

# **Optimal Spatial Deployment of Carbon Dioxide Capture and Storage**

**Given a Price on Carbon Dioxide**

**Michael J. Kuby<sup>1</sup>**

**Jeffrey M. Bielicki<sup>2</sup>**

**Richard S. Middleton<sup>3</sup>**

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<sup>1</sup> School of Geographical Sciences and Urban Planning, Arizona State University, [mikekuby@asu.edu](mailto:mikekuby@asu.edu).

<sup>2</sup> Energy Technology Innovation Policy, Belfer Center for Science and International Affairs, Harvard Kennedy School, 79 John F. Kennedy St. Cambridge, MA 02138, [bielicki.harvard@gmail.com](mailto:bielicki.harvard@gmail.com).

<sup>3</sup> Los Alamos National Laboratory, Earth and Environmental Sciences, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos NM 87545, [rsm@lanl.gov](mailto:rsm@lanl.gov).

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### **ABSTRACT**

Carbon dioxide capture and storage (CCS) links together technologies that separate carbon dioxide (CO<sub>2</sub>) from fixed point source emissions and transport it by pipeline to geologic reservoirs into which it is injected underground for long-term containment. Previously, models have been developed to minimize the cost of a CCS infrastructure network that captures a given amount of CO<sub>2</sub>. The CCS process can be costly, however, and large-scale implementation by industry will require government regulations and economic incentives. The incentives can price CO<sub>2</sub> emissions, through a tax or a cap-and-trade system, or involve the purchase of CO<sub>2</sub> by oil companies for enhanced oil recovery from depleted oil fields. This paper extends the earlier mixed-integer linear programming model to endogenously determine the optimal quantity of CO<sub>2</sub> to capture and optimize the various components of a CCS infrastructure network, given the prices to emit CO<sub>2</sub> into the atmosphere or inject it into oil fields. The model minimizes the cost of capturing, transporting, storing, selling, or emitting CO<sub>2</sub>. The model is applied to a network of CO<sub>2</sub> sources, CO<sub>2</sub> reservoirs, and candidate CO<sub>2</sub> pipeline links and diameters in California.

**KEYWORDS: pipeline, network, optimization, model, infrastructure, location, CCS**

### **1. INTRODUCTION**

According to the Intergovernmental Panel on Climate Change (IPCC 2007), “warming of the climate system is unequivocal,” and “most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG [greenhouse gas] concentrations.” Carbon dioxide (CO<sub>2</sub>) is the most worrisome GHG emission, in part because the energy resources (such as fossil fuels) and

technologies upon which present-day economies are based emit enormous amounts of CO<sub>2</sub> (e.g., IPCC 2005). Without intervention, CO<sub>2</sub> emissions will continue to increase and at least double their 2004 levels by the middle of the century, and in order to *stabilize* CO<sub>2</sub> emissions at their 2004 levels by 2054, approximately 26 Gt of CO<sub>2</sub> emissions per year must be mitigated ((Pacala and Socolow 2004). Carbon capture and storage (CCS) is one existing technology that can be deployed among a portfolio of mitigation technologies to meet this challenge. CCS is costly, however, and will require credible and legitimate economic incentives in order to be deployed widely. Towards this end, this paper presents a geospatial optimization model that deploys integrated CCS systems over space as a result of these economic incentives.

A CCS system has three steps: CO<sub>2</sub> capture, CO<sub>2</sub> transportation, and CO<sub>2</sub> storage. CO<sub>2</sub> is captured at fixed point sources, such as coal-fired power plants, cement manufacturing facilities, and ethanol refineries. It is then compressed to a liquid or supercritical fluid so that it can be transported—most feasibly by pipeline (Svensson et al. 2004; Doctor et al. 2005)—to geologic formations such as depleted oil and gas fields and deep saline aquifers. The CO<sub>2</sub> is then injected into these geologic “storage reservoirs” using standard techniques that have been used in the oil and gas industry for many decades.<sup>4</sup> In essence, CCS keeps CO<sub>2</sub> out of the atmosphere by injecting it underground into formations that have contained fluids for hundreds of thousands of years. CCS is generally considered to be an important technological option because it allows societies to continue using their existing carbon-based infrastructure while minimizing the adverse effects of using that infrastructure on the earth’s climate system.<sup>5</sup> For example, coal is the largest and least-expensive primary source of energy for electric power generation in the two

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<sup>4</sup> Since the early 1970s, CO<sub>2</sub> has been injected into some oil reservoirs for enhanced oil recovery (EOR), and natural gas has been injected for short-term storage in underground formations for approximately a century.

<sup>5</sup> CCS is considered to be a “bridging technology”—one that can be deployed now until renewable energy technologies can be developed, demonstrated, and deployed at commercial scale ((Riahi, Rubin, and Schrattenholzer 2004); (Metz et al. 2005)).

countries with the largest CO<sub>2</sub> emissions—the United States and China.<sup>6</sup> Both of these countries have massive investments in coal mines, railroads, and ports, and much of this infrastructure is used to support the electric power industry. In 2005, coal-fired power plants in the United States alone emitted approximately 2 GtCO<sub>2</sub> (Energy Information Administration 2009). If the CO<sub>2</sub> produced by, say, 60% of these coal-fired power plants were captured and compressed for storage, this volume of CO<sub>2</sub> would roughly equal the amount emitted from 20 million barrels of oil the United States consumes daily (MIT 2007). Pacala and Soclow (2004) define emissions stabilization “wedges” as another proxy for the scale of the CO<sub>2</sub> emissions mitigation challenge; one wedge equals 3.7 GtCO<sub>2</sub> (1 GtC) of mitigated emissions, and seven such wedges are required to stabilize global emissions in 2054 at the 2004 level. To contribute one wedge, CCS would have to be implemented on 800 GW of baseload coal-fired power plants worldwide (Pacala and Socolow, 2004). For comparison, the total coal-fired electrical generating capacity in the United States in 2007 was 336 GW (EIA, 2009).

One economic incentive for capturing CO<sub>2</sub> can involve using the CO<sub>2</sub> for enhanced oil recovery (EOR)—a process that is typically implemented on mature oil fields to reinvigorate oil production. CO<sub>2</sub>-EOR can increase oil recovery from 20-40% of the original oil in place (OOIP) to as much as 60% of OOIP (EPRI, 1999). In United States, CO<sub>2</sub>-EOR began in the early 1970s and there are now more than 80 operational CO<sub>2</sub>-EOR projects (Bielicki 2009a). A small interconnected network of CO<sub>2</sub> pipelines in Texas and New Mexico transports CO<sub>2</sub> that is produced from a few natural geologic deposits to a number of oil fields, primarily in West Texas. At present, only a handful of CO<sub>2</sub>-EOR projects use CO<sub>2</sub> from anthropogenic sources.<sup>7</sup> CCS

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<sup>6</sup> In 2007, the United States and China each emitted approximately 6 GtCO<sub>2</sub>.

<sup>7</sup> The Weyburn carbon sequestration project is one example. A 320 km-long CO<sub>2</sub> pipeline transports CO<sub>2</sub> that is captured from Dakota Gasification plant, in North Dakota, to Saskatchewan, Canada, where the CO<sub>2</sub> is injected into the Weyburn oil field for enhanced oil recovery. CO<sub>2</sub> injection at Weyburn is expected to add an incremental 155 million barrels of oil to production and store 30MtCO<sub>2</sub> by 2035. (See, for example, <http://www.ieagreen.org.uk/glossies/weyburn.pdf>.)

with the CO<sub>2</sub> used for EOR entails shifting the source of this CO<sub>2</sub> from natural deposits to anthropogenic sources. Increasing the scale of existing CO<sub>2</sub>-EOR activities by approximately 100-fold would only constitute a single Pacala and Soclow (2004) wedge. The scale of EOR prospects is limited and CO<sub>2</sub>-EOR cannot provide lasting opportunities for CO<sub>2</sub> emissions mitigation.

