

# **Optimal design of pipelines network for CO<sub>2</sub> transport**

by

Chengchuan Zhou

Dr. Lincoln Pratson, Advisor  
2014

Master's Project submitted in partial fulfillment of the  
requirements for the Master of Environmental Management degree  
in the Nicholas School of the Environment of Duke University

April 2014

## **Abstract**

Carbon capture and storage (CCS) is widely regarded as an important technical alternative to mitigate CO<sub>2</sub> emission. But the planning of the deployment of CCS infrastructure has been a challenging problem, because many constraints have to be considered simultaneously, with a great number of sources and sinks. Moreover, some inevitable nonlinear factors in real-life cases make the design problem even more complex. In this study, an mixed-integer programming (MIP) model for optimal design of pipeline network for CO<sub>2</sub> transport in previous studies is retrofitted, and geographical impacts on the pipeline construction cost is incorporated, which is realized on a combined platform of GAMS and ArcGIS. The new model is also applied to a real-life case in Texas to test its performance. The design result shows that the new model is effective and comprehensive for pipeline networks design.

Key words: CO<sub>2</sub> capture and sequestration, CO<sub>2</sub> transport, optimization, pipeline network

## Table of Contents

<b>Introduction</b> .....	7
<b>Approach</b> .....	10
<b>Case Study</b> .....	19
<b>Result</b> .....	22
<b>Comparison</b> .....	28
<b>Conclusion</b> .....	30
<b>References</b> .....	31

## **Introduction**

Carbon capture and storage (CCS) has become an important technical alternative to reduce carbon dioxide emission, especially for large point sources. Pipeline transport is widely regarded as an efficient and effective means for large-scale and long-distance CO<sub>2</sub> transport. The design of pipeline network for CO<sub>2</sub> transport can largely affect the cost and the reliability of the CCS project, and it is necessary to develop methods to address the problem of the optimal design of the pipeline network. However, the optimal design of pipeline network for CO<sub>2</sub> transport for a real-life case is difficult to achieve generally, because many constraints have to be considered simultaneously, with a great number of sources and sinks. Moreover, the problem becomes more complex when considering some nonlinear factors, like the fluid mechanics of the CO<sub>2</sub> flows, the allocation of the intermediate sites and the selection of pipelines routes.

Source-sink matching method (Dooley et al., 2006) is a widely used method for the optimal design of a CCS project in an early stage. The algorithm of this method matches carbon sources with sequestration sinks and links them with pipelines, aiming to minimize the sum of capture cost, sequestration cost and pipeline cost. Intermediate sites (including pump stations and intersection sites with or without pumps) are not included in this model, and CO<sub>2</sub> pipelines are not allowed to merge or split. This deficiency makes the design result far away from the optimal one when the number of sources and sinks is large, and leads to a severe problem of redundant pipeline construction. In the work of Prasodjo and Pratson (2011), the source-sink matching model is applied to study the optimal design of the pipeline network for CO<sub>2</sub>

in Texas on the platform of GAMS. Moreover, the authors spatially optimize the source-sink matching design result on the platform of ArcGIS, considering geographical impacts on the pipeline construction cost, and assign hubs at places where CO<sub>2</sub> flows merge or split in the final configuration of the pipeline network. In the work of Middleton et al. (2009), the authors develop a source-sink matching model called SimCCS. First, the model applies a pre-optimization algorithm to generate a candidate pipeline network, also based on the impacts of geographical factors on the pipeline construction cost on the platform of ArcGIS. Then the model matches sources with sinks, allowing CO<sub>2</sub> flows to merge or split at sources or sinks, and applies pipes of different diameters to link them, depending on the mass flow rates in the pipelines, to minimize the total cost of the CCS project. The author takes California as an example, with 37 sources and 14 sinks, and compares the total cost of a point-to-point pipeline system and that of a SimCCS pipeline network system, indicating that the latter one is more cost effective due to the scale effect of the network system. In the work of Middleton et al. (2012), the authors develop a new model called SimCCS<sup>TIME</sup>, based on the previous SimCCS model, to optimize the deployment of CCS infrastructure in each time period for a multi-period CCS project. SimCCS<sup>TIME</sup> is designed to deal with dynamic optimization problems, while SimCCS can only address static optimization problems. In the work of Jensen et al. (2013), the authors propose a four-step pipeline planning methodology, based on a combination of concepts of previous studies, which can be used to calculate the length, cost and time scheduling of a hypothetical multi-period network. The methodology identifies

