ENERGY TECHNOLOGY INNOVATION POLICY

A joint project of the Science, Technology and Public Policy Program and the Environment and Natural Resources Program
Belfer Center for Science and International Affairs

HARVARD Kennedy School
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

Returns to Scale in Carbon Capture and Storage Infrastructure and Deployment

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Discussion Paper 2008-04
May 2008

energytechnologypolicy.org

Returns to Scale for Carbon Capture and Storage Infrastructure and Deployment [*][†][‡]

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Original, May 22, 2008, updated August 1, 2008

Abstract

The degree to which carbon capture and storage (CCS) is deployed will be partly determined by the returns to scale of the technological system that captures, transports, and stores carbon dioxide (CO_2). This technological system spatially connects the organization of CO_2 point sources with the organization of geologic CO_2 storage reservoirs. These point sources and storage reservoirs are heterogeneous in the amount of CO_2 that they produce or store and in the costs of capturing or storing CO_2, and the associated cost structures interact to determine the returns to scale for the entire coupled system. The *SimCCS* cost-minimizing geospatial deployment model is used to deploy CCS for a variety of combinations of CO_2 sources and injection reservoirs and determine the returns to scale for CCS deployment and unravel the determinants thereof. *SimCCS* minimizes the total costs of the entire capture, transport, and storage system by simultaneously determining how much CO_2 is captured from each source, how much CO_2 is stored in each storage reservoir, and assigning CO_2 flows through pipeline networks that include trunk distribution lines that are routed to minimize the influence of the social and physical topography. The returns to scale for the entire CCS system involves the interaction of the cost structures for each link in the CCS chain - capture at the source, transport through the network, and storage at the reservoir -

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[*] This paper is was also presented at the *7th Annual Conference on Carbon Capture and Sequestration*, May 5-8, 2008 and an earlier version will be available in the conference proceedings.

[†] This paper has benefitted from conversations with John Holdren, Juha Kiviluoma, Richard Middleton, and Richard Zeckhauser

[‡] Portions of this work have been funded by: BP Alternative Energy, BP Climate Mitigation Initiative, The Energy Foundation, Shell Exploration and Development Company, Zero Emissions Research Technology (ZERT) funded through Los Alamos National Laboratory, and the Joseph G. Crump Fellowship.

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each of which is modeled with cost structures that allow for increasing returns to scale. While it is possible that these cost structures can reinforce each other, the variability of source and reservoir costs and capacities interact with the spatial organization of sources and reservoirs to limit and ultimately reverse the returns to scale for CCS as the scale of the system expands.

1 Introduction

A major issue with technological deployment of any kind is the scale at which it can be deployed. Interest in carbon capture and storage (CCS) has emerged in part because of the potential for the technology to substantially reduce CO_2 emissions to the atmosphere. To do so, however, CCS must be deployed at a grand scale, and the degree to which CCS will be deployed will be partly determined by the "returns to scale" of the technological system. While CCS will be subject to a myriad of social acceptance, legal, and regulatory issues - especially in countries with a participatory social and governmental structure - each of which has the potential to impede the scale and pace at which CCS is deployed, this paper focusses on CCS technologies and how they interact to determine the overall returns to scale for the deployment of CCS as a system.

Returns to scale, and the determinants thereof, are important for an understanding and planning of the industrial, and in the case of CCS, the spatial, organization of activities and technological deployment. CCS spatially couples CO_2 sources with CO_2 injection reservoirs, and will involve major infrastructure and policy planning issues and potentially enormous business opportunities. One of the major questions related to planning for CCS is where to locate injection reservoirs and thus where to focus efforts for site-specific characterization of reservoir geology for storage. Potential reservoir storage basins generally cover quite extensive areas. Where within a potential basin should the injection reservoir be located? The answer will depend, in part, on the spatial heterogeneity and distribution of CO_2 production and CCS costs incurred at the source(s), the spatial heterogeneity and distribution of geologic storage capacity and CCS costs incurred at the reservoir(s), and the clustering, or density, of these source and storage points. In addition to geologic characteristics, storage reservoir locations should be determined in part by their proximity to sources and other (potential) reservoirs and the returns their deployment. Further, from a business standpoint, industries desire to know which parcel of land to purchase for its underlying geology and its overlying proximity to CO_2 sources, likely pipeline routes, other injection reservoirs, and the scale at which this parcel of land can naturally provide potentially monopolistic carbon storage services.

Returns to scale can be characterized by the movement along the average cost curve. If average costs are decreasing, it can be beneficial to expand activities until the average costs reverse and start to increase. A familiar situation with decreasing average costs is when high fixed costs and constant variable costs exist. In this situation, the costs to install a piece of equipment, for example, are increasingly spread out over the full capacity of the equipment. Decreasing average costs also arise from declining marginal costs as the capacity of a component expands. In other words, per unit costs are minimized at maximum operating capacity; the average cost curve is decreasing, and it is desirable to operate the equipment at full capacity, or scale.

Scientific or engineering laws can also produce decreasing average costs as scale increases. For example, the amount of fluid that can flow through a pipeline, $\dot{m}$, is related, in part, to the cross-sectional area of the pipeline which, in turn, is determined by the square of the pipeline diameter, $\dot{m} = f(A_c) = f(D^2)$. Flow increases in a proportion greater than the increase in the diameter, and thus larger diameter pipelines should be preferred to smaller diameter pipelines. In addition, the pressure drop, ΔP, the flowing fluid experiences due to friction within the flow regime internal to the pipeline, is inversely related to D^5: $\Delta P(\dot{m}) = f(\frac{1}{D^5})$. As the pipeline diameter increases, the pressure drop decreases substantially, the amount of compression and pressurization necessary decreases, and, since the costs to compress or pressurize a fluid are linearly related to the pressure drop, the costs decrease more than the proportional increase in the diameter. The amount of fluid that can flow through a pipeline increases non-linearly with diameter, and the cost to pressurize this fluid for transport decreases nonlinearly with diameter. Further, the marginal cost of constructing a pipeline decreases with diameter (as will be shown in Section 2). Taken both separately (and collectively) these engineering "facts" suggest that networking individual pipelines together so that CO_2 flows can be aggregated into larger diameter trunk distribution lines should also reduce average costs.

A conventional way to model determine the returns to scale for a system with more than one input is to use the Cobb-Douglas structural form for a "production function":

$$Y = Ax_1^{\alpha_1}x_2^{\alpha_2} \tag{1}$$

where Y is output and x_1 and x_2 are inputs. In the two-input Cobb-Douglas production function in Equation 1, x_1 and x_2 are often taken to be capital and labor and Y is some good being produced. "Returns to scale," in this case, describe the proportional change in output for a proportional change in the inputs. If output increases less than the increase in inputs, returns to scale are decreasing. If the output changes in direct proportion to the change in inputs, returns to scale are constant, and if the output increases more than the proportional increase in inputs, then returns to scale are increasing. Increasing returns to scale are also referred to as positive economies of scale. If each of the inputs is multiplied by some factor, say γ, then the returns to scale are determined by how much Y changes. If it changes by more than γ, then the returns to scale are increasing. For this to occur, the sum of the exponents, $\alpha_1 + \alpha_2$, must be greater than one. Returns to scale are constant if this sum equals one, and decreasing if $\alpha_1 + \alpha_2 < 1$.[1] Economies of scale are usually defined as

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[1] If each input is multiplied by γ, assume the output changes by δ: $\delta Y = A(\gamma x_1)^{\alpha_1}(\gamma x_2)^{\alpha_2} = A\gamma^{\alpha_1+\alpha_2}x_1^{\alpha_1}x_2^{\alpha_2}$. The proportional change in output, δ, depends on the exponent on γ which is the sum of α_1 and α_2.