Policy levers can also provide an economic incentive to avoid emitting CO<sub>2</sub> into the atmosphere. By imposing a cost of emitting CO<sub>2</sub>, market-based mechanisms encourage CO<sub>2</sub>-producing facilities to internalize at least some of the environmental and social costs related to the CO<sub>2</sub> they release. There are essentially two types of market-based mechanisms: a CO<sub>2</sub> tax, and a CO<sub>2</sub> cap-and-trade system. In the case of a CO<sub>2</sub> tax, a governmental agency establishes the cost of emitting a tonne of CO<sub>2</sub>, and producers decide how much to reduce their emissions, if any. With a cap-and-trade system, a governmental agency issues permits allowing producers to emit some quantity of CO<sub>2</sub> and establishes a market mechanism for buying and selling these permits. In this case, the government sets the number of permits, and thus the right to emit CO<sub>2</sub>, and the market determines the price of these permits. In either case, these additional costs create a disincentive to using processes that emit CO<sub>2</sub>, and thus emitters must determine whether it is in their best interest to reduce their carbon emissions or pay the “price on CO<sub>2</sub>.”

Worldwide, market-based mechanisms for CO<sub>2</sub> emissions mitigation are gaining momentum and starting to be implemented. “Carbon” taxes have been implemented in Norway, Sweden, Finland, the Netherlands, and Italy, while Ireland and New Zealand are considering them as well. The European Union has implemented the EU ETS CO<sub>2</sub> cap-and-trade system, and the United States has voluntary CO<sub>2</sub> trading through the Chicago Climate Exchange. Several provinces or municipalities in North America have taken initiative and imposed CO<sub>2</sub> taxes, such as in Boulder

(Colorado, USA), the Bay Area Air Quality Management District (California, USA), and British Columbia (Canada). As of 2009, the United States, Australia, among others, are taking steps to implement cap-and-trade systems.

A CO<sub>2</sub> tax motivated the largest and longest continuously operated project in which CO<sub>2</sub> is injected for storage. The Sleipner West project, operated by Statoil, began in 1996 as a response to a CO<sub>2</sub> tax implemented by the Norwegian Government in 1991. At Sleipner, CO<sub>2</sub> is separated from natural gas produced from the Utsira formation and about 1 MtCO<sub>2</sub>/yr is re-injected into that formation underneath an 800m impermeable layer of shale. The CO<sub>2</sub> content of the produced natural gas is 9.5% and must be separated because it far exceeds customer requirements. The CCS operations at Sleipner are set such that Statoil, by not emitting this CO<sub>2</sub>, avoids paying the CO<sub>2</sub> tax, which is currently about US\$50/tCO<sub>2</sub>.<sup>8</sup> One Pacala and Socolow (2004) wedge would be attained by 3,500 Sleipner projects.

Revenues from CO<sub>2</sub> used for EOR can be helpful in the early phases of CCS deployment, but CO<sub>2</sub> taxes or emissions permits are essential to develop an economic case for deploying CCS on a large-enough scale that will substantially contribute to mitigating future CO<sub>2</sub> emissions. Once widely implemented, the CO<sub>2</sub> used for EOR is likely to be free to the oil-field operator, in part because there will be an oversupply. In fact, CO<sub>2</sub> sources will likely pay firms downstream in the value chain to take their CO<sub>2</sub>.

Overall, CCS will need to be planned as efficiently as possible in order to reduce costs and take advantage of the economies of scale and utilization inherent in all three phases of the CCS

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<sup>8</sup> It must be noted that, given the CO<sub>2</sub> content of the natural gas at Sleipner, it would not be economical to produce this gas without the CO<sub>2</sub> tax. As a result, in addition to spawning this CCS project, the CO<sub>2</sub> tax also served to turn this natural gas resource into a natural gas reserve.

system (Bielicki 2009b). Substantial cost savings are possible by matching CO<sub>2</sub> supplies to nearby reservoirs, deploying large-diameter trunk pipelines into which CO<sub>2</sub> captured from multiple sources is combined, and spreading the costs of each component over as much tonnage as possible (Bielicki 2009b, Middleton and Bielicki 2009b). Network optimization models have the potential to make significant contributions to the successful deployment of CCS systems. In this manner, Middleton and Bielicki (2009a) developed a model that minimizes the total cost of capturing, transporting, and storing *a given quantity of CO<sub>2</sub>*. That model, *SimCCS*, is a coupled geospatial optimization engineering-economic model that optimally deploys integrated CCS systems over space. *SimCCS* shows where CCS activities should occur for a given quantity of CO<sub>2</sub> emissions to be mitigated. In that sense, *SimCCS* could optimize CCS systems for the total CO<sub>2</sub> emissions quota set by the permits for a given set of CO<sub>2</sub> sources in a cap-and-trade system.

This paper extends the Middleton and Bielicki (2009b) and Middleton et al. (2007) models to endogenously determine, as a function of the economic incentives, the optimal quantity of CO<sub>2</sub> for a CCS system to capture, transport, and store. The *SimCCS: CO<sub>2</sub> Price* model minimizes the total cost of capturing, transporting, storing, and *releasing* CO<sub>2</sub>. The objective function presented in this paper explicitly incorporates the price of emitting CO<sub>2</sub> and the monetary benefit of using CO<sub>2</sub> for EOR. If, by developing an efficient integrated system, some CO<sub>2</sub> from some sources can be stored in geologic reservoirs at a cost below the CO<sub>2</sub> price, the model will choose to do so. If not, the model will pay the CO<sub>2</sub> price and emit it to the atmosphere. The model developed in this paper fills an analytical need essential to efficiently deploy CCS as a system of interconnected technologies encouraged by viable economic incentives.

Section 2 presents the Middleton and Bielicki (2009b) model, and Section 3 presents the expanded model that includes the CO<sub>2</sub> price and the value of CO<sub>2</sub> if it is used for EOR in the

objective function. The model is tested on a small but realistic data set consisting of twelve potential sources and five potential storage reservoirs (depleted oil fields) in California (Section 4).<sup>9</sup> The results of this application for a range of CO<sub>2</sub> prices are presented in Section 5, and a discussion and conclusions follow in Section 6.

## **2. PRIOR RESEARCH ON CCS INFRASTRUCTURE PLANNING MODELS**

Middleton and Bielicki (2009b) identify seven key decisions that a CCS model should coordinate: (1) how much CO<sub>2</sub> to capture (2) at which sources; (3) where to construct pipelines (4) of what size; (5) which reservoirs should store CO<sub>2</sub>, (6) how much to inject in each one, and (7) how to distribute CO<sub>2</sub> from the dispersed sources through the network to the reservoirs. These core decisions have to be simultaneously optimized in order to understand the cost of the integrated CCS process. Identifying where to construct a realistic pipeline network has provided a great challenge for previous infrastructure models and therefore has often been highly simplified. Moreover, the high spatial dependency between CCS components (CO<sub>2</sub> sources, pipelines, and reservoirs) makes this simultaneous optimization a complex problem.

Early work in the CCS literature highly simplified the CCS deployment problem by focusing on one or two of these seven decisions. The most common simplifying assumptions were related to CO<sub>2</sub> transportation by pipeline. For example, MIT (2006) and ISGS (2005) assumed that a single CO<sub>2</sub> pipeline directly connects a single source to a single injection site. ISGS (2005) also assumed all CO<sub>2</sub> must be captured at each source, regardless of system-wide economics, as did Dooley et al. (2006) which also assumed a minimum and maximum distance for pipelines between sources and reservoirs. Kobos et al. (2007) matches sources and reservoirs incrementally by spatially branching out to the next closest option. None of these CCS

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<sup>9</sup> We leave an EOR example for future work when costs and capacities can be estimated with more accuracy.



infrastructure models considers the system-wide economics and deploys a pipeline network that is capacitated, realistically routed, and can generate high-capacity trunk lines.