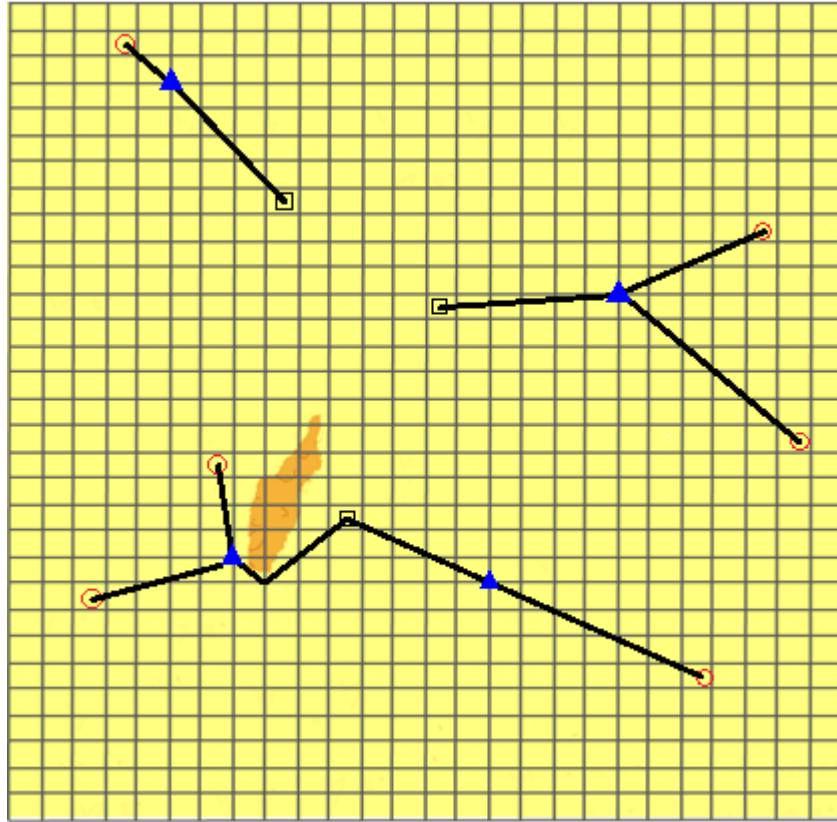
the clusters of CO<sub>2</sub> emission sources and geologic sinks under consideration and then connects the sources and sinks with pipelines.

In the work of Zhou et al. (2014), the authors put forward a superstructure based mixed-integer programming approach to address the problem of optimal design of pipeline network for CO<sub>2</sub> transport. The model minimizes the total cost of the CCS project including CO<sub>2</sub> capture cost, CO<sub>2</sub> transport cost and CO<sub>2</sub> sequestration cost. Apart from the mass balance constraints, the model also takes pressure requirements into consideration. During the process of optimally designing the configuration of the pipeline networks, the model allows intermediate sites, like pump stations, to be set in the region under consideration, and applies pipes of different diameters to connect the sites.

In this study, an extension of the previous model in the work of Zhou et al. (2014) is introduced. The model is retrofitted and the impacts of geographical factors on the pipeline construction cost are integrally taken into consideration. The optimal design of the pipeline networks is achieved on a combined platform of GAMS and ArcGIS. The new model is also applied to a real-life case to solve the optimal design problem of pipeline networks in Texas to test its effectiveness.

### **Approach**

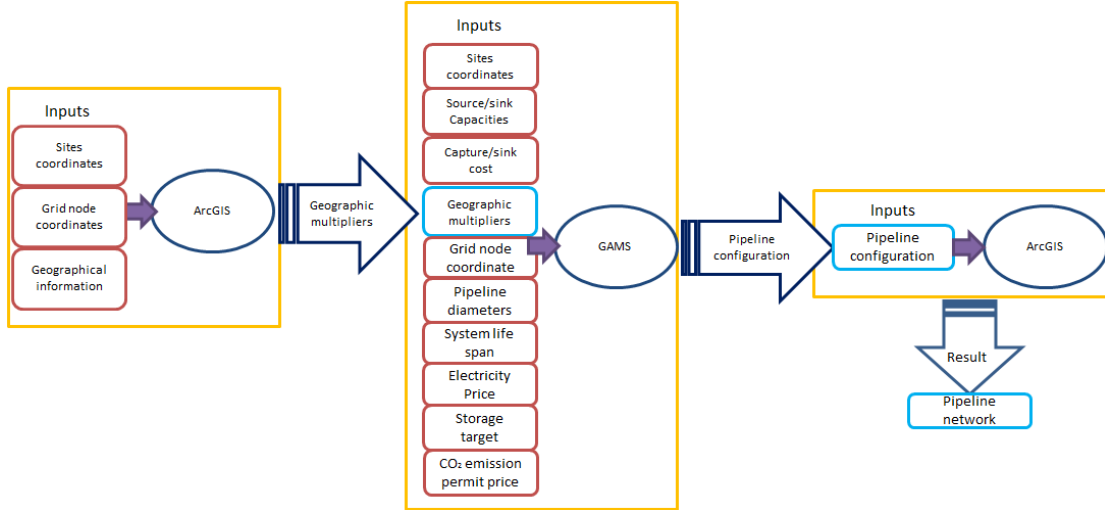
This study retrofits the previous model in the work of Zhou et al. (2014) and the geographical information is incorporated in the optimization process. The new model is also constructed based on a superstructure representation of the optimal design problem, which is shown in Fig. 1. The color of the region under consideration represents the local geographical multiplier of the pipeline construction cost, and locations with higher construction cost due to geographical factors are colored darker. First, the region under consideration is meshed into grid. The nodes of the grid, the sources (red circles) and the sinks (black squares) are potential places for intermediate sites (blue triangles, including pump stations and intersection sites with or without pumps) involved in the CCS project. Whether an intermediate site is to be built, or not built, at each node, source, or sink is managed by binary variables, but intermediate sites cannot be assigned at other locations than these nodes, sources, or sinks. In this way, the infinite number of potential places for intermediate sites is restricted to a finite number, which makes it possible for the model to program and solve the optimization problem. Similarly, a pipeline can only be built (or not built) between sources, sinks, and intermediate sites, which is also managed through binary variables. Because of the introduction of the grid, the construction costs of the potential pipelines between sources, sinks, and intermediate sites can be calculated beforehand and introduced as known parameters prepared for picking over by the model.