$\alpha_1 + \alpha_2 - 1$, so that they are either positive (increasing returns to scale), negative (decreasing returns to scale), or zero (constant returns to scale) (Berndt, 1996).

While each of these types of positive economies of scale exist within the CCS system, and there is potential for them to reinforce each other as the technologies are coupled together, CCS involves the spatial coupling of heterogeneous sources with heterogeneous injection reservoirs. Capture and compression costs, incurred at the source, vary across sources in part due to the type of facility that is producing the CO_2 (coal power plant, cement manufacturer, etc.), in part due to the variance in the amount of CO_2 that a particular facility produces, and in part due to the distance that the CO_2 must be transported. Injection and storage costs, incurred at the reservoir, vary in part due to the geologic characteristics of the formation into which CO_2 is being injected as well as the amount of CO_2 that can be stored in the reservoir (the reservoir's capacity). Further, the source-reservoir combination is spatial and as the transportation network expands to handle larger capacities it will extend farther away spatially from injection reservoirs in addition to capturing CO_2 from more costly sources. This paper investigates the determinants of the returns to scale for the overall CCS system: the linking together of CCS technologies and the spatial matching of CO_2 sources and storage reservoirs.

Section 2 briefly describes the *SimCCS* (Middleton and Bielicki, 2008) scalable infrastructure model for CCS, a general geospatial optimization methodology that is extendable to a wide range of infrastructure planning problems. For this paper, it is coupled to an engineering-economic model for CO_2 transport and storage (Bielicki, 2008). *SimCCS* deploys CCS infrastructure by minimizing the total estimated costs of the entire capture-transport-storage system. It generates pipeline networks that include trunk distribution lines and are routed to minimize their impact on the social and physical topography.

SimCCS is run for a variety of combinations of CO_2 sources and potential injection reservoirs for California, as described in Section 2.1. Section 3 presents the results of the optimized deployment determined by *SimCCS*, and explores the returns to scale in two ways. First, the returns to scale for pipeline transportation networks are compared to the results from the commonly assumed dedicated straight pipelines from a single source to a single injection reservoir (Section 3.1). Second, the returns to scale for the entire CCS system - in which both capture and storage costs are modeled with their potential for positive economies of scale (fixed costs with constant variable costs), and pipelines are modeled with a Cobb-Douglas structure that indicates the positive economies of scale for CO_2 transportation - are explored (Section 3.2).

The returns to scale for the coupled technological system of CCS are determined by a complicated interaction of source and reservoir costs and capacities, the variability thereof, the spatial density of sources and reservoirs, and the number of sources and reservoirs that are being considered for deployment. Section 4 presents the major conclusions and discusses their importance.

2 Methodology and Data for Deploying Carbon Capture and Storage Infrastructure

An engineering-economic model for CO_2 transport by pipeline and storage by subsurface injection through wells (Bielicki, 2008) is used in conjunction with the *SimCCS* geospatial optimization methodology (Middleton and Bielicki, 2008) to optimize the deployment of the entire CCS technology system by minimizing the total estimated fixed and variable costs for CO_2 capture, transport, and storage over a timeframe. Pipeline construction costs in the Bielicki (2008) engineering-economic model are derived from an analysis for 15 years of pipeline construction costs (1990-2005) as published in the *Oil & Gas Journal*. A simplified representation of the estimated construction costs for an onshore pipeline is shown in Equation 2.

$$PL_{cost} = \$1,686,630 \cdot 1.0541^{Y} \cdot (D_{PL})^{0.9685} \cdot (L_{PL})^{0.7315} \tag{2}$$

where Y is the year since 1990 that in which the pipeline is constructed, D_{PL} is the pipeline diameter [m], and L_{PL} is the length of the pipeline [km]. Markets for materials, rights of way, labor, and construction equipment exist in a complicated interaction of markets, which is represented by the annual growth in costs Y. Equation 2 is in the Cobb-Douglas form of Equation 1, so that the returns to scale for CO_2 flows are evident.[2] Although Equation 2 shows that the marginal cost of pipeline construction with respect to its length is decreasing, *SimCCS* currently specifies that pipeline construction costs be constant per unit length. As such, pipeline construction costs are normalized to a 100 km length ($L_{PL} = 100$ km). Annual pipeline operating costs are taken from Heddle, Herzog and Klett (2003); McCoy and Rubin (2005); MIT (2006); McCoy and Rubin (2007).

CO_2 pressurization requirements in this engineering-economic model are based on simplified representations of fluid flow through pipelines and the resulting pressure drop over the pipeline's length, which is mostly a function of the pipeline diameter.[3] At present, *SimCCS* does not simultaneously optimize and iterate pressure drop calculations within and along pipelines and it does not keep track of pressure drops as it considers potential routes during the optimization. As a result, all CO_2 pressurization is assumed to occur at the source. It is assumed that the CO_2 arrives at the reservoir at a 10 MPa minimum allowable pressure, in order to keep the CO_2 above its critical pressure of 7.4 MPa. All pump and compressor costs for the sources and reservoirs are taken from IEAGHG (2002), their efficiencies are set at 75%, and electricity is priced at \$70 per MWh.

The potential for returns to scale at the source and the reservoir are included by modeling

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[2] Section 1 introduces the fact that Pressurization Costs $= f(\Delta P) = f(\frac{1}{D^5})$, and $\dot{m} = f(D^2)$. Construction cost in Equation 2 $= f(D^{0.9685})$. In both cases, cost increases less than the increase in $\dot{m}$ as the D increases.

[3] See McCoy and Rubin (2007) and Vandeginste and Piessens (2008) for analytic frameworks that incorporate the properties of CO_2 as it flows through a single pipeline.

each source or reservoir with its representative fixed and variable costs. CO_2 capture costs are based on the studies cited in IPCC (2005), which are adjusted in two ways to make them comparable across studies and between industrial sectors. First, the financing is removed using the parameters in the original studies, and the levelized annual costs are converted to their present fixed and variable cost values. The fixed and variable costs are separated to represent the positive economies of scale that result by deploying a higher percentage of the source's capacity. In addition, *SimCCS* (Middleton and Bielicki, 2008) does not have a temporal component, so all of the costs must be in their present values for comparison. Second, studies typically include the cost of compression to some relatively arbitrarily determined pressure for CO_2 transportation by pipeline. Compression is included in capture cost studies in order to compensate for processes that operate, and thus capture CO_2, at different initial pressures. The final pressure, however, is not uniform across the studies so the costs are normalized using the assumptions in the original study for compression to 10 MPa. Pressurization requirements above that 10 MPa are determined by the engineering-economic model for CO_2 transportation and storage in Bielicki (2008).

As with the source costs, reservoir costs are modeled with fixed and variable costs, converted to present values. The fixed reservoir cost for site evaluation and screening is taken from McCoy and Rubin (2005), and the variable cost depends on the flow of CO_2 to the reservoir and the geologic properties of the reservoir. This flow rate is spread out over multiple injection wells as is determined by the "injectivity" of the reservoir. Reservoir injectivity in Bielicki (2008) is calculated based on an integration of the Darcy flow equation for fluid flow in a porous media and determined by the geologic parameters of the reservoir (formation permeability, reservoir thickness, etc.) and the properties of the injected fluid.[4] Other formation parameters, namely reservoir temperature and pressure, determine the density

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[4] The Bielicki (2008) formulation is consistent with Law and Bachu (1996), which is used by McCoy and Rubin (2005) and Heddle, Herzog and Klett (2003).

and viscosity of the CO_2 in the subsurface which, in Bielicki (2008), are calculated from regressions describing the equations of state for CO_2 (Span and Wagner, 1996)[5]. These CO_2 properties also determine the reservoir injectivity. Well drilling costs are based on analyses done by Advanced Resources International (e.g., ARI, 2005) and an analysis of data presented by the Joint Association Survey of Drilling Costs (API, 2000). It is assumed that the CO_2 arrives at the injection reservoir at 10 MPa, and further repressurization, if necessary, based on iterations of reservoir pressure, injectivity, and pressure drop in the three inch diameter injection wells, is conducted at the reservoir. Estimated CO_2 capacities in the reservoir are based on the density of CO_2 in the subsurface as it would replace the volume of fluid, such as oil, that has been produced from the reservoir.