Middleton and Bielicki (2009b) and Middleton et al. (2007) introduced a mixed-integer linear programming model that minimizes the cost of CCS infrastructure to meet exogenously given CO<sub>2</sub> storage targets. Their Scalable Infrastructure Model for CCS (*SimCCS*) used a three-step approach to generate and solve this problem. The approach combines methods and approaches from operations research and geographic information systems (GIS):

1. Develop a cost surface for pipeline construction and generate least-cost routes between sources and sinks;
2. Based on these direct pipelines, generate a candidate network of potential links and nodes for an integrated network; and
3. Find an optimal solution to the resultant pipeline network-design problem.

The *SimCCS* model was formulated as follows:

$$\text{MINIMIZE } \sum_{i \in S} (F_i^s s_i + V_i^s a_i) + \sum_i \sum_{j \in N_i} \sum_d F_{ijd}^p y_{ijd} + \sum_i \sum_{j \in N_i} V_{ij}^p x_{ij} + \sum_{j \in R} (F_j^r r_j + V_j^r b_j) \quad (1)$$

$$\text{S.T. } x_{ij} - \sum_{d \in D} \max Q_{ijd}^p y_{ijd} \leq 0 \quad \forall i \in I, j \in N_i \quad (2)$$

$$x_{ij} - \sum_{d \in D} \min Q_{ijd}^p y_{ijd} \geq 0 \quad \forall i \in I, j \in N_i \quad (3)$$

$$\sum_{j \in N_i} x_{ij} - \sum_{j \in N_i \cap R} x_{ji} - a_i + b_i = 0 \quad \forall i \in I \quad (4)$$

$$a_i - Q_i^s s_i \leq 0 \quad \forall i \in S \quad (5)$$

$$b_j - Q_j^r r_j \leq 0 \quad \forall j \in R \quad (6)$$

$$\sum_{i \in S} a_i \geq T \quad (7)$$

$$\sum_{d \in D} y_{ijd} \leq 1 \quad \forall i \in I, j \in N_i \quad (8)$$

$$y_{ijd} \in 0,1 \quad \forall i \in I, j \in N_i, d \in D \quad (9)$$

$$s_i \in 0,1 \quad \forall i \in S \quad (10)$$

$$r_j \in 0,1 \quad \forall j \in R \quad (11)$$

$$x_{ij} \geq 0 \quad \forall i, j \in N_i \quad (12)$$

$$a_i \geq 0 \quad \forall i \in S \quad (13)$$

$$b_j \geq 0 \quad \forall j \in R \quad (14)$$

## DECISION VARIABLES

$x_{ij}$  = Units of CO<sub>2</sub> transported from node  $i$  to node  $j$  (tonnes)

$y_{ijd} \begin{cases} 1, & \text{if a pipeline is constructed from node } i \text{ to node } j \text{ with diameter } d \\ 0, & \text{otherwise} \end{cases}$

$s_i \begin{cases} 1, & \text{if source at node } i \text{ is opened} \\ 0, & \text{otherwise} \end{cases}$

$r_j \begin{cases} 1, & \text{if reservoir at node } j \text{ is opened} \\ 0, & \text{otherwise} \end{cases}$

$a_i$  = Amount of CO<sub>2</sub> produced at node  $i$  (tonnes)

$b_j$  = Amount of CO<sub>2</sub> sequestered/stored at node  $j$  (tonnes)

## INPUTS

$F^s, F^p, F^r$  = Fixed cost for opening a source, constructing a pipeline, or opening a reservoir (\$)

$V^s, V^p, V^r$  = Variable cost for capturing CO<sub>2</sub> from a source, transport through a pipeline, or into a reservoir (\$ per tonne)

$Q^s, Q^p, Q^r$  = CO<sub>2</sub> capacity of a source node, pipeline, or reservoir (tonnes)

$T$  = Target amount of CO<sub>2</sub> to be sequestered (tonnes)

## SETS

$I$  = All nodes in the network

$N_i, N_j$  = Nodes adjacent to nodes  $i$  or  $j$

$R$  = Reservoir nodes

$S$  = Source nodes

$D$  = Pipeline diameters

The model combines elements from classic facility location such as the capacitated fixed-charge and network-design models. The objective function (1) minimizes the sum of fixed and variable costs for source capture, pipeline transport, and reservoir injection. Note the subscript  $d$  on the  $Y_{ijd}$  variable indicating whether or not a pipeline of diameter  $d$  is built from  $i$  to  $j$ . The model uses several possible discrete pipeline diameters, each with its particular fixed cost and capacity. This enables economies of scale to be represented in the model in a manner similar to how Osleeb et al. (1986) modeled different sizes of coal port handling equipment. Constraints (2) and (3) require that, if the pipelines are built, the CO<sub>2</sub> flow through pipelines must be less than the maximum capacity and greater than the minimum capacity. Constraint (4) is a typical mass-balance constraint ensuring that all CO<sub>2</sub> captured at or flowing into a node must be injected

underground at, or transported away from, the node. Constraints (5) and (6) are CO<sub>2</sub> supply and storage capacity constraints for each source and reservoir, similar to those in capacitated fixed-charge problems. Constraint (7) specifies the system-wide CO<sub>2</sub> target amount—which is replaced by the model developed in Section 3 of this paper. Constraint (8) allows only one pipeline (of any diameter) to be built on any arc  $ij$ . Constraints (9) - (14) are integrality and non-negativity constraints.

As mentioned above, Middleton and Bielicki (2009b) identify seven decisions that a comprehensive CCS infrastructure deployment model should consider. Their *SimCCS* model makes these decisions optimally and simultaneously, but it is based on setting the total amount of CO<sub>2</sub> that should be captured. Their model endogenously determines how much CO<sub>2</sub> to capture *from each source*, but the total amount to capture is an exogenous input in (7). In other words, the model above imposes a predetermined target amount, and only determines how to spread that total among various sources. In this paper, we extend this approach by incorporating the price on CO<sub>2</sub> from market-based mechanisms and EOR prices for CO<sub>2</sub> in order to endogenously determine how much *total* CO<sub>2</sub> to capture.

### 3. MODEL

The *SimCCS: CO<sub>2</sub> Price* model formulated here endogenously solves for all seven decisions needed for CCS infrastructure planning. The formulation is the same as Middleton and Bielicki (2009b) model except for a few changes. The new objective function (15) includes both a cost for carbon emitted (15d), and revenue from CO<sub>2</sub> injected for enhanced oil recovery (15e). In (15d), the coefficient  $C$  is the CO<sub>2</sub> tax rate per tonne, or alternatively, the prevailing market price for a one-tonne CO<sub>2</sub> emission credit. It is multiplied by  $(Q_i^s - a_i)$ , the amount of CO<sub>2</sub> *not captured* at  $i$ , and summed over all source nodes  $i \in S$ . In part (15e), the EOR revenue from CO<sub>2</sub>

sold for EOR is subtracted from the objective function because these earnings reduce the total system cost. For each reservoir node  $j \in R$ , the price at which oil companies will buy CO<sub>2</sub>,  $E_j$ , is multiplied by the amount sold for EOR,  $b_j$ , and summed over all reservoir nodes  $j$ . For the purposes of generality, if a reservoir does not buy CO<sub>2</sub> for EOR, the purchase price  $E_j$  can be set to zero, as we do in the case study in this paper for all reservoir nodes. The only other change to the model is to remove constraint (7) that forced the total amount of CO<sub>2</sub> captured to sum to an exogenously specified target amount.