**Fig.1** Superstructure representation of the pipelines network for CO<sub>2</sub> transport (Circle Source, Square Sink, Triangle Pump station)

In order to incorporate the geographical impacts on the pipeline construction cost and retrofit the previous superstructure based MIP model<sup>6</sup>, the handling of the geographical multipliers of the potential pipelines is necessary, which depends on the platform of ArcGIS in this study. Given the geographical multipliers, the extended MIP model can be solved to achieve the optimal design of the pipeline networks, taking the geographical impacts and other factors integrally, on the platform of GAMS with the solver CPLEX<sup>7</sup>. In our study, the final optimal design result of the pipeline networks is also mapped out on the platform of ArcGIS, in order to visually show the pipeline network configuration. Fig. 2 is a graphic illustration of the roadmap of this study.





**Fig.2** Model illustration

To be specific, the mixed-integer programming (MIP) model in our study can be outlined as follows<sup>6</sup>:

$$\text{Minimize } U \text{ obj} = \text{capture} + \text{storage} + \text{pipe} + \text{pump} + \text{carbon}$$

s.t.

$$h^{mc}(x, y) = 0, g^{mc}(x, y) \leq 0 \begin{cases} \text{CCS target (optional)} \\ \text{Conservation of mass} \\ \text{Capabilities of sources and sinks} \\ \text{Single pipe constraint} \end{cases}$$

$$h^{sc}(x, y) = 0, g^{sc}(x, y) \leq 0 \begin{cases} \text{Pressure drop of carbon dioxide flow} \\ \text{Pressure drop constraints} \\ \text{Pressure rise constraints} \end{cases}$$

$$x \in R^n, y \in Y = \{0,1\}^m$$

To be specific, the outputs of the new model are as follows<sup>5</sup>:

- (1) Select the sources to capture carbon dioxide from, and decide on the quantity of carbon dioxide to be captured at each selected source.
- (2) Select the sinks to sequestrate carbon dioxide in, and decide on the quantity of carbon dioxide to be sequestrated at each selected sink.

- (3) Decide on the number of intermediate sites, with their positions and values of pressure rise.
- (4) Decide on whether to construct a pipeline between any two sites, with the diameter of the pipeline.
- (5) Decide on the mass flow rates in the pipelines.
- (6) Guarantee that the pressure of the carbon dioxide is within the safe range throughout the pipeline network system, which is from 8.6 MPa and 15 MPa.

The following assumptions have to be held, in order that a valid MIP optimization model can be constructed<sup>5</sup>:

- (1) The range of pressure rise of a pump is from 0 to 6.4 MPa. The upper bound is derived from the difference of 15 MPa and 8.6 MPa. Carbon dioxide newly captured at sources has the pressure of 15 MPa.
- (2) The cost of pumps is mainly electricity cost, and other costs are negligible in magnitude. The electricity price is 0.6 yuan/(kWh). The cost of extra carbon dioxide emission caused by electricity consumption by the pumps is measured by the price of the permit for carbon dioxide emission, which is 17 euros/ton (137.7 yuan/ton). The carbon dioxide intensity of electricity is 0.977kg/kWh.
- (3) The pipe cost is a function of pipe length and pipe diameter. The expression is as shown above.
- (4) The pressures of different inlet flows of a certain site must be a constant. This assumption requires the inlet flow with pressure higher than the constant to depressurize before flowing into the node, through throttles valves or other

devices. On the other hand, the pressures of outlet flows of a certain site can be different because they can be pressurized separately.