The *SimCCS* (Middleton and Bielicki, 2008) implementation deploys carbon capture and storage systems by minimizing the total costs of the entire capture-transport-storage system. The methodology generates potential pipeline routes by applying a shortest path algorithm to a spatial 'cost surface' which contains cell values that represent the difficulty of building infrastructure through that cell. This process routes pipelines to minimize construction in cost-enhancing areas, such as river crossings, national parks, and urban areas, and thus incorporates the social and physical topography of the region where CCS is to be deployed. Potential pipeline routes are determined between every source and reservoir, every source and every other source, and every reservoir and every other reservoir. A mixed-integer linear programming model is used to minimize the total costs of the system by choosing how much CO_2 is captured from each source, how much is stored in each storage site, and a pipeline network - chosen from the potential routes - that couples deployed sources and reservoirs with a networked system composed of trunk and distribution lines. The methodology considers standard pipeline diameters chosen from those built in the United States between 1990 and 2005, as listed in the *Oil & Gas Journal* with minimum and maximum CO_2 flowrates

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[5] The Span and Wagner (1996) data was downloaded from webbook.nist.gov

consistent with MIT (2006), and pipeline construction costs are determined by the Bielicki (2008) engineering-engineering economic model as summarized above. The spatial cost surface representing the cost multipliers associated with the social and physical topography is an updated version of MIT (2006), which includes rivers, highways, railroads, wetlands, state and national parks, and urban areas.[6]

2.1 CO_2 Source and Reservoir Data

CO_2 source and potential oil and gas field reservoir characteristics were downloaded from the Westcarb database[7]. The source database includes annual CO_2 production and facility type (e.g., coal-fired power plant, refinery) and latitude and longitude locations for the point sources. The reservoirs are polygons for the oil and gas fields and include reservoir temperature and pressure, thickness, depth permeability, and cumulative production. Potential reservoir injection sites were thus taken to be the centroid of the polygon representing the reservoir. Both CO_2 sources and CO_2 reservoirs were separated into sets which were then combined in various combinations for potential CCS deployment. The characteristics of each of the sets is shown in Table 1, and the combinations of these sets are shown in Table 2.

The sets listed in Table 1 are chosen so that, for the most part, smaller combinations are subsets of larger combinations. For example, S4 is a subset of both S12 and S37 just as R3 is a subset of R5 and R14. This subsetting procedure mimics the consideration of more sources and/or reservoirs for deployment. It is also important because the potential arcs and nodes in the pipeline transportation network are also subsets as the number of points served (sources plus reservoirs) is expanded. SB23, SLA18, and R54-R5 are notable departures from this approach and were explicitly chosen because of the difference in how cost and capacity are distributed over these sources and reservoirs. For example, SB23 has

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[6] The degree to which a cell is to be avoided depends on its value relative to the others. As a result, 1 was added to the base value (originally 0) in MIT (2006).

[7] www.westcarb.org, last accessed February 2008

Table 1: Source and Reservoir Data Characteristics

		CO_2 Capacity[a]		**Estimated Costs** [$\$/t_{CO_2}$][b]	
	Description	Mean	Std. Dev.	Mean	Std. Dev.
Sources					
S4	4 Largest	3,889	1,108	39.86	0.18
S12	12 Largest	2,886	962	45.09	7.80
S37	37 Largest	1,752	986	44.17	7.12
SB23	23 Largest sources, Bay Area	952	756	42.33	6.38
SLA18	18 Largest sources, LA Area	1,358	765	45.35	7.50
Reservoirs					
R1	Largest	410,554	-	3.68	-
R2	2 Largest	328,769	115,661	2.75	1.32
R3	3 Largest	270,643	129,710	2.78	0.97
R5	5 Largest	210,718	123,115	3.86	1.80
R14	14 Largest	110,639	105,917	4.01	1.15
R54-R5	6th through 54th Largest	18,497	21,911	3.60	2.05

[a] Source capacities are in CO_2 production [kt/yr] and reservoir capacities are total storage [kt].
[b] Levelized annual costs assuming an amortization factor of 11% over 25 years.

many smaller capacity sources when compared to the other sets of sources, and R54-R5 has many small capacity storage reservoirs. SB23 and SLA18 also contain sources clustered in particular areas (San Francisco Bay Area, Los Angeles, respectively).

Each set of sources, except for SB23 and SLA18, were combined with each set of reservoirs.[8] Table 2 shows the combinations that were explicitly chosen, and how some combinations intentionally did not have enough storage capacity for the CO_2 that could be captured from the set of sources. With storage constrained as such, it is possible that the optimization might choose to deploy sources or reservoirs it otherwise would not have.

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[8] Memory limitations prohibited the S37R54-R5 combination.

Table 2: Source-Reservoir Combinations

Combination	Source Production [kt/yr]	Reservoir Capacity [kt]	Over/Under Capacity[a]
S4R1	13,265	410,554	Over
S4R2	13,265	657,539	Over
S4R3	13,265	811,390	Over
S4R5	13,265	1,053,589	Over
S4R14	13,265	1,548,955	Over
S4RR54-R5	13,265	906,357	Over
S12R1	29,483	410,554	Under
S12R2	29,483	657,539	Under
S12R3	29,483	811,390	Over
S12R5	29,483	1,053,589	Over
S12R14	29,483	1,548,955	Over
S12RR54-R5	29,483	906,357	Over
S37R1	56,259	410,554	Under
S37R2	56,259	657,539	Under
S37R3	56,259	811,390	Under
S37R5	56,259	1,053,589	Under
S37R14	56,259	1,548,955	Over
SB23R14	21,903	1,548,955	Over
SLA18R14	24,440	1,548,955	Over

[a] Over 25 years of production from the sources.

3 System Deployment Results and Discussion

Table 3 shows the number of potential pipeline arcs and nodes generated by *SimCCS* for each combination of source-reservoir set that was considered. As briefly described in Section 2, *SimCCS* generates potential pipeline routes that minimize the impact on the social and physical topography, as indicated by a spatial ‘cost surface.’ One potential arc is created between every source and every reservoir, and since it is possible that sources and reservoirs could serve as interstitial nodes in the overall transportation network, *SimCCS* also generates a potential arc between every source and every other source as well as between every reservoir and every other reservoir. When these routes intersect, an extra node is generated,