MIN

$$\underbrace{\sum_{i \in S} (F_i^s s_i + V_i^s a_i)}_{(a)} + \underbrace{\sum_{i \in I} \sum_{j \in N_i} \sum_{d \in D} F_{ijd}^p y_{ijd}}_{(b)} + \underbrace{\sum_{i \in I} \sum_{j \in N_i} V_{ij}^p x_{ij}}_{(c)} + \underbrace{\sum_{j \in R} (F_j^r r_j + V_j^r b_j)}_{(d)} + \underbrace{\sum_{i \in S} C(Q_i^s - a_i)}_{(d)} - \underbrace{\sum_{j \in R} E_j b_j}_{(e)} \quad (15)$$

$$\text{S.T.} \quad x_{ij} - \sum_{d \in D} \max Q_{ijd}^p y_{ijd} \leq 0 \quad \forall i \in I, j \in N_i \quad (16)$$

$$x_{ij} - \sum_{d \in D} \min Q_{ijd}^p y_{ijd} \geq 0 \quad \forall i \in I, j \in N_i \quad (17)$$

$$\sum_{j \in N_i} x_{ij} - \sum_{j \in N_i} x_{ji} - a_i + b_i = 0 \quad \forall i \in I \quad (18)$$

$$a_i - Q_i^s s_i \leq 0 \quad \forall i \in S \quad (19)$$

$$b_j - Q_j^r r_j \leq 0 \quad \forall j \in R \quad (20)$$

$$\sum_{d \in D} y_{ijd} \leq 1 \quad \forall i \in I, j \in N_i \quad (21)$$

$$y_{ijd} \in \{0,1\} \quad \forall i \in I, j \in N_i, d \in D \quad (22)$$

$$s_i \in \{0,1\} \quad \forall i \in S \quad (23)$$

$$r_j \in \{0,1\} \quad \forall j \in R \quad (24)$$

$$x_{ij} \geq 0 \quad \forall i, j \in N_i \quad (25)$$

$$a_i \geq 0 \quad \forall i \in S \quad (26)$$

$$b_j \geq 0 \quad \forall j \in R \quad (27)$$

Where, in addition to the variable definitions in Section 2:

$E_j$  = EOR price for CO<sub>2</sub> at reservoir  $j$

$C$  = Carbon credit price

An alternate objective function (28) would collect all the coefficients multiplied by the captured variables  $a_i$  and injection variables  $b_j$  into new variable cost coefficients,  $V^s$  and  $V^r$ .

$$\sum_{i \in S} (F_i^s s_i + V_i^s a_i) + \sum_{i \in I} \sum_{j \in N_i} \sum_{d \in D} F_{ijd}^p y_{ijd} + \sum_{i \in I} \sum_{j \in N_i} V_{ij}^p x_{ij} + \sum_{j \in R} (F_j^r r_j + V_j^r b_j) \quad (28)$$

Where:

$V^s$  = Variable cost at source = (capture cost at  $i$ ) – (CO<sub>2</sub> price)

$V^r$  = Variable cost at reservoir = (storage cost at  $j$ ) – (EOR price for CO<sub>2</sub> at  $j$ )

#### 4. STUDY AREA AND DATA

The new model in Section 3 is tested on a network of twelve CO<sub>2</sub> sources and five potential CO<sub>2</sub> reservoirs in California. This model requires the development of a candidate set of pipeline arcs and cost parameters. These data are generated using separate capture, transportation, and storage sub-models as summarized in Figure 1. Accurate data are crucial for this model, because the decision to capture or release CO<sub>2</sub> emissions critically depends on whether the “delivered cost” (delivered to underground storage reservoirs) is less than the CO<sub>2</sub> price.

FIGURE 1 ABOUT HERE

Figure 2 shows the locations of the twelve sources of CO<sub>2</sub> (red), the five potential CO<sub>2</sub> storage reservoirs (green), the relative costs of building pipelines on each cell (yellow to brown), and the candidate network of pipeline routes (blue). These sources are the twelve largest CO<sub>2</sub> point sources in California according to the WESTCARB<sup>10</sup> database from which the data were downloaded. These sources include eight natural gas power plants and four oil refineries. CO<sub>2</sub> can be captured by separating it out of the exhaust gas mixtures<sup>11</sup> produced by facilities by a variety of technologies, including amine-scrubbers and membrane separation. Typically, at most 90% of the CO<sub>2</sub> that is produced can be captured. The reservoirs are the five oil fields with the largest CO<sub>2</sub> storage capacities. These oil fields were also downloaded from the WESTCARB database. The processes indicated in Figure 1 were used in Bielicki (2009a) to estimate the costs and capacities to capture CO<sub>2</sub> from each individual source, based on the industrial sector with which the facility is associated, and to inject CO<sub>2</sub> into the potential oil field reservoirs, based on the geologic conditions and parameters as well as the amount of oil that has been produced from the oil fields.<sup>12 13</sup>

#### FIGURE 2 ABOUT HERE

Pipeline costs and capacities were also determined by the processes shown in Figure 1 and are based on regressions of data for 15 years of pipeline construction in the United States and the simple fluid mechanics relationships detailed in Middleton and Bielicki (2009b). The pipeline infrastructure routing uses a spatial cost surface in which the values stored in each cell of the map represent a cost multiplier incurred by routing infrastructure through that cell. These cost factors are based on the physical characteristics of the land and the presence of social infrastructure; they are taken from MIT (2006) and are shown in Table 1. The shading of the

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<sup>10</sup> <http://www.westcarb.org>.

<sup>11</sup> The concentration of CO<sub>2</sub> in the gasses emitted by a typical coal-fired power plant is around 10-15%.

<sup>12</sup> To be consistent with the review of CO<sub>2</sub> capture cost studies in IPCC (2005), the costs are in 2000 USD.

<sup>13</sup> The source production capacity is on an annual basis, whereas the reservoir storage capacity is a total storage volume. We convert this total storage volume to an annual amount by assuming a project lifetime, which is set to 25 years for this example.

map in Figure 2 represents these cost factors, as added together, and thus the degree to which infrastructure routing decisions should seek to avoid that cell. A shortest path algorithm is applied to this cost surface in order to determine the potential routes for pipeline infrastructure. This a raster-based GIS procedure with eight cardinal and diagonal directions of travel with each 1x1 km cell.

#### TABLE 1 ABOUT HERE

Following Middleton and Bielicki (2009a), a two-step process was used to create the candidate pipeline network. First, a shortest path algorithm determined the least-cost path from every source-reservoir, source-source, and reservoir-reservoir combination. Next, these routes were used as the basis for developing a simplified network of candidate links and nodes. To do so, routes that lay directly on top of each other were merged into a single route. Then, nodes were inserted wherever routes combined, bifurcated, originated, or terminated. Finally, several automated rules of thumb simplified the network, such as collapsing small triangles into a single node if the vertices were within a set spatial tolerance.

Given a set of sources and a set of reservoirs, the process described above generated the candidate network between them (blue lines in Figure 2). The model in (15) – (27) then simultaneously and optimally chose which sources, reservoirs, and segments of the candidate network should be deployed, and at what CO<sub>2</sub> capacity for each, based on the economic incentives in place. For this analysis, the economic incentives in place used market-based mechanisms to establish a CO<sub>2</sub> price. This analysis did not include potential prices paid for CO<sub>2</sub> that will be used for EOR, in part because accurate price data for what oil companies will pay for CO<sub>2</sub> for EOR at particular oil fields in California is, at present, difficult to estimate,<sup>14</sup> and in part

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<sup>14</sup> A general rule of thumb is that CO<sub>2</sub> for EOR costs about 2% of the WTI price of oil. Spatial deployment of CCS, however, will depend on the heterogeneity in costs, capacities, and locations (Bielicki, 2009a). Using this 2% for all CO<sub>2</sub> reservoirs will only impact deployment by vertically shifting the cost curves in Figures 3 and 5.



because policy levers that put a price on CO<sub>2</sub> emissions will be the primary long term economic driver for CCS deployment. Therefore, all EOR prices were set to zero.