(5) The density of CO<sub>2</sub> in our model is regarded to be 731kg/m<sup>3</sup> as a constant.

Our model neglects the density variance of carbon dioxide in the pipeline network due to the temperature changes and pressure changes.

The inputs of the model are as listed below<sup>5</sup>:

- (1) Geographic coordinates of the sources and the sinks.
- (2) Geographic coordinates of the nodes of the grids.
- (3) Geographical multipliers of the construction cost of the potential pipelines between sources, sinks, and intermediate sites
- (4) The capacities of the sources and the sinks.
- (5) Capture/storage costs of the sources/sinks.
- (6) Alternative diameters of the pipelines.
- (7) Electricity price and carbon emission permit price.
- (8) Life span of the system.
- (9) Target quantity of carbon dioxide to be sequestered. (optional)

The mathematical representation of the model is as follows<sup>6</sup>:

**Set**

I, J =

{Source 1, Source 2, Source 3, ..., Sink 1, Sink 2, Sink 3, ..., Node 1, Node 2, Node 3, ...}

Sites

N = {Node 1, Node 2, Node 3, ...} Grid Nodes, a sub set Sites

$SO = \{\text{Source 1, Source 2, Source 3, } \dots \}$  Sources, a sub set of Sites

$SI = \{\text{Sink 1, Sink 2, Sink 3, } \dots \}$  Sinks, a sub set of Sites

$D = \{\text{Diameter 1, Diameter 2, Diameter 3, } \dots \}$  Types of pipelines with different diameters

### **Continuous variables**

$\text{rise}_{i,j}$  Pressure rise of  $\text{CO}_2$  flow from site  $i$  to site  $j$  at site  $i$ ,  $\text{rise}_{i,j} \in [0, 6.4]$ ,

unit: MPa

$F_{i,j}$  Mass flow rate of  $\text{CO}_2$  from site  $i$  to site  $j$ , positive variable, unit: kg/s

$c_i$   $\text{CO}_2$  captured at site  $i$ , positive variable, unit: kg/s

$k_i$   $\text{CO}_2$  sequestered at site  $i$ , positive variable, unit: kg/s

$\text{pd}_{i,j}$  Pressure drop of  $\text{CO}_2$  flow from site  $i$  to site  $j$ , caused by friction of the pipe,

$\text{pd}_{i,j} \in [0, 6.4]$ , unit: MPa

$\text{po}_{i,j}$  Pressure of outflow from site  $i$  to site  $j$ ,  $\text{po}_{i,j} \in [8.6, 15]$ , unit: MPa

$\text{pi}_j$  Pressure of inflow at site  $j$ ,  $\text{pi}_j \in [8.6, 15]$ , unit: MPa

capture cost Capture cost of the CCS project, unit: yuan

storage cost Storage cost of the CCS project, unit: yuan

pipe cost Pipeline construction cost of the CCS project, unit: yuan

pump cost Pump O&M cost of the CCS project, unit: yuan

carbon cost  $\text{CO}_2$  emission permit cost of the CCS project, unit: yuan

total cost Total cost of the CCS project, unit: yuan

### **Discrete variables**

$y_{i,j,d}$  Binary variable, if there is a pipeline of type  $d$  connecting  $i$  and  $j$ , it equals 1.

Otherwise, it equals 0

### Parameters

$\theta_k^{LB}$  The lower bound of the  $k$ th subinterval of the domain of  $rise_{i,j}$ , unit:

MPa

$\theta_k^{UB}$  The upper bound of the  $k$ th subinterval of the domain of  $rise_{i,j}$ , unit:

MPa

$\delta_p^{LB}$  The lower bound of the  $p$ th subinterval of the domain of  $F_{i,j}$ , unit: kg/s

$\delta_p^{UB}$  The upper bound of the  $p$ th subinterval of the domain of  $F_{i,j}$ , unit: kg/s

$\alpha_p$  The slope of the piecewise linear function in the  $p$ th subinterval of the domain of  $F_{i,j}$ , unit: kg/s

$\beta_p$  The intercept of the piecewise linear function in the  $p$ th subinterval of the domain of  $F_{i,j}$ , unit:  $\text{kg}^2/\text{s}^2$

$L_d$  Diameter of the pipeline of type  $d$ , unit: m

$S_d$  Cross-sectional area of the pipeline of type  $d$ , unit:  $\text{m}^2$

$dis_{i,j}$  Distance between site  $i$  and site  $j$ , unit: km

$geo_{i,j}$  Geographical multipliers of the construction cost of the potential pipeline between site  $i$  and site  $j$ , unit: km