Table 3: Number of Potential Nodes / Arcs Generated by *SimCCS*

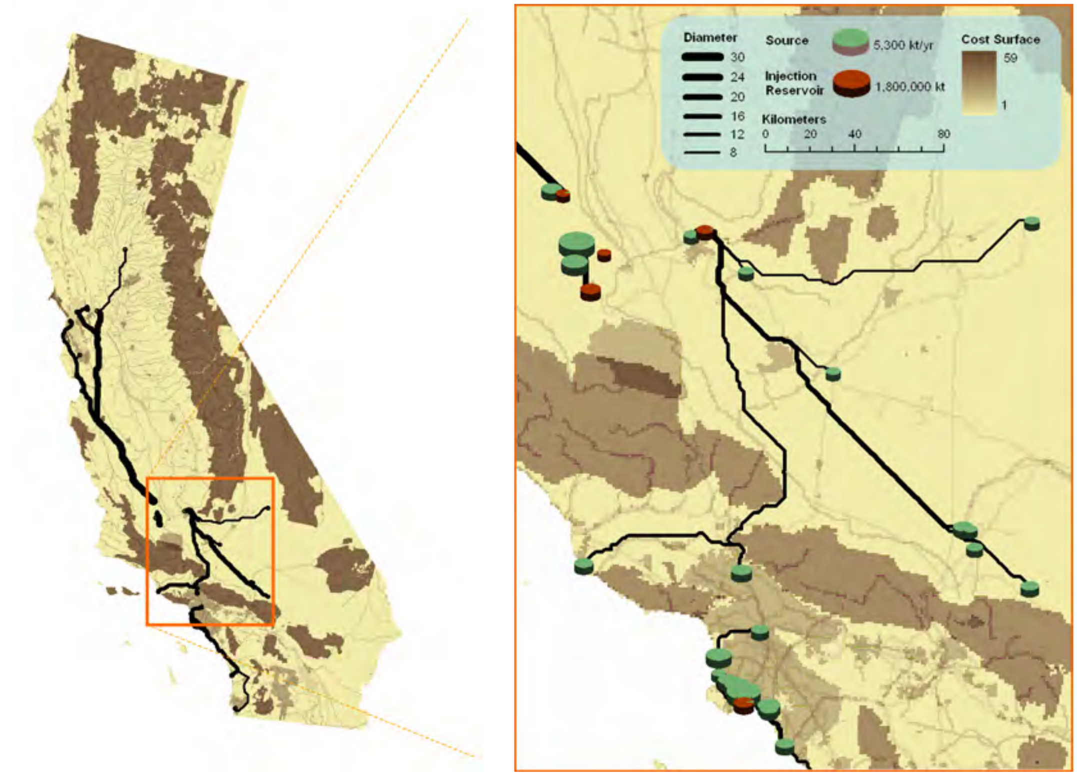
	R1	R2	R3	R5	R14	R54-R5
S4	8/18	16/42	17/44	21/56	88/288	443/1648
S12	39/108	57/166	58/168	61/184	178/576	519/1948
S37	240/778	243/778	246/798	250/816	330/1104	
SLA18					335/1138	
SB23					124/332	

representing a potential terminus for a trunk distribution line. Duplicate arcs (where potential routes overlap) are removed. The number of arcs and nodes is thinned by removing equivalent triangles within a user-modifiable distance (set to one kilometer for the models presented here). The CCS transportation network that is deployed is chosen from these sets of potential arcs and nodes, which are shown in Table 3.

Figure 1 shows an example deployment for S37R5. The sources and reservoirs are sized by their production and storage capacities, respectively, and the different widths of the pipelines indicate different diameters that are deployed. It is evident from Figure 1 that pipeline networks with trunk distribution lines are being generated - that CO_2 flows from multiple sources are being aggregated into larger diameter pipelines. Figure 1 also shows that the deployed CCS system is not necessarily optimal when fully networked: Four totally separate pipeline systems are deployed.

3.1 Comparison of Returns to Scale in Pipeline Networks

As noted in Section 2, the capital cost to build a pipeline is empirically determined to have increasing returns to scale: the average cost per tonne of CO_2 decreases as the diameter increases, so that it is desirable to aggregate CO_2 flows from multiple sources into larger diameter pipelines. A CCS system will require many pipelines, each of which can exhibit increasing returns to scale.



(a) (b)

Figure 1: California Example: Optimized Deployment in California, 56 Mt_{CO_2}/yr from S37 R5: (a) Cost Surface and Pipeline Network, (b) Deployed Sources, Injection Sites, and Pipelines North of Los Angeles

Previous work to match CO_2 sources with CO_2 injection sites[9] have assumed that CO_2 pipelines will connect a single source to a single injection site (ILSGS, 2005; Dooley et al., 2006; MIT, 2006), that these pipelines will be straight (ILSGS, 2005; Dooley et al., 2006), have a minimum and maximum distance between sources and injection sites (Dooley et al., 2006), and that all of the CO_2 will be captured from a particular source, regardless of whether or not the combination of fixed and variable costs at other locations make it economical to capture only a portion of the CO_2 produced by a source (Dooley et al., 2006). *SimCCS* (Middleton and Bielicki, 2008) produces a realistic network which facilitates a comparison between prior assumptions and the benefits of the network and its inherent aggregation of

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[9] Otherwise known as 'Source-to-Sink Matching'.

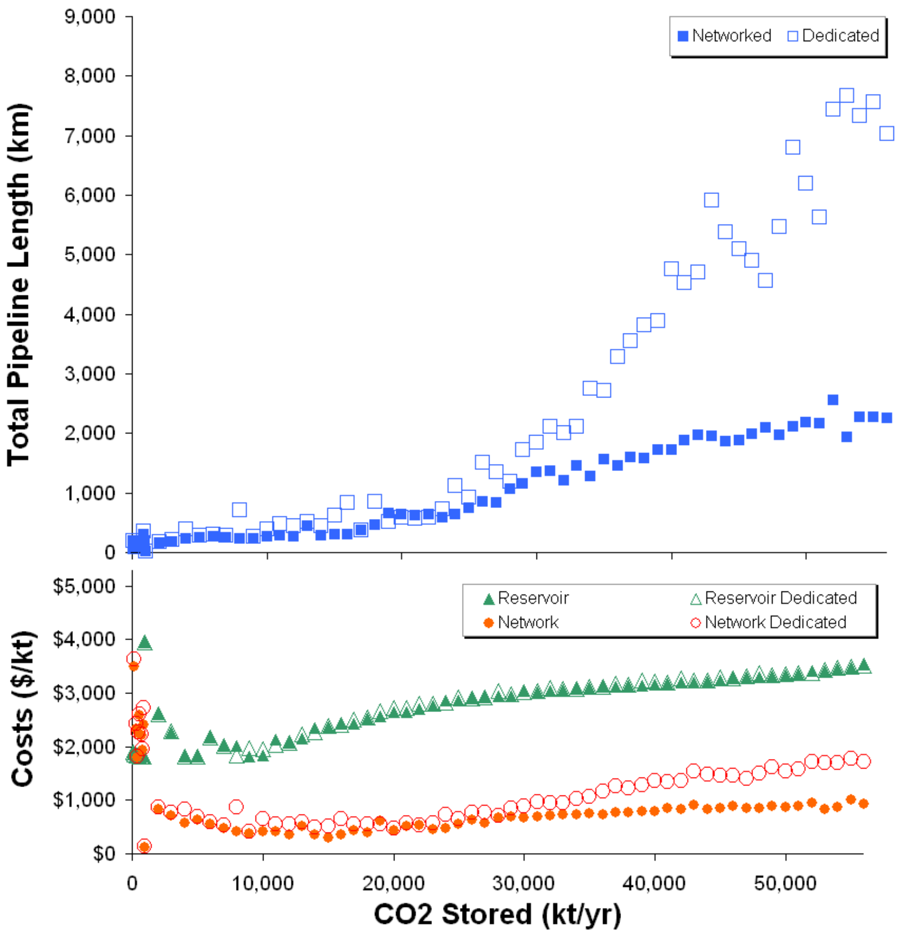

Figure 2: Networked Pipelines versus Single Dedicated Pipelines for S37R14

CO_2 flows into larger diameter pipelines.

Figure 2 compares the cost of networked pipelines, as deployed by *SimCCS* (Middleton and Bielicki, 2008), with the equivalent single pipelines connecting the sources and reservoirs that are deployed for S37R14.[10] The solid points are for the optimized system with a CO_2 transportation network. The hollow points are for deployment with dedicated pipelines. The same cost surface is used for the networked pipelines and the dedicated pipelines, so that *SimCCS* chooses from the same set of routes. At the upper end of the scale, the total length

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[10] Figure 2 is modified from Middleton and Bielicki (2008). This figure replaces a previous version which contained an error in the source-reservoir matching.

of the dedicated pipelines is approximately 3.5x that of the networked pipelines and the cost to transport CO_2 is roughly doubled. Further, the cost of transporting CO_2 in the network is essentially flat above 30 Mt_{CO_2}/year, whereas costs associated with dedicated pipelines are increasing. Figure 2 shows that networked pipelines where CO_2 flows are aggregated into larger diameter pipelines can reduce costs and extend positive economies of scale.

