline routes, and Table 1 summarizes the length and cost of the pipelines in the hypothetical network.

Roughly 10 750 km (6680 miles) of pipeline could hypothetically 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 reduction would equal roughly 403.4 Mtonnes of CO_2/year (444.7 Mtons/year) for the PCOR Partnership region. Meeting the IEA BLUE Map scenario is dependent upon two critical assumptions. The first, put forward by the Energy Research Group at Dalhousie University,[20] 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 CO_2 emission capture (which equates to a 98% CO_2 emission capture rate in 2050 using values described by the Energy Research Group[20]) would actually be attained. If these assumptions are correct, 330 Mtonnes/year (364 Mtons/year) of CO_2 would be stored in the Canadian portion of the PCOR Partnership region. When coupled with the expected U.S. CO_2 storage of 221 Mtonnes/year (244 Mtons/year), the overall reduction for the PCOR Partnership region would be about 551 Mtonnes/year (607.4 Mtons/year) by 2050 (i.e., for phases I and II).

■ CONCLUSION

The PCOR Partnership's methodology for estimating pipeline routes and timing appears to work reasonably well. The hypothetical phased network that was produced during the case study test of the methodology seems to agree with results obtained by others.

Dooley et al.[30] estimated that about 45 000 km of pipeline would be needed in the United States by 2050 to meet a scenario in which atmospheric CO_2 is stabilized at 450 ppmv. The hypothetical pipeline estimates obtained using the PCOR Partnership methodology indicate that the length required for the U.S. portion of the region totals 5260 km (3270 miles). This seems low, but the average pipeline segment would be shorter in the PCOR Partnership region than in many other areas of the United States because of the relatively short distance between clusters of large CO_2 sources and appropriate geologic sinks (especially EOR opportunities). These results also indicate that an extensive pipeline network may not be required to transport to storage locations the quantity of CO_2 required to meet the emission reduction targets for the PCOR Partnership region.

The IEA notes that long-term strategies are needed to both cluster CO_2 sources and develop CO_2 pipeline networks to optimize source-to-sink transmission of CO_2.[1] The PCOR Partnership's pipeline-routing methodology for estimating hypothetical phased pipelines could help to meet this challenge.

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Notes

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■ NOMENCLATURE

$M = millions of U.S. dollars (2009 value)
CCUS = carbon capture, utilization, and storage
CEPA = Canadian Energy Pipeline Association
CO_2 = carbon dioxide
DSS = decision support system
ECBM = enhanced coalbed methane
EIA = U.S. Energy Information Administration
EOR = enhanced oil recovery
IEA = International Energy Agency
IECM = Integrated Environmental Control Model
IOGCC = Interstate Oil and Gas Compact Commission
Mton = million short tons
Mtonnes = million metric tons
NATCARB = National Carbon Sequestration Database and Geographic Information System
NETL = National Energy Technology Laboratory

O&M = operating and maintenance
PCOR = Plains CO_2 Reduction Partnership
ppmv = parts per million by volume
U.S. DOE = United States Department of Energy
U.S. EPA = United States Environmental Protection Agency

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