$ep$  Electricity price factor, used to calculate for expenditure on a certain quantity of electricity, unit: yuan/(MPa·kg)

$tm$  Time factor, represent the life span of the system, unit: s

$cp$  Carbon price factor, used to calculate the expenditure on carbon dioxide emission permits for carbon dioxide emission caused by a certain quantity of

electricity consumption, unit: yuan/(MPa·kg)

T Target of CO<sub>2</sub> to be sequestered, unit: kg/s

f Friction factor of the pipe

ρ Density of CO<sub>2</sub> flow, unit: kg/m<sup>3</sup>

e<sub>i</sub> CO<sub>2</sub> emitted at site i, unit: kg/s

u<sub>i</sub> Maximum CO<sub>2</sub> sequestration capacity at site i, unit: kg/s

cap<sub>i</sub> CO<sub>2</sub> capture cost at site i, unit: yuan/kg

sink<sub>i</sub> CO<sub>2</sub> sequestration cost at site i, unit: yuan/kg

### Objective function

total cost = capture cost + storage cost + pipe cost + pump cost + carbon cost (1)

$$pipe\ cost = \sum_{i,j,d} [(73.2 \cdot L_d^2 + 28.67 \cdot L_d + 23.79) \cdot dis_{i,j} + 1.22] \cdot y_{i,j,d} \cdot geo_{i,j} \cdot 10^5, i \neq j \quad (2)$$

$$pump\ cost = tm \cdot ep \cdot \sum_{i,j} (\theta_k^{UB} \cdot F_{i,j}), i \neq j \text{ if } rise_{i,j} \in [\theta_k^{LB}, \theta_k^{UB}] \quad (3)$$

$$capture\ cost = tm \cdot \sum_i cap_i \cdot c_i \quad (4)$$

$$storage\ cost = tm \cdot \sum_i sink_i \cdot k_i \quad (5)$$

$$carbon\ cost = tm \cdot cp \cdot \sum_{i,j} (\theta_k^{UB} \cdot F_{i,j}), i \neq j \text{ if } rise_{i,j} \in [\theta_k^{LB}, \theta_k^{UB}] \quad (6)$$

### Constraints

CCS Target (optional)

$$\sum_i c_i \geq T \quad (7)$$

Conservation of mass

$$\sum_{j \neq i} F_{j,i} + c_i = \sum_{j \neq i} F_{i,j} + k_i \quad (8)$$

Single pipe constraint

$$\sum_d y_{i,j,d} = \begin{cases} 1 & \text{if } F_{i,j} > 0 \\ 0 & \text{otherwise} \end{cases} \quad i \neq j \quad (9)$$

Pressure drop of CO<sub>2</sub> flow

$$pd_{i,j} \geq f \cdot \frac{(\alpha_p \cdot F_{i,j} + \beta_p) \cdot dis_{i,j}}{2\rho \cdot L_d \cdot S_d^2}, i \neq j \text{ if } y_{i,j,d} = 1, F_{i,j} \in [\delta^{LB}_p, \delta^{UB}_p] \quad (10)$$

Pressure drop constraint

$$pd_{i,j} = \begin{cases} (p_{o_{i,j}} - p_{i_j}) & \text{if } F_{i,j} > 0 \\ 0 & \text{otherwise} \end{cases}, i \neq j \quad (11)$$

Pressure rise constraint

$$rise_{i,j} = \begin{cases} p_{o_{i,j}} - p_{i_i} & \text{if } F_{i,j} > 0 \\ 0 & \text{otherwise} \end{cases}, i \neq j \quad (12)$$