3.2 Returns to Scale for the Entire CCS System

The graphs in Figures 3-5 present levelized annual cost[11] curves for a variety of combinations of sources and reservoirs as deployed by *SimCCS*. These figures are used to explore the returns to scale for each component of the CCS chain as well as the overall system. The overall costs are shown and are disaggregated into the components that are incurred at each segment of the CCS chain: at the sources, in the transportation network, and at the reservoirs. Overall and source costs are are indicated on the primary Y axis and reservoir and transportation costs are shown on the secondary Y axis. This section describes the returns to scale in two ways. First, the costs resulting from the minimum-cost deployed system, as optimized by *SimCCS*, are compared between combinations of source and reservoir sets (S4R2 vs. S37R14, for example). If the cost curves shift down, for example, as the scale of the potential system increases (e.g., the total number of sources and reservoirs considered for deployment) the returns to scale are increasing. If the cost curves shift up, then the returns to scale are decreasing. The second approach taken here is to describe the changes in curvature of these curves within and between combinations of source and reservoir sets. Flat sections of the curves indicate constant returns to scale, and the regions where the curves are decreasing indicate increasing returns to scale.

Figure 3 shows nine combinations of S4, S12, and S37 with R2, R5, and R14. This figure is primarily intended to indicate the returns to scale as more sources and/or reservoirs

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[11] The levelized annual costs are based on an 11% amortization per year of present costs over 25 years.

are considered - of having more capture and storage options to choose from. The graphs with grey backgrounds are those combinations where CO_2 production by the sources in the combination is greater than the total estimated capacity of the reservoirs in the combination, so that there is an additional constraint on storage. Figure 4 shows S4 and S12 combined with R5 and and R54-R5 to indicate the effect of the different distributions of costs and capacities over potential storage reservoirs, and Figure 5 shows S12, SLA18, SB23, and S37 combined with R14 to illustrate the effect of the spatial clustering of sources as well as the different distributions of costs and capacities over different sources. Three combinations are included in multiple figures (S12R5 in Figures 3 and 4, S12R14 in Figures 4 and 5, and S37R14 in Figures 3 and 5) to ease the comparison within and between the figures.

The overall costs are mostly made up of costs incurred at the source - typically 75-90% of the overall costs. About 5-10% of the overall costs are incurred at the reservoir, and the balance by the transportation network. In general, the overall cost curve for a particular combination of sets of sources and reservoirs is mostly determined by the changes in deployed source costs, but the minima of the overall cost curve is also influenced by the reservoirs and transportation network costs, especially at small scales. For example, a really cheap source will likely be deployed early, when the scale of the overall system is still low. In this case, the source cost curve will dip dramatically, but the overall costs are unlikely to have such a pronounced dip because of the different characteristics of the returns to scale in the transportation network and the reservoir(s) that are deployed. At low scales, for example, the benefits of potentially networking pipelines together are unlikely to be fully realized and the average cost of the transportation network is still high. While the source cost curve will likely start to increase, and the returns to scale for source deployment will likely start to decrease, after this real cheap source is deployed, the returns to scale for the transportation network at the scale at which this particular source is deployed are still increasing. The overall cost curve, being the sum of the source, transportation network, and reservoir costs,

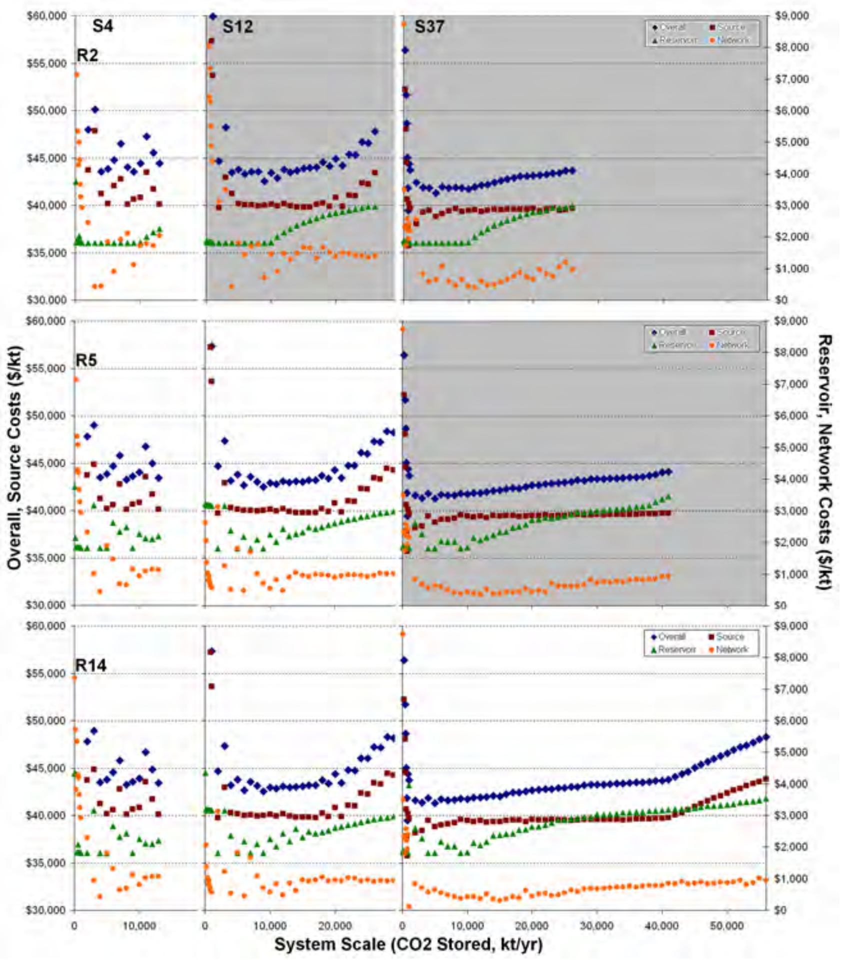

Figure 3: Levelized Annual Cost Curves when Sources and Reservoirs Considered are Expanded

depends on the changes in the cost curves for all of the components of the system.

Holding the reservoirs constant, Figures 3 and 4 indicate that the costs for all of the components decrease as the number of sources considered for deployment increase. Even though the mean source cost increases from S4 to S12 and S37 (Table 1), the variability does as well (relative to S4, the means and standard deviations of costs for S12 and S37 are roughly equal). Expanding the number of sources for deployment can include more cheaper sources in the set being considered for deployment, and, along with the potential reduction in source costs as the number of deployable sources increases, it is possible that

