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Analysis of Properties Influencing CO_2 Transport Using a Pipeline and Visualization of the Pipeline Connection Network Design: Korean Case Study

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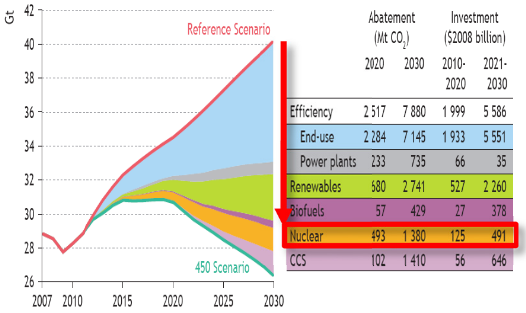
ABSTRACT

Carbon Capture and Storage (CCS) technologies involve three major stages, i.e., capture, transport, and storage. The transportation stage of CCS technologies has received relatively little attention because the requirements for CO_2 transport differ based on the industry-related conditions, geological, and demographical characteristics of each country. In this study, we analyzed the properties of CO_2 transport using a pipeline. This study has important implications for ensuring the stability of a long-term CCS as well as large cost savings, as compared to the small cost ratio as a percentage of the entire CCS system. The state of CO_2, network topologies, and node distribution are among the major factors that influence CO_2 transport via pipelines. For the analysis of the properties of CO_2 transport using a pipeline, the CO_2 pipeline connections were visualized by the simulator developed by Lee [11] based on the network topologies in CO_2 transport. The case of Korean CCS technologies was applied to the simulation.

Key words: *Carbon Capture and Storage (CCS), Simulator, CO_2 Transport, Network Topology, Pipeline Property.*

1. INTRODUCTION

Climate change is a complex phenomenon and its impacts are hard to predict far in advance. Global warming is the one of the serious problem of climate change and primarily a problem of too much carbon dioxide in the atmosphere – which acts as a blanket, trapping heat and warming the planet. Fig. 1 presents the International Energy Agency's (IEA's) prediction regarding the amount of CO_2 emissions.



	Abatement (Mt CO_2)		Investment ($2008 billion)	
	2020	2030	2010-2020	2021-2030
Efficiency	2 517	7 880	1 999	5 586
End-use	2 284	7 145	1 933	5 551
Power plants	233	735	66	35
Renewables	680	2 741	527	2 260
Biofuels	57	429	27	378
Nuclear	493	1 380	125	491
CCS	102	1 410	56	646

Fig. 1. CO_2 Emissions and Reductions [8]

There are several alternative ways to reduce CO_2, including energy efficiency, renewable energy, biofuels, nuclear power, and CO_2 capture and storage/sequestration (CCS). By 2030, using all of the available alternative methods, it is estimated that CO_2 emissions will be reduced from 40 to 26 gigaton (GT) [8]. Among the aforementioned methods, 19% of the CO_2 emission reduction will be achieved by CCS. CCS is used to describe a set of technologies aimed at capturing carbon dioxide emitted from large emission plant such as petroleum plants, cement plant and the other industrial plants which are related with energy sources before it enters the atmosphere. And then CCS has a role of compressing carbon dioxide and injecting it deep underground such as seabed in geologically secure lands and ensuring it remains stored there indefinitely. CCS is expected to reduce CO_2 emission rate by at least 15% and at most 55% by 2100 [8].

The key driving force behind taking CCS is the need to be cost-effective to tackle the global issue of climate change by reducing CO_2 emissions where there are continuing and rising demands for energy.

CCS system is divided into three steps – capture, transport and storage. The stage of capturing CO_2 is a core technology which accounts for almost about 70% of the CCS system cost. The main technologies for capturing CO_2 are as pre-combustion capture technology, post-combustion capture technology and oxy-fuel combustion technology. The stage of storage as a technique for storing CO_2 in deep seabed or land, has been actively researched to find the problems inherent about its compatibility and stability.

In contrast, a transportation stage has received relatively little attention in the whole CCS technologies because the requirements for CO_2 transport differ to the conditions

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regarding industries, geological and demographical characteristics each country. Furthermore, most studies for CO_2 pipeline transportation problem focus on constructing pipelines regarding technological analysis for stability/durability of transporting CO_2. There are few studies analyzing parameters' relationships in the transportation stage. The analysis of CO_2 transportation network is important of that it results in a large cost savings and ensures the stability of a long-term CCS contrary to the small ratio of the cost as a percentage of the entire CCS.