## 5. RESULTS

Figure 3 shows the results for a range of CO<sub>2</sub> prices from \$40/tCO<sub>2</sub> to \$75/tCO<sub>2</sub>. The model was run at \$1/t increments from \$40/t to \$50/t and \$5/t increments from \$50/tCO<sub>2</sub> to \$75/tCO<sub>2</sub>. Each individual point in the figure is a distinct optimization in which the model selected to deploy integrated CCS systems from the set of twelve potential sources, five potential reservoirs, and the candidate network described in Section 4. The model does not capture any CO<sub>2</sub> from any point sources until the CO<sub>2</sub> price reaches \$44/t, when it deploys a system that handles approximately 7 Mt/year. Below this \$44/t, it is cost-effective to release the CO<sub>2</sub> to the atmosphere and incur the CO<sub>2</sub> price penalty rather than build and operate the CCS infrastructure necessary to mitigate those emissions. As the CO<sub>2</sub> price increases, the model deploys more extensive CCS systems to capture more CO<sub>2</sub> from more sources and store that CO<sub>2</sub> in more reservoirs. This increase plateaus around \$48/t, where a 21 Mt/yr system is deployed. The system does not expand again until the CO<sub>2</sub> price reaches \$65/t.

### FIGURE 3 ABOUT HERE

A general expansion of the CCS system as the CO<sub>2</sub> price increases is expected. Since the system will incur whichever expense is cheapest (pay the CO<sub>2</sub> price or deploy CCS), more opportunities to deploy CCS should become cost effective as the CO<sub>2</sub> price increases. The plateau at 21Mt/year from \$48/t to \$60/t, however, indicates a large break in the ability to deploy CCS. The model deploys integrated CCS systems as an increasing “step function” (Figure 3), based on the complicated relationship between fixed and variable costs and capacities for CO<sub>2</sub> sources and reservoirs as well as their spatial orientation within and between these points, as determined by economics and geology.

As can be seen in the irregularity of the “steps” in Figure 3, some CO<sub>2</sub> price increments yield larger increases in CCS deployment than others. A \$6/t increase in the CO<sub>2</sub> price from \$42/t to \$48/t expands deployment from nothing to a system that captures 21Mt/year. In contrast, the \$12/t increase from \$48/t to \$60/t does not expand deployment at all. Even though the increase in the CO<sub>2</sub> price is twice as large, there is no resulting increase in CO<sub>2</sub> emissions mitigation by deploying CCS. Some deployment possibilities still exist, but they do not become economically feasible until the CO<sub>2</sub> price exceeds \$60/t.

Figure 4 shows the spatial deployment of CCS at the \$48/t price. Eight of the twelve sources and four of the five reservoirs are deployed in two distinct CCS regions – one in the Los Angeles area and one extending from the San Francisco Bay area south to the southern portion of the central valley. There are actually two separate systems in the LA area. In one system, a single dedicated pipeline connects one source with one reservoir, while in the other a different reservoir stores CO<sub>2</sub> captured from two sources (one just north of the reservoir and one just south of the reservoir). The other region where CCS is deployed connects five sources, two in the Bay area, one a little farther south, and two in the southern portion of the central valley, with two reservoirs located close to the latter three sources. The CO<sub>2</sub> captured from the two Bay area sources is combined into a 20-inch diameter pipeline with the CO<sub>2</sub> captured from a source farther down the Pacific coast. This CO<sub>2</sub> is then transported a few hundred kilometers south, where the CO<sub>2</sub> is also combined with that captured from two other sources into another 20-inch diameter pipeline that transports the CO<sub>2</sub> to a very large storage reservoir into which a portion of this total amount of CO<sub>2</sub> is stored. Another 12-inch diameter pipeline is built from one of the sources through the location of a potential reservoir (which is not deployed) and connects to a 16-inch diameter pipeline that emanates from the very large reservoir that is deployed. The excess CO<sub>2</sub>

flows combine into a 20-inch diameter pipeline that transports CO<sub>2</sub> to a reservoir located farther away. The rest of the CO<sub>2</sub> is stored in this reservoir.<sup>15</sup>

#### FIGURE 4 ABOUT HERE

These two reservoirs are each partially deployed because the process used by Bielicki (2009a) to estimate costs and capacities, as in Figure 1, is based on data in which the fixed costs for deployment (site characterization) do not depend on the geologic characteristics of the reservoir but the variable costs do (e.g., McCoy and Rubin, 2005). The large reservoir is used because it has the same fixed cost as the smaller reservoir that is deployed, but the geologic conditions of the smaller reservoir are such that the variable costs are roughly half of what they are for the larger deployed reservoir. The reservoir that is skipped over has variable costs that are roughly twice that of the larger reservoir, and it is thus more cost effective to transport CO<sub>2</sub> to a cheap storage reservoir that is farther away than to utilize the nearby, but much more costlier, one. The deployment of the 12- and 16-inch diameter pipelines which then combine their CO<sub>2</sub> flows into the 20-inch diameter pipeline, which extends to the faraway reservoir, illustrates the cost tradeoffs between the lengths of CO<sub>2</sub> pipelines and their diameters.

The economies of scale for pipeline transportation of CO<sub>2</sub> suggest that it is desirable to combine CO<sub>2</sub> flows into large diameter pipelines; doing so reduces unit costs (Middleton and Bielicki, 2009b; Bielicki, 2009a). In this manner, spatial orientations are important because where sources or reservoirs are located relative to each other affects the potential to combine CO<sub>2</sub> flows. The plateau between \$48/t and \$60/t occurs partly because it is not economically feasible to combine enough flows to justify building the next-largest 24-inch CO<sub>2</sub> pipeline, even though it potentially offers even greater economies of scale. Since pipelines are capacitated, spare capacity in deployed pipelines can be utilized by more fully deploying sources and

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<sup>15</sup> The amount of CO<sub>2</sub> stored in the reservoirs appear as slivers in Figure 4 because the total storage capacity is quite large compared to the actual amount that is stored in each reservoir.

reservoirs. But when either the sources or reservoirs in a network subsystem are fully deployed, the subsystem would have to extend spatially to take advantage of the large diameter pipelines, which may be impractical if the sources or reservoirs are too far away.

For maximum economic efficiency, firms and policy-makers should seek to equate marginal costs with marginal benefits. For CCS, the marginal benefit is avoiding paying the CO<sub>2</sub> price (per tonne). The marginal cost can be computed as change in the total cost from one system scale to another, divided by the associated change in the tonnes of CO<sub>2</sub> captured. Figure 5 transposes the axes and the curve from Figure 3 and overlays the marginal costs calculated in this paper with the *SimCCS- CO<sub>2</sub> Price* model (15) – (27) as well as those from the original *SimCCS* (Middleton and Bielicki, 2009b) using (1) – (14).<sup>16</sup> The axes are switched to be consistent with the convention in economics of graphing a supply curve as “price vs. quantity.” As Figure 5 shows, the model output does indeed produce results in line with the marginal costs calculated from its own output as well as the alternative formulation in (1) for the original *SimCCS*. An important finding from this comparison is that the marginal costs calculated from the new *SimCCS: CO<sub>2</sub>Price* model are much better behaved than those from the old model, which fluctuate up and down. The monotonically increasing marginal costs of the new model are a direct result of the fact that marginal benefit (CO<sub>2</sub> price) is the driving force of the model. In contrast, the variability of marginal costs from the original *SimCCS* model (1) – (14) results in part from the fact that quantity, not price, is driving the system. Because many of the investments are lumpy, but regular increments of total quantity captured must be satisfied, the marginal costs can go up and down from one solution to the next. Also, the *SimCCS* model generated high but decreasing marginal costs for 1 Mt/year to 3 Mt/year of CO<sub>2</sub> because *SimCCS* forces it to capture

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<sup>16</sup> The marginal costs presented here are calculated by using the data that brackets the price and quantity. For example, for 1 MtCO<sub>2</sub> increments, the marginal cost calculated for *SimCCS* at 5 MtCO<sub>2</sub>/year would be  $(Cost_{4MtCO_2/yr} - Cost_{6MtCO_2/yr}) / (Quantity_{4MtCO_2/yr} - Quantity_{6MtCO_2/yr})$ .

those amounts regardless of cost, whereas the *SimCCS: CO<sub>2</sub> Price* model can choose not to capture any small quantities of CO<sub>2</sub> if it is not economical.