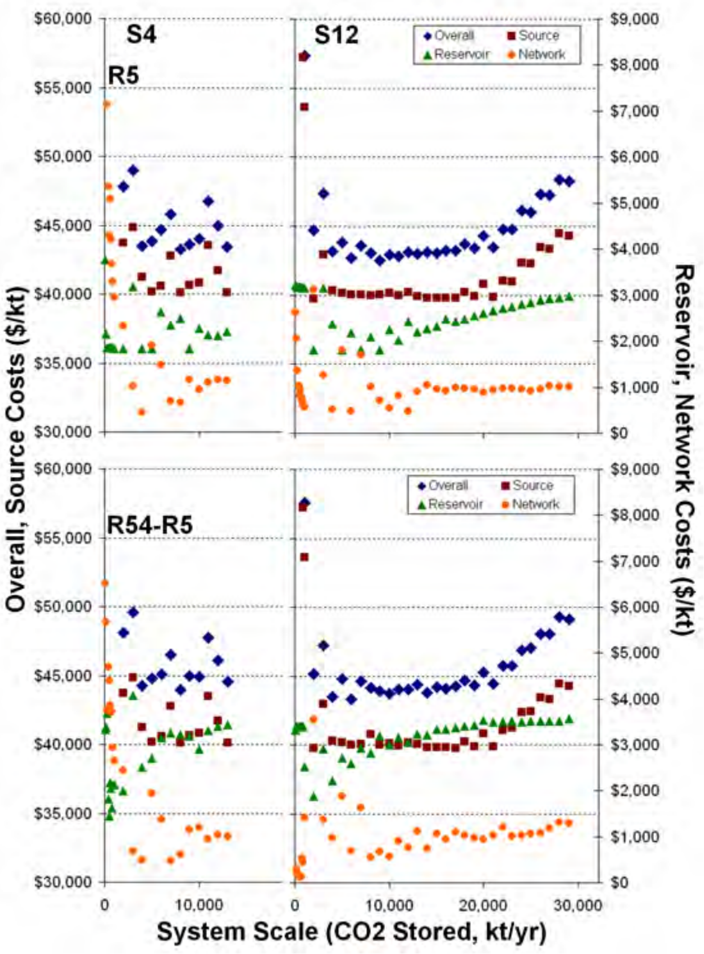

Figure 4: Levelized Annual Cost Curves for Storage Reservoir Capacity Distribution Differences

reservoir and transportation network costs can decrease as well. Figures 3 and 4 show such reductions in transportation costs and deployed reservoir costs. A decrease in the spatial proximity of sources considered for deployment is one mechanism that can reduce transportation costs when more sources are considered for deployment. If deployable sources are closer to each other, CO_2 flows can be readily aggregated into larger diameter pipelines closer to the point(s) of capture. The overall length of the transportation network should decrease as more sources are potentially deployable because less individual pipelines need to be constructed. The reduction in transportation costs can also arise when the additionally

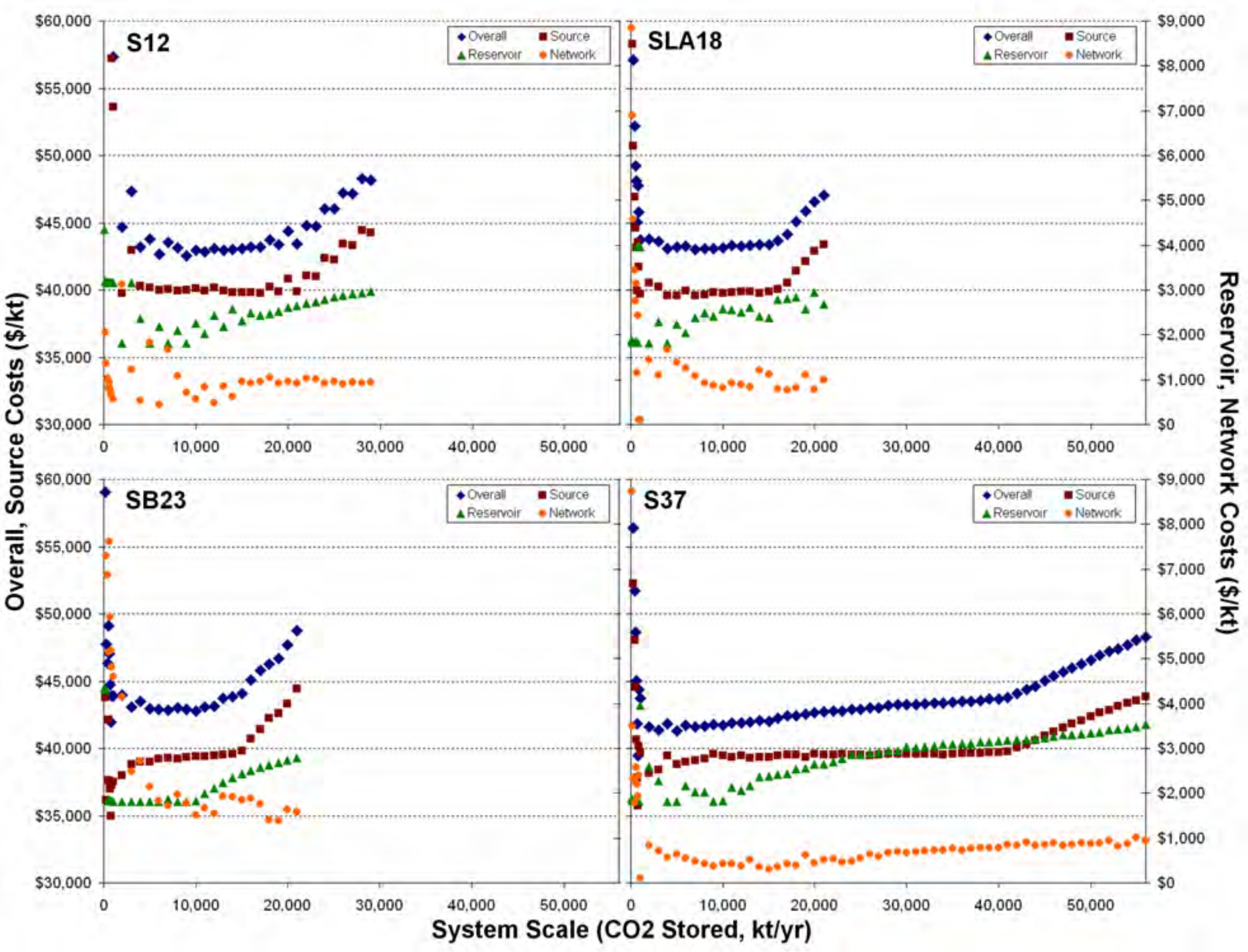

Figure 5: Spatial Clustering and Variation in Sources S12, SLA18, SB23, and S37 Combined with R14

considered sources are closer to potential reservoirs and thus the transportation pipelines are shorter. Table 5 shows the number of pipeline arcs, and the their total length, that are deployed, and provides evidence for these effects. Holding reservoir sets constant, the total length of the deployed network is shorter for S12 than for S4 in eleven of eighteen combinations of scale and source-reservoir sets. Further, the deployed network is shorter in twenty-four of the twenty-eight scale and source-reservoir set combinations, where S37 can be compared to S12.

Having deployable sources that are closer to reservoirs can also reduce the deployed reservoir costs. Transportation costs tend to be less than reservoir costs and it can be beneficial to transport CO_2 a little farther to a cheaper reservoir. At some point, however, the incremental transportation distance can become prohibitive so that closer reservoirs are deployed, even if they are more expensive. Figure 5, particularly the comparison between S12R14 and S37R14, shows such reductions in reservoir costs as the number of deployable sources increases.

The reduction in source costs in Figures 3 and 4 as reservoirs are held constant and the number of deployable sources increases continues if the original sources are retained in the deployable set, even if the newly considered sources have higher estimated costs. The less costly sources can still be deployed and will likely be deployed at low scales because, in general, source costs are the majority driver of deployment. When the expanded number of sources are are not subsets, such as if they are limited to a particular geographic area (SLA18 and SB23 in Figure 5), however, deployed source costs do not necessarily decrease as the number of deployable sources increases. The number of sources increases from SLA18R14 to SB23R14 in Figure 5, and while the SB23 are more costly, on average, they also produce less CO_2 (Table 1) than the SLA18 sources. Except for scales above approximately 16 Mt_{CO_2} per year, deployed source costs are lower for SB23R14 than for SLA18R14. Overall costs, however, are the same or higher in SB23R14 than in SLA18R14, in part because the transportation costs are higher for SB23R14 than SLA18R14. These higher transportation costs are partly a result of the R14 reservoirs being located farther away from the San Francisco Bay area than they are for the Los Angeles area, so the distances are greater, and partly a result of the lower CO_2 production by the Bay area sources (Table 1) and the more numerous smaller diameter pipelines that must be constructed in order to connect sources with the larger diameter trunk distribution lines (Table 5). Further, even though the same set of reservoirs is being considered, some different ones are deployed in SB23R14 than in SLA18R14 and those that are deployed in both combinations are deployed to different degrees. As shown in Table 4, in general, more reservoirs are deployed in SLA18R14 than in SB23R14, and the reservoir deployments are more costly (Figure 5). Table 4 also shows that, in part due to the lower CO_2 production capacity, SB23R14 also deploys more sources than SLA18R14.