There exist lots of parameters which affect to the pipelines such as the diameter of the pipeline, CO_2 flow rate, and the pipeline length and so on [2], [3], [5]-[7], [9], [10], [12], [13], but it needs to know how they influence to the connection of pipelines among the CO_2 emission sites.

In this study, it is assumed that CO_2 is transported only via pipelines. If CO_2 emission sources are not processed by CCS systems, they all release CO_2 into the air and generate a penalty cost proportional to the amount of CO_2. We give a cost analysis for properties of the pipelines how they affect the entire CCS systems.

We propose a pipeline network model that considers the pipeline cost model that was analyzed in previous studies and the location of the pipeline. It uses regional information from where the pipeline is installed, the state and density of the CO_2 flowing through the pipeline, and the terrain. These aspects of the CCS system model are more realistic and efficient than those of existing studies.

2. RESEARCH BACKGROUD

Recent studies have analyzed the various technical factors that gradually affect pipelines. Z.X. Zhang [18] studied initial CO_2 pipeline transport, focusing on which CO_2 states were more cost effective transportation modes based on comparisons of the liquefied and supercritical phases of CO_2.

As the pressure drop of liquid CO_2 is less than that of supercritical CO_2, he concluded that the transport of CO_2 in its liquefied state was more cost-effective.

In contrast, Nimtz [15] concluded that supercritical CO_2 allowed for high-pressure transport without changing phases, making it suitable for pipeline transport. Dongjie Zhang [4] completed an economic evaluation of the pipeline from a hydrodynamic perspective and McCoy [14] presented a methodology that was more suitable for pipeline design than the existing research, with an emphasis on engineering. However, none of these studies included an integrated investigation with the organic relation to CO_2 capturing and transportation technology.

Many studies have included cost estimations based on the case of natural gas pipelines in the cost analysis of CO_2 pipelines. However, such analyses considering the properties of natural gas pipelines do not produce realistic results. CO_2 pipeline design differs significantly from natural gas pipeline design, specifically in the compression step, which changes the properties of CO_2 and thus affects the internal design requirements. Knoope [16] analyzed a cost model with changes in toughness that focused on a CO_2 pipeline's wall thickness and steel grade. And Knoope also analyzed uncertainty and cost depending on the location of the pumping station. Lee [11] proposed an algorithm to determine the location and the number of the intermediate storage hub and develop a simulator for the connection network of the carbon dioxide emission site. The simulator also provides the course of transportation of the carbon dioxide.

3. PROBLEM DESCRIPTION

3.1 Properties of the pipeline transport

In this section, the state of CO_2 and the cost factors of pipeline estimation models are defined to investigate the relationship among properties. Before estimating the pipeline cost, it is important to address the phase change in the CO_2 to be transported to the intermediate storage through the CO_2 emission site. The state of transporting CO_2 via pipelines is the most crucial properties. For example, the state of the collected CO_2 is 1 bar and 25℃ at room temperature. The phase of the CO_2 being transported via pipelines is affected by numerous pipeline factors such as the number of compressors and pumps, the internal design of the pipeline's diameter, the friction, the viscosity inside the pipeline, etc. In the following sections, we describe how the designs for pumps and compressors change with the state of the transported CO_2 and analyze the effects which such changes have on the design of the pipelines.

3.1.1 Compressor and pump designs

The temperature and pressure of the CO_2 captured from emission sources are 1 bar and 25℃. The pressure differs based on the state of the CO_2 being transported through the pipeline (e.g., supercritical state, high density state, and low temperature state). The assumptions for the three representative phases of CO_2 are as follows.

Table 1. The representative states of CO_2 [1]

	Supercritical	High density	Low temperature
Temperature	40°	10°	-20°
Pressure	140 bar (14 MPa)	85 bar (8.5 MPa)	65 bar (6.5 MPa)

There are two methods for increasing the pressure up to the levels shown in Table 1. To increase the pressure of the gas CO_2, compressors are required. Pumps are suitable for boosting the pressure in the liquid state. To adapt these compressor and pump costs to the pipeline connection network problem, we need to know how many compressors and pumps are required at each distance interval depending on the state of the CO_2. The most important factor affecting the distance interval of each pump is the pressure drop.

The pressure drop, adapted from Kang [1], is described in Table 2. The number of pump stations required per 200 km of pipeline is also given.