## FIGURE 5 ABOUT HERE

By reversing the axes, the steady increase in CO<sub>2</sub> emissions mitigation between \$42/t to \$48/t from deploying CCS appears relatively flat and horizontal in Figure 5. Dooley et al. (2006) also find a flat section in their CCS supply curve for CO<sub>2</sub> sources and injection basins throughout the United States. Dooley et al. (2006) graph the cost of deploying CCS and their flat section occurs at a different cost level and extends for more than 21 Mt/year, but their result is likely to be an artifact of the assumptions in their approach.<sup>17</sup>

## 6. CONCLUSIONS

CCS is an energy technology that can reduce CO<sub>2</sub> emissions to the atmosphere from CO<sub>2</sub>-emitting facilities and thus contribute to mitigating climate change. CCS is costly, however, and needs credible economic incentives to be deployed. Ultimately, CCS will be deployed or not based on whether it will be less expensive for emitters to capture, transport, and store (and possibly sell) their CO<sub>2</sub> than to pay the cost of venting it into the atmosphere. This is not an easy comparison to make without a model such as the one developed here, because CCS is a set of costly technologies integrated across space. While the capture cost lies wholly within each

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<sup>17</sup> Unlike the process described in Figure 1 and used in Bielski (2009a), from which the data used here were taken, Dooley et al. (2006) assume a constant cost of storage within each type of storage reservoir (e.g., oil field, natural gas field, saline aquifer). Their storage costs do not depend on the characteristics and parameters of the specific formation and does not include capacity constraints on individual injection locations. Further, their approach assumes that if a CO<sub>2</sub> source is located on top of a potential storage *basin*—not a viable storage reservoir—the CO<sub>2</sub> is transported 10 miles to be injected into that basin. Since potential basins in the United States cover large areal extents, a large majority of the CO<sub>2</sub> sources sit atop these basins. As such there will be many of these 10-mile transportation calculations. Moreover, CO<sub>2</sub> is assumed to be transported by a single dedicated pipeline from a source to an injection location in that basin. Since their cost curve is a plot of rank-ordered pair-wise matching of sources with injection locations, these 10-mile segments with highly similar CO<sub>2</sub> transportation costs, combined with the constancy of the storage cost assumptions, will generate a lot of similar costs for CO<sub>2</sub> transportation and storage. These assumptions and their approach can explain a large portion of the flat section of their cost curve.

source's control, the ultimate "delivered cost" (delivered underground, that is) critically depends on the potentially large economies of scale in pipeline transportation and geologic injection. The cost of transporting and storing CO<sub>2</sub> from a single source depends greatly on coordination within and across the CO<sub>2</sub> value chain. Achieving the lowest delivered cost, and determining if it is lower than the CO<sub>2</sub> price, involves a spatial coupling of sources and reservoirs and the associated pipeline network design and sizing. The model developed here was designed for, and applied to, optimizing an interconnected system of CO<sub>2</sub> sources, CO<sub>2</sub> pipeline networks, and CO<sub>2</sub> reservoirs given an economic incentive from a CO<sub>2</sub> price implemented by policy or the price of CO<sub>2</sub> sold for EOR.

The case study results confirm the need for such a model. The results show that it can be difficult to anticipate how CCS would be deployed optimally in a given geographic setting. The organization of CCS depends on a multitude of particulars and interactions between the CO<sub>2</sub> sources, the CO<sub>2</sub> reservoirs, and the candidate routes for the CO<sub>2</sub> pipeline network. The results here show that infrastructure deployment is not always sensitive to the CO<sub>2</sub> price. A given increment in CO<sub>2</sub> prices can yield much more emissions mitigation than at another price. Coordinating CCS efforts among sources and reservoirs is imperative. The model results could also be used to anticipate the quantities and spatial distribution of CCS deployment at various CO<sub>2</sub> prices. Likewise, the previously published *SimCCS* model would be useful in anticipating the costs for industry to deploy CCS in order to meet a given CO<sub>2</sub> quantity target within a CO<sub>2</sub> cap-and-trade system.

A CO<sub>2</sub> price will result from policy interventions that use market-based mechanisms to limit CO<sub>2</sub> emissions. While theoretically equivalent, CO<sub>2</sub> taxes may be preferred over CO<sub>2</sub> cap-and-trade systems. A tax provides price certainty, and companies know what to expect their costs

will be. They can then apply models such as this in order to decide whether or not it is cheaper to capture and store their CO<sub>2</sub> emissions. With a CO<sub>2</sub> tax, however, the total quantity of emissions reduced is uncertain. On the other hand, a cap-and-trade system sets this quantity, and the cost of emitting CO<sub>2</sub> is the market price for a permit to do so. This CO<sub>2</sub> price could fluctuate significantly, but the total emissions are certain. Cap-and-trade systems may be more politically palatable to tax-averse electorates, because words like “trade” and “market” are used instead of “tax.” Once in place, either market-based mechanism could be tweaked to match the outcome of the other mechanism: the tax could be adjusted to produce the desired emissions reductions, or the number of permits could be adjusted to achieve a desired permit cost. With perfect knowledge and economic certainty, the two systems are equivalent, but the deployment on the ground can be quite different depending on the path of the CO<sub>2</sub> price or CO<sub>2</sub> quantity. A third option, which may be more amenable in an uncertain world (Roberts and Spence 1976), is to implement a cap-and-trade system with a maximum-price “safety valve.” Price volatility is reduced in this hybrid option because if the CO<sub>2</sub> price reaches this safety valve, more permits are issued (Stavins 2007). In the context of climate change, some authors suggest that such a hybrid system is likely to operate much more like a CO<sub>2</sub> tax because the CO<sub>2</sub> price should be constantly bumping up against the safety valve (Furman et al. 2007). In any event, the evolution of CCS activities depends on the history of incentives and how they have been implemented as well as the expectations of them and their implementation in the future. A CO<sub>2</sub> price is a necessary economic driver.

The model presented here goes further than previous models in endogenously solving for the interrelated CCS decisions. Future work could develop a dynamic form of this model that phases in pipelines of different sizes and deploys CO<sub>2</sub> sources and CO<sub>2</sub> reservoirs over time as a result of the future schedule of intended CO<sub>2</sub> prices. This model is also limited to the CO<sub>2</sub> emissions

that are mitigated by CCS alone, assuming that the CO<sub>2</sub>-emitting facilities are still operating in the carbon-constrained world. It does not consider the *additional* emissions that would be mitigated by the substitution of less CO<sub>2</sub> intensive options such as natural gas, nuclear, or renewable (e.g., biomass, wind, solar) electrical generating facilities.