Capabilities of sources and sinks

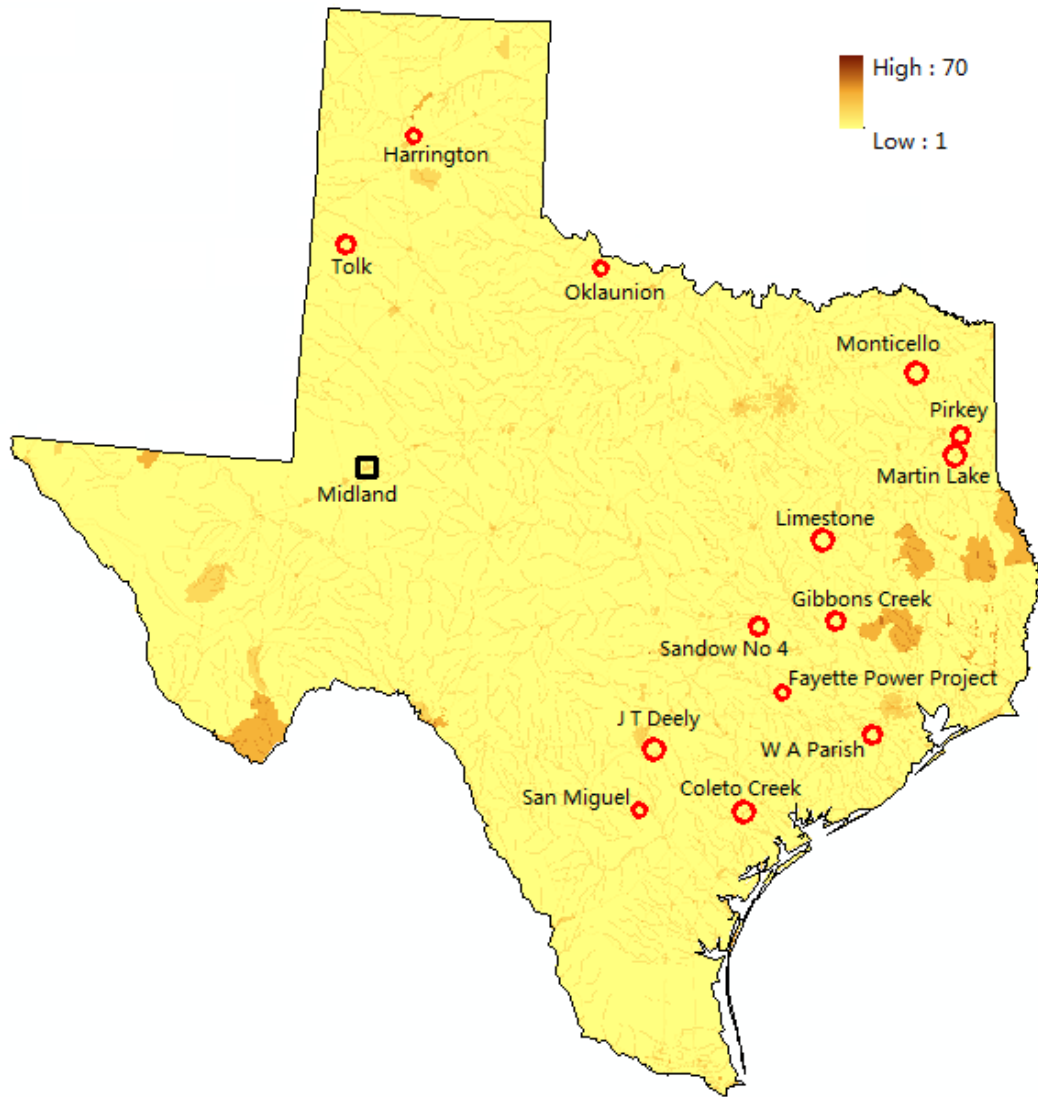
$$c_i \leq e_i \quad (13)$$

$$k_i \leq u_i \quad (14)$$

### **Case Study**

The model in this study is applied to design the pipeline network for CO<sub>2</sub> transport in Texas and the database comes from the study of Prasodjo (2011). The region under consideration is shown in Fig. 3<sup>8</sup>. Red circles represent CO<sub>2</sub> emission sources, and the black square represent the CO<sub>2</sub> sink. As presented in the figure, the sources and the sink are shown on the map of the cost surface developed at Massachusetts Institute of Technology (MIT) (2007). The cost surface is a raster layer with a cell size of 1 km<sup>2</sup>, where the cell values indicating the multipliers of an assumed baseline pipeline construction cost. i.e. a location with geographical factors leading to higher pipeline construction cost is assigned a larger multiplier and looks darker in the map, and the construction cost of pipelines at this location is also larger accordingly.





**Fig.3** Region under consideration—Texas

CO<sub>2</sub> emission sources in this case are power plants selected by the Nicholas Institute’s version of the U.S. Energy Information Agency’s National Energy Modeling System (NI-NEMS) (2008), which are the cost effective ones for retrofitting with CCS technology. The information of these power plants is shown in Table 1<sup>1</sup>.

**Table 1** Database of sources

Source	Longitude	Latitude	Capacity (GW)	CO <sub>2</sub> capture cost (\$/t)
--------	-----------	----------	---------------	-------------------------------------

Tolk	-102.57	34.19	1.14	34.47
Harrington	-101.75	35.3	1.08	34.74
Oklunion	-99.18	34.08	0.72	36.74
Monticello	-95.04	33.09	1.98	31.75
Pirkey	-94.49	32.46	0.72	36.74
Martin Lake	-94.57	32.26	2.38	30.85
Limestone	-96.26	31.42	1.85	32.09
Gibbons Creek	-96.08	30.62	0.45	39.06
WA Parish	-95.64	29.48	3.97	28.33
Sadow No 4	-97.06	30.56	1.14	34.47
Fayette Power Project	-96.75	29.91	1.69	32.53
San Miguel	-98.48	28.7	0.41	39.51
JT Deely	-98.32	29.31	1.50	33.12
Coletto Creek	-97.21	28.71	0.60	37.64

As to the sink, Midland is selected as the only sequestration site in our case.