Holding the number of deployable sources constant, Figure 3 indicates that the overall costs tend to remain the same or slightly decrease as the reservoirs considered for deployment expands. Source and reservoir costs tend to remain unchanged, however reservoir costs increase when there is insufficient storage capacity that can be deployed. The distribution of storage capacity over the number of deployable reservoirs also influences the deployed reservoir costs. Figure 4 shows that more numerous, yet smaller capacity, reservoirs increases deployed reservoir costs even if the mean cost storage cost is lower. As shown in Table 1, the total reservoir storage capacity is roughly equal for R5 and R54-R5, however it is spread out over almost ten times as many reservoirs in R54-R5 than in R5. In addition the reservoir costs, though lower on average, are more variable. Expanding the number of reservoirs, for the same set of sources is likely to open up a reservoir that is closer to a source and thus make it attractive for deployment. Although transportation costs have the potential to be lower when reservoirs are closer to sources, such a potential reduction in transportation costs does not typically compensate for the variability in reservoir costs and capacities. Transportation costs tend to be about the same when deployable storage capacity does not constrain deployment, but increases when reservoir storage capacity is limited relative to source production and when the storage capacity is distributed over many potential reservoirs.

In Figure 3, the overall cost curves for S12R5 and S12R37 are relatively flat between 5 Mt_{CO_2}/yr and 15 Mt_{CO_2}/yr - around \$43-44 per tonne of CO_2 - suggesting constant returns to scale in this region and increasing returns to scale below it. This flatness is mostly driven by the curvature of the source curve because the shapes of the average cost curves for sources and reservoirs tend to cancel each other out in this region. Deployed reservoir costs reverse around 7 Mt$_{CO_2}$ per year whereas the transportation network is still exploiting positive economies of scale until around 15 Mt$_{CO_2}$ per year, where the curve reverses a little and then plateaus until the minimum potential capacity of the system.

Expanding the potential number of points served (i.e., the number of deployable sources and reservoirs) generally increases the scale where a particular system cost is breached. Using the \$43-44/t$_{CO_2}$ where the cost curve for S12R5 starts to increase, and decreasing economies of scale set in, as a basis for comparison, it is clear from Figure 3 that returns to scale increase as the potential system expands; S12R5 breaches \$44/t$_{CO_2}$ around 18 Mt$_{CO_2}$ per year and S37R14 does so around 30 Mt$_{CO_2}$ per year. Similarly, where storage capacity is constrained in S37R2 and S37R14, \$44/t$_{CO_2}$ is breached around 25 Mt$_{CO_2}$ per year and 30 Mt$_{CO_2}$, respectively, mostly because the source cost curve is flat (costlier sources, if deployed, are deployed at larger scales) and the change in the overall cost curve is primarily a result in the escalation of reservoir costs and with a secondary contribution from the increase in transportation costs.

The flat section of the overall average cost curve for S12R5 begins around 5 Mt$_{CO_2}$ per year. As the number of deployable sources increases (to S37) the overall cost curve flattens sooner, around 3 Mt$_{CO_2}$per year, regardless of constraints on the storage capacity. Economies of scale are expanding.

The cost curves for S12R5 and S12R14 are virtually identical, in part, because the deployment is almost the same in (Tables 4 and 5).[12] For S12, it appears as though it is unnecessary to consider the nine extra reservoirs, and suggests that there are limits to the number of reservoirs that need to be considered.

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[12] Even though the total network length is roughly the same for S12R5 and S12R14 (Table 5), the number of deployed arcs is higher in S12R14 because *SimCCS* generates more arcs and more interstitial nodes that divide these arcs as the total number of sources and reservoirs considered increases.

Table 4: Numbers of Sources and Reservoirs (S, R) Deployed

	CO_2 System Capacity [Mt/yr]									
Combination	1	5	10	15	20	25	30	35	40	45
S4R1	1, 1	2, 1	3, 1							
S4R2	1, 1	2, 1	3, 2							
S4R3	1, 1	2, 1	3, 2							
S4R5	1, 1	2, 1	3, 2							
S4R14	1, 1	2, 1	3, 2							
S4R54-R5	1, 2	2, 10	3, 17							
S12R1	1, 1	2, 1	4, 1	5, 1						
S12R2	1, 1	2, 1	4, 2	5, 2	8, 2	10, 2				
S12R3	1, 1	2, 1	4, 2	5, 2	8, 3	10, 3				
S12R5	1, 1	2, 1	4, 2	5, 2	8, 4	10, 4				
S12R14	1, 1	2, 1	4, 2	5, 2	8, 6	10, 5				
S12R54-R5	1, 2	2, 10	4, 18	5, 22	8, 25	10, 32				
S37R1	2, 1	4, 1	5, 1	9, 1						
S37R2	2, 1	4, 1	5, 2	9, 2	12, 2	16, 2				
S37R3	2, 1	4, 1	5, 2	9, 3	12, 3	15, 3	17, 3			
S37R5	2, 1	4, 1	5, 2	9, 4	11, 4	15, 4	17, 4	20, 4	25, 5	
S37R14	1, 1	4, 1	5, 2	9, 5	13, 6	14, 7	18, 8	20, 8	25, 5	29, 10
SB23R14	3, 1	7, 1	9, 2	18, 4	22, 4					
SLA18R14	1, 1	4, 2	8, 3	10, 3	16, 5					

4 Conclusions and Discussion

The character of the potential returns to scale for the CCS system can have a significant impact on the degree to which CCS is deployed, and the planning necessary to realize as much of the climate-mitigating potential of CCS as possible.Carbon capture and storage involves the deployment of a system of interlinked technologies, each of which has its own representative cost structure and potential for positive economies of scale. Each segment of the CCS chain - capture at source, transportation in pipeline, and storage in reservoir - can benefit from increasing returns to scale, but the coupling of the technological cost structures over space determines the returns to scale for the overall system. This paper

Table 5: Numbers of Arcs and Total Network Length [km] Deployed

	CO_2 System Capacity [Mt/yr]									
Combination	1	5	10	15	20	25	30	35	40	45
S4R1	3	5	6							
	299	463	892							
S4R2	6	8	11							
	306	470	858							
S4R3	6	8	9							
	306	470	371							
S4R5	6	9	11							
	306	497	400							
S4R14	9	12	27							
	306	513	365							
S4R54-R5	20	71	86							
	309	683	606							
S12R1	7	11	13	23						
	455	461	630	974						
S12R2	6	13	15	27	33	34				
	432	469	670	1002	1190	1276				
S12R3	2	13	9	18	28	34				
	19	469	190	533	1085	1382				
S12R5	2	13	11	23	25	33				
	19	469	188	542	753	992				
S12R14	6	24	23	44	54	64				
	19	515	196	586	939	1048				
S12R54-R5	10	74	75	111	124	156				
	87	626	391	860	1062	1295				
S37R1	20	22	17	41						
	357	275	258	619						
S37R2	15	16	22	42	50	89				
	320	248	278	549	854	1614				
S37R3	16	17	23	30	46	75	92			
	320	248	288	305	610	1133	1347			
S37R5	15	18	26	30	42	67	69	90	119	
	311	248	276	305	474	751	1366	1554	2071	
S37R14	1	26	27	39	68	76	98	126	126	152
	11	246	258	308	643	737	1341	1554	1724	1886
SB23R14	14	55	65	101	109					
	407	581	752	1563	1683					
SLA18R14	1	23	31	41	48					
	9	357	520	718	520					

used a geospatial optimization methodology (Middleton and Bielicki, 2008) coupled with an engineering-economic model for CO_2 transportation and storage (Bielicki, 2008) to deploy CCS systems and unravel the returns to scale for the coupled technological CCS system. While source costs tend to drive the deployment of CCS, the variability in costs, capacities, and spatial orientation of sources and reservoirs determines the returns to scale for the coupled system.