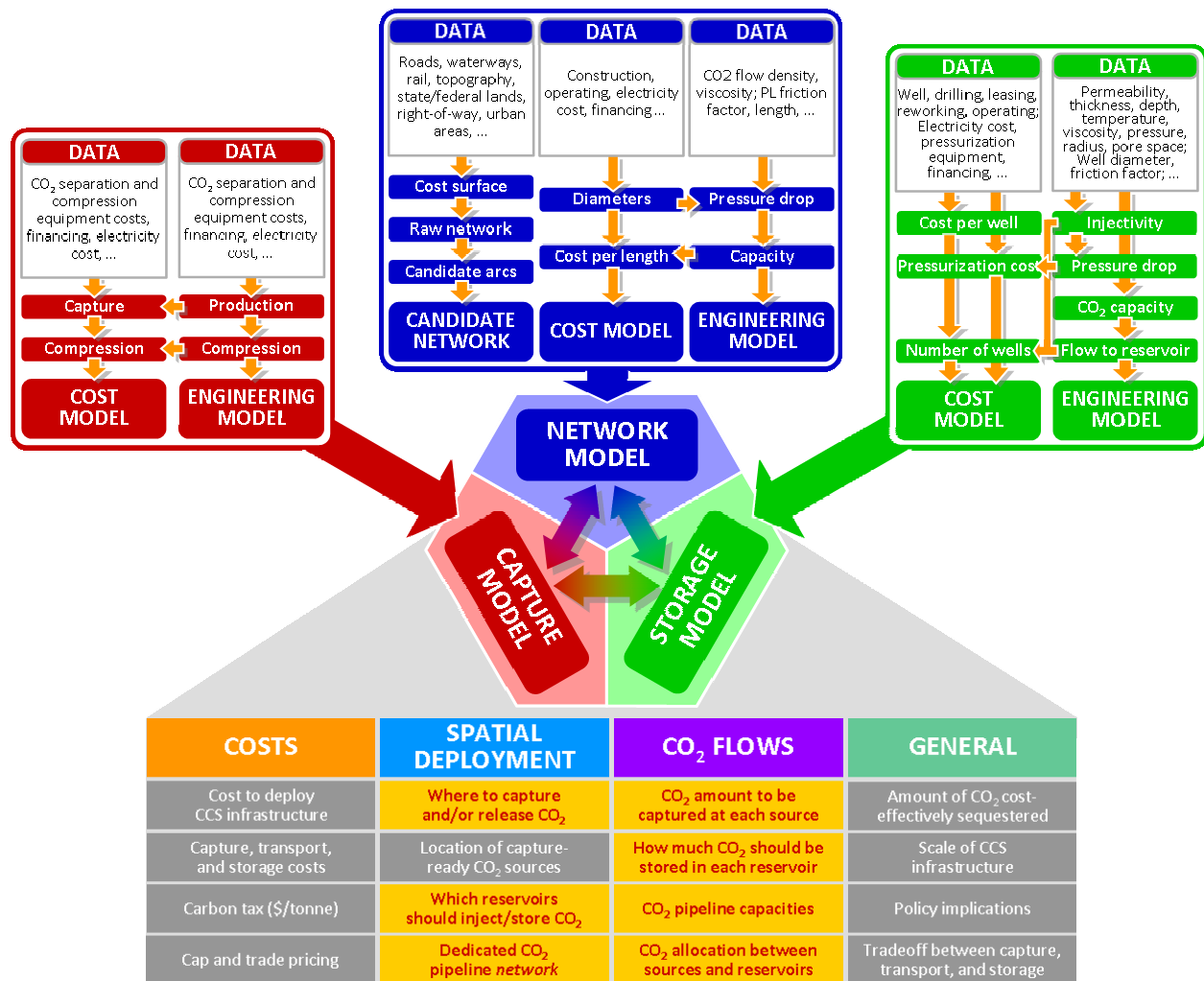


Figure 1: SimCCS Flow Diagram

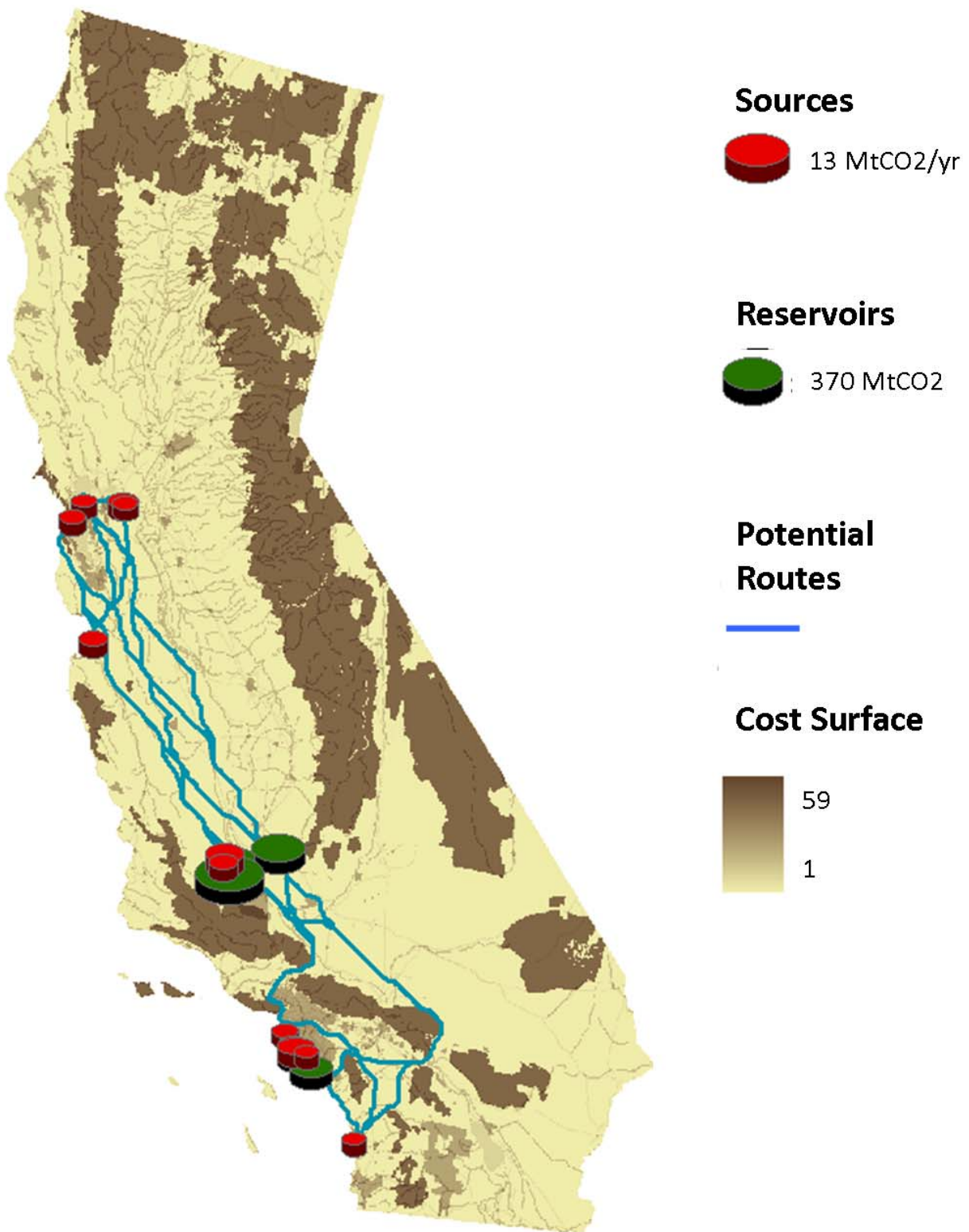
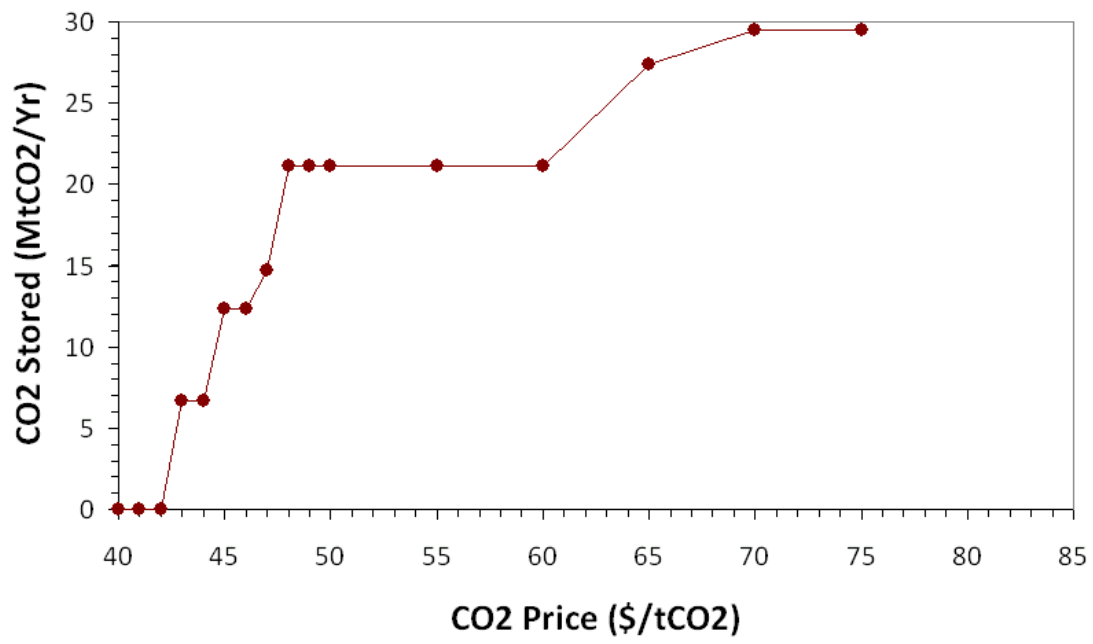