There are a number of Enhanced Oil Recovery (EOR) fields and saline aquifers surrounding Midland, with a total capacity of no less than 30432 Mt CO<sub>2</sub><sup>9</sup>. The storage cost of CO<sub>2</sub> in EOR fields is negative, which means sequestering CO<sub>2</sub> in EOR fields will raise oil production and thus is profitable, while the storage cost of CO<sub>2</sub> in saline aquifers is positive. In our case, the storage cost of CO<sub>2</sub> at Midland is roughly regarded as zero<sup>10</sup>.

The CCS project is planned to have a life span of 15 years, and is designed to transport all the emissions from the selected power plants to Midland for storage. The alternative diameters of the pipelines are 12 in (0.3048 m), 16 in (0.4064 m), 20 in (0.508 m), 24 in (0.6096 m), 30 in (0.762 m), 34 in (0.8636 m), and 40 in (1.016 m) respectively.

## **Results**

The minimum total cost for the CCS project in the Texas case is about \$28.661 billion, with the capture cost to be \$23.576 billion, the pipeline construction cost to be 4.131, the pump cost to be 0.796 billion, and the carbon dioxide emission permit cost to be 0.158 billion. The total length of the pipelines is 2505.0 km, with the 12 in pipelines to be 597.8 km, the 16 in pipelines to be 441.8 km, the 20 in pipelines to be 359.0 km, the 30 in pipelines to be 210.1 km, the 34 in pipelines to be 353.7 km, and the 40 in pipelines to be 542.6 km. The design result of the pipeline network of the CCS project is shown in Fig. 4. Fig. 5 is the enlarged graph of the design result. Green lines represent the pipelines, and the widths of the lines are positively correlated with the diameters of the pipelines. The blue triangles represent the pump stations, while the purple stars represent the intersection sites without pumps. Table 2<sup>1</sup> and Table 3 are numerical details of the design result.



**Fig.4** Design result



**Fig.5** Design result (enlarged)

**Table 2** Design result (I)<sup>1</sup>

source/sink	CO <sub>2</sub> captured (Mt per year)	CO <sub>2</sub> sequestrated (Mt per year)
Tolk	3.41	0
Harrington	2.66	0
Oklaunion	0.72	0
Monticello	5.93	0
Pirkey	4.56	0
Martin Lake	6.11	0
Limestone	6.48	0
Gibbons Creek	3.35	0

WA Parish	4.27	0
Sadow No 4	4.08	0
Fayette Power Project	1.48	0
San Miguel	1.52	0
JT Deely	7.14	0
Coletto Creek	5.09	0
Midland	0	56.8

**Table 3** Design result (II)

<b>Pipeline</b>	<b>Diameter (in)</b>	<b>CO<sub>2</sub> flow rate (kg/s)</b>	<b>pressure rise (MPa)</b>	<b>Length (km)</b>
Harrington→T1	12	84.35	0	164.5
T1→Tolk	12	84.35	6.035	0
Tolk→Midland	20	192.48	0	269.4
Oklunion→T2	12	22.83	0	352.8
T2→N2	12	22.83	2.881	0
Monticello→T3	16	188.04	0	96.3
T3→Pirkey	16	188.04	6.01	0
Pirkey→ Martin Lake	30	332.64	0	26.2
Martin Lake→T13	34	526.39	0	219.8
T13→Limestone	34	526.39	3.1	0
Limestone→T4	34	731.87	0	121.0
Gibbons Creek→N3	16	106.23	0	91.4
WA Parish→T7	16	135.4	0	123.4
T7→Fayette Power Project	16	135.4	3.01	0
Fayette Power Project→T5	20	182.33	0	89.6
T4→N3	34	731.87	3	0
N3→T5	34	838.1	0	12.9
T5→Sadow No 4	34	1020.43	3.01	0
Sadow No 4→N1	40	1149.81	0	178.8
San Miguel→T8	12	48.2	0	80.5
Coletto Creek→T9	16	161.4	0	
T8→J T Deely	12	48.2	3.01	0

T9→J T Deely	16	161.4	6.01	0
J T Deely→N1	30	1585.82	0	183.9
N1→T10	40	1585.82	0	0
T10→T11	40	1585.82	5	125.5
T11→T12	40	1585.82	5	127.5
T12→N2	40	1585.82	5	0
N2→Midland	40	1608.65	0	110.8

---

### **Comparison**

In this part, the method of source-sink matching model is applied to the same case in Texas, and the comparison between this model and our method is shown below.