Returns to scale can be determined by the character of the average cost curve. All else equal, it is desirable to expand the scale of an operation to the point where the average cost curve starts to increase, and returns to scale start to decrease. At the most basic level, the returns to scale for CCS as a system depend on the scale at which it is deployed. Returns to scale are not constant; they do not continually increase as the system expands and they do not continually decrease as the system expands. The returns to scale vary with the CO_2 capacity of the capture-transport-storage system, or the scale of the deployment. At “small” scales, returns to scale are increasing, suggesting that it is efficient to expand the system to capture and store more CO_2. At “large” scales, however, the returns to scale are decreasing, suggesting that it would be more efficient to scale the system back.[13] Overcentralization of CCS activities is possible.

Source costs make up the majority of the costs of the integrated CCS system, however the variability of source and reservoir costs and capacities determines the shape of the average cost curve. The region where the average cost curve is flat, between increasing returns to scale and decreasing returns to scale, suggests the efficient scale of deployment. The range over which the returns to scale are constant is inversely related to the variability in source and reservoir costs and capacities; returns to scale are constant over a larger range of scales when the variability is low. The distribution of costs and capacities over sources and reservoirs has

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[13] “Small” and “Large” are relative to the total amount of CO_2 being produced by the sources and and storable in the reservoirs being considered for deployment. “Small” is typically 10-30% of the total source production, assuming that there is overcapacity for storage.

a significant impact on the curvature of the of the average cost curves. As the variability of costs and capacities increases, the minimum of the average cost curve is more pronounced, and thus the scale at which increasing returns to scale reverse and decreasing returns to scale set is clearer. The region where constant returns to scale exist decreases. This effect helps make the deployment of infrastructure more robust, in the sense that the optimal infrastructure for one scale (the sources, reservoirs, and pipeline routes that are deployed) is retained in the optimal deployment over a wider range of scales.

Increasing the number of sources or reservoirs that can be deployed generally decreases the overall costs of the entire system, even as mean and variance of estimated source costs are roughly the same. More plentiful cheap sources and reservoirs can be deployed at larger scales, in part because the sources and reservoirs might be located closer to each other. In general, it is desirable to have more source and reservoir options to deploy, however in the (present and likely to continue) case where geologic characterization and storage reservoir capacity preparation lags behind CO_2 source production capacity, storage capacity serves as a constraint that escalates the costs and reduces the returns to scale for CCS. Further, the distribution of storage capacity can increase overall costs and decrease the returns to scale if, for example, many small capacity reservoirs must be considered.

While transportation network costs tend to be lower as more sources and reservoirs are considered, the region where constant returns to scale set in depends on the spatial orientation of the servable points (sources and reservoirs) relative to each other and how the costs and capacities are distributed over that spatial orientation. As more sources and reservoirs are considered, the transportation network can contain more disconnected and dispersed pipelines at low system scales, and the potential networking of pipelines can begin to have a noticeable impact at higher system capacities. Returns to scale for the transportation network tends to push the lower limit of the range of constant returns to scale to higher scales, however the influence on the overall cost curve is not to great because the transportation network is, in general, the smallest contributor to the overall average cost of the system. Constant returns to scale in transportation by pipeline tend to set in at larger scales than the returns to scale for deployed sources. This is a result of the spatial orientation and potential aggregation of CO_2 flows into networked infrastructure. If all of the sources are clustered near to each other, for example, the CO_2 flows can be aggregated into large diameter trunk distribution lines at small distances from the sources in order to take advantage of the returns to scale from pipeline transportation using larger diameters. In this case, the full advantage of trunk distribution lines cannot be exploited at smaller scales. If the reservoirs are dispersed, it is possible that they will be located close to sources and it is thus possible that CO_2 will be transported with dispersed pipelines that are not connected much and thus the potential returns to scale from transportation cannot be exploited. CO_2 flows can be aggregated more easily when the sources are located close to each other and when the reservoirs are located close to each other, and thus constant returns to scale for transportation set in at lower scales. Like source and reservoir costs, however, the transportation network tends to have decreasing returns to scale at large system capacities. This is basically a result of the network extending to include spatially removed and/or costlier sources. The additional pipelines that are deployed do not have the same potential to contribute to the networked system as do the pipelines from more centrally located sources.

For CCS as a system, overcentralization and overdispersion of activities are both possible. At one end of the spectrum, one reservoir could store the CO_2 produced from a single source nearby. This proximity would be beneficial in that the distance that CO_2 would need to be transported from the source to the reservoir would be lower, and perhaps the impact on the visual environment might be reduced, but it can be beneficial to transport the CO_2 a little farther to a less costly reservoir. In addition, aggregating CO_2 flows from multiple sources into trunk distribution lines can more fully exploit the positive economies of scale for CO_2 transportation by pipeline, and servicing less reservoirs than sources can thus be beneficial.

Taken to the extreme, all of the CO_2 produced in the United States, for example, could be stored in a single extremely high capacity and cheap reservoir. Intuitively, however, even if such a single reservoir capable of storing all of the CO_2 produced in the United States existed, it would not be advantageous to store all of that CO_2 in it. At some point as sources are farther and farther away from this reservoir, it will become advantageous to open up a second reservoir somewhat removed from this first reservoir. This second reservoir would, ideally, be located in a place proximal to many sources.

This reservoir locating process has implications for the choice of where to conduct site-specific geologic characterization for CO_2 storage. The choice of where within a potential storage basin to focus efforts on understanding the amenability of the geology to contain and store CO_2 should consider the returns to location in addition to the geologic potential. These returns depend on the location of the site relative to sources of CO_2 as well as to other potential storage reservoirs. Since it is likely that a CO_2 storage permitting process will be enacted to regulate the underground injection of CO_2, permits could give beneficial consideration to those reservoirs and injection sites that are located in relation to the locations of production and other storage opportunities.

Finally, it is unlikely that actual activities would deploy an 'optimal' transportation network from the viewpoint of the overall system, especially since a number of independent agents with their own independent interests will likely be involved in constructing pipelines and connecting them to reservoirs (which these independent agents might themselves own). Since the infrastructure that is deployed is sensitive to the scale at which the overall system is operated, the likely bottom-up generation of infrastructure will probably be efficient for scales much less than the scale associated with the total amount of CO_2 that is captured, transported, and stored. Since major infrastructure deployments, such as pipelines, are subject to regulatory oversight, the location of trunk distribution pipelines can be influenced, perhaps by providing incentives for particular routes and connections between particular places. Independent agents can then couple into such a trunk distribution backbone as they wish. Governments, for example, can consider the efficiency of scale and operation of the total system in such a way that the individual actions of independent agents might not, but the path dependent evolution of the infrastructure can be influenced to mimic closer to approach so-called “optimal” deployment, based on the returns to scale or potential routes and how they are proximal to the industrial and geologic organization of CO_2 production and storage opportunities.

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