Figure 2: Candidate Network for California Example



**Figure 3: Results for 12 Sources and 5 Reservoirs in California**

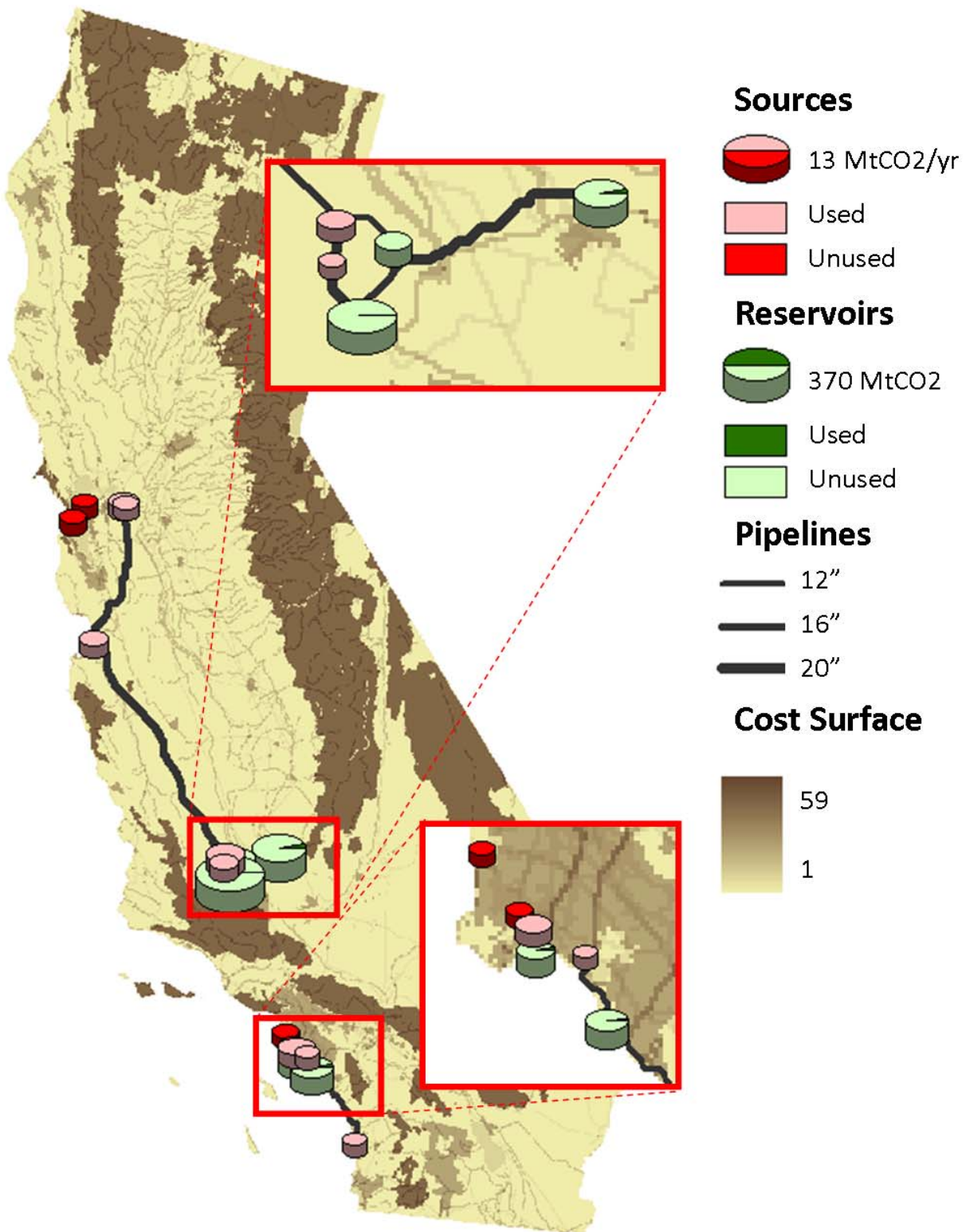
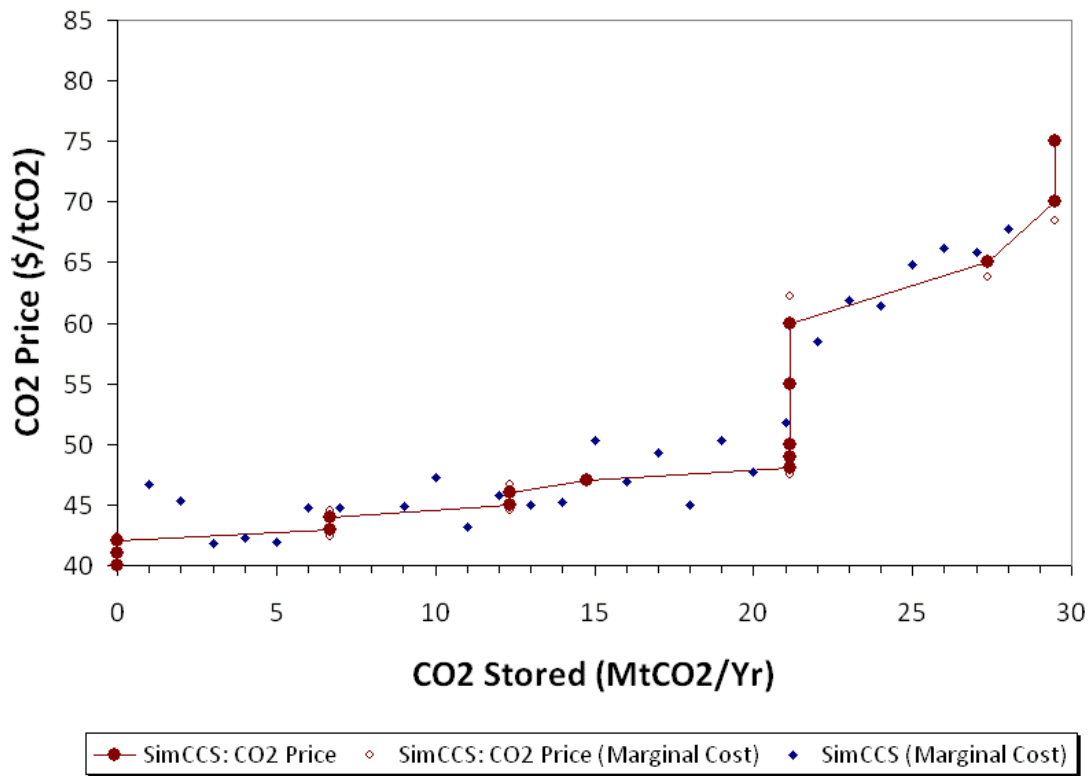


Figure 4: Spatial Deployment with \$48/t CO<sub>2</sub> Price



**Figure 5: *SimCCS*: CO<sub>2</sub> Price Model Output and Marginal Costs from Original *SimCCS* Model**

**Table 1: Cost Surface Values for Pipeline Routing**

<b>Feature</b>	<b>Value</b>
Waterway	10
Highway	3
Railroad	3
State Park	15
National Park	30
Wetland	15
Urban	15
Slope	0.1 – 0.8
Base	1

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