The design result of the source-sink matching model is shown in Fig. 6. Fig. 7 is the enlarged graph of the design result. The blue lines here represent the pipelines, while the other symbols have the same meanings as above. As the source-sink matching model doesn't take the problem of CO<sub>2</sub> pressure into consideration, the model doesn't make decision on the pipeline diameters. Thus, pipelines of 12 in are applied to calculate the lower bound of the total project cost, while 40 in are applied to calculate the upper bound of the total project cost. The total project cost range is \$30.142 billion (12 in)—\$45.026 billion (40 in), with the capture cost to be \$23.576 billion, and the pipeline construction cost range to be \$6.566 billion (12 in)—\$21.450 billion (40 in). The total length of the pipelines is 8246.4 km.





**Fig.6** source-sink matching result



**Fig.7** source-sink matching result (enlarged)

The result shows that the total project cost of the design result of source-sink matching model is much larger than that of our method. The reason is that there is too much redundant pipeline construction in the region under consideration and we can clearly see that there are some pipelines share the same paths. It is also worth mentioning that the total project cost of the design result of source-sink matching model doesn't take pump cost or carbon dioxide emission permit cost into consideration, which means the total project cost of this method should have been

even larger. Accordingly, our model performs much better than the previous source-sink matching model.

## **Conclusions**

In this study, we retrofit a previous model in the work of Zhou et al. (2014), and introduce a new model by incorporating the geographical factors to achieve a more comprehensive design result. The model aims to minimize the total cost including capture cost, storage cost and transportation cost, which subjects to mass balance constraints and pressure requirements. The new model is then applied to design the pipeline network in Texas, and the design result confirms its effectiveness. The comparison between our model and the source-sink matching model in previous studies shows that our model is the more cost-effective one, because it well solves the problem of redundant pipeline construction.

In future studies, the model can also be applied to cases with multiple sinks and storage costs can also be introduced to further study its performance. Besides, other factors, like reservoir leakage risk, which is related to the characteristics of the potential reservoirs, such as permeability, depth and thickness, can be included in the model to make it more comprehensive.

## References

1. Dooley, J., Dahowski, R., Davidson, C., Wise, M., Gupta, N., Kim, S., Malone, E. (2006) Carbon Dioxide Capture Geologic Storage: A Core Element of a Global Energy Technology Strategy to Address Climate Change. Technical report Global Energy Technology Strategy Program, Battelle, Joint Global Change Research Institute.
2. Prasodjo, D., & Pratson, L. (2011). OptimaCCS Carbon Capture and Storage Infrastructure Optimization.
3. Middleton, R. S., & Bielicki, J. M. (2009). A scalable infrastructure model for carbon capture and storage: SimCCS. *Energy Policy*, 37(3), 1052-1060.
4. Middleton, R. S., Kuby, M. J., Wei, R., Keating, G. N., & Pawar, R. J. (2012). A dynamic model for optimally phasing in CO<sub>2</sub> capture and storage infrastructure. *Environmental Modelling & Software*, 37, 193-205.
5. Jensen, M. D., Pei, P., Snyder, A. C., Heebink, L. V., Botnen, L. S., Gorecki, C. D., ... & Harju, J. A. (2013). Methodology for Phased Development of a Hypothetical Pipeline Network for CO<sub>2</sub> Transport during Carbon Capture, Utilization, and Storage. *Energy & Fuels*.
6. Zhou, C., Liu, P., & Li, Z. (2014). A superstructure based mixed-integer programming approach to optimal design of pipeline network for large-scale CO<sub>2</sub> transport. Accepted by *AIChE Journal*.
7. GAMS Development Corporation (2013). CPLEX 12. In: GAMS Development Corporation (Washington, DC). GAMS: The Solver Manuals. Washington, DC: GAMS Development Corporation, 93-142.
8. Herzog, H., W. Li, Z. Hongliang, M. Diao, G. Singleton, and M. Bohm. (2007). West Coast Regional Carbon Sequestration Partnership: Source – Sink Characterization and Geographic Information System – Based Matching. California Energy Commission, PIER Energy Related Environmental Research Program.
9. National Energy Technology Laboratory. (2008). Retrofitting Coal-Fired Power Plants for Carbon Dioxide Capture and Sequestration (CCS) - Exploratory Testing of NEMS for Integrated Assessments. National Energy Technology Laboratory. U.S. Department of Energy.
10. Eccles, J. K., Pratson, L., Newell, R. G., & Jackson, R. B. (2012). The impact of geologic variability on capacity and cost estimates for storing CO<sub>2</sub> in deep-saline aquifers. *Energy Economics*, 34(5), 1569-1579.
11. Zheng Z. (2009). Research on CCS Source-sink Match System and Near-term Demonstration Opportunities in China. Thesis, presented to Tsinghua University in P. R. China, in partial fulfillment of the requirements for the degree of Master of Science.