Table 2. Pressure drop depending on the state of CO_2 [1]

	Pressure drop (bar/m)	# of Pipelines (200 km)
Supercritical	4.03E-03	4
High density	1.06E-03	2
Low temperature	6.42E-05	1

Thus, the equation should be changed to consider the number of pumping stations for each state of CO_2. To induce the total cost of compressors and pumps according to such changes, we use the modified cost equation developed by McCollum and Ogden [3].

$$C_{total} = C_{compressor} + C_{pump} * N_{pump}$$

Given the use of equations that include many assumptions, it is important to note how the models are affected by small changes in the factors involved.

3.1.2 Pipeline cost estimation models

In this section, we focus on the pipeline connection costs. The pipeline transportation models are divided into onshore and offshore pipelines. To sequestrate CO_2 in the seabed, the offshore pipeline model must be considered. We assume the onshore pipeline transportation and estimated pipeline cost models are summarized in Table 3 below with the following researchers: Ogden, MIT, Ecofys, IEA GHG PH4/6, IEA GHG 2005/2 and IEA GHG 2005/3.

Table 3. CO_2 pipeline cost estimation models [3]

	Pipeline cost Equation (capital cost + O&M cost)
Ogden	$Total\ annual\ cost(\$) = 700 * \left(\frac{m}{1600}\right)^{0.48} * \left(\frac{L}{100}\right)^{0.24} * (CRF + O\&M\ factor) * L$ $m = C_1\sqrt{\left(\frac{1}{f}\right)}\left[\frac{\left(P_{inpipe}^2 - P_{outpipe}^2 - C_2\left\{\frac{G\Delta h P_{avg}^2}{Z_{avg}T_{avg}}\right\}\right)}{GT_{avg}Z_{avg}L}\right]^{0.5} D^{2.5}E$
MIT	$Total\ annual\ cost(\$) = (20{,}989 * D * L * CRF) + (3{,}100) * L$ $f = \frac{1}{4\left[-1.8\log\left\{\frac{6.91}{Re} + \left(\frac{12\left(\frac{\varepsilon}{D}\right)}{3.7}\right)^{1.11}\right\}\right]^2},\ D^5 = \frac{32fm^2}{\pi^2\rho\left(\frac{\Delta P}{\Delta L}\right)}$
Ecofys	$Total\ annual\ cost = \left(1100€\right) * \left(1 + O\&M\ factor\right) * F_T * D * L / \left[\{(1+i)^n - 1\} / i(1+i)^n\right]$ $D^5 = \frac{8fm^2}{\pi^2\rho\left(\frac{\Delta P}{L}\right)}$
IEA GHG PH4/6	$Total\ annual\ cost = CRF * F_L * F_T * 10^6 * [(0.057 * L + 1.8663) + (0.00129 * L) * D + (0.000486 * L + 0.000007) * D^2]$ $Annual\ pipeline\ O\&M\ cost =$ $120000 + 0.61(23213 * D + 899 * L - 259269) + 0.7(39305 * D + 1694 * L - 351355) + 24000$ $\Delta P = \frac{2.252 fL\rho Q^2}{D^5}$
IEA GHG 2005/2	$Total\ annual\ cost(€) = (1 + O\&M\ factor) * F_T * 10^6 * [(0.057 * L + 1.8663) + (0.00129 * L*D+0.000486*L+0.000007*D2]\{1+in- 1/ i1+in]$ $D = \left[\frac{m}{0.25\pi\rho v}\right]^{0.5} /0.0254$
IEA GHG 2005/3	$Total\ annual\ cost = \left(1 + O\&M\ factor\right) * 4335 * \left(\frac{m}{24}\right)^{0.5}$ $D = \left[\frac{4m}{18.41\pi\rho_N}\right]^{0.5}$
Parameter	m=CO_2 flow rate, C_1 =18.921, f=friction factor, P_{inlet} =pipeline inlet pressure[kPa], P_{outlet}=pipeline outlet pressure [kPa], C_2=0.06836, G=CO_2 specific gravity=1.519, Δh=change in elevation[m], P_{avg} =average pipeline pressure, Z_{avg} =CO_2 compressibility at P_{avg} , T_{avg} =average temperature[K], L=pipeline length[km], D=pipeline diameter[m], E=pipeline efficiency, CRF=capital recovery factor, v = average flow velocity [m/s],F_T = correction factor for terrain, n = operational lifetime [years], i = discount rate, F_L = location factor, μ=CO_2 viscosity, ε=pipeline roughness factor, Re=Reynold's number=$\frac{4m}{\pi*\mu*D}$, ΔP=pressure drop, ρ=CO_2 density

The six pipeline cost models derived individually by other assumptions are classified. We can see how the diameters of each pipeline cost model are different. The diameter is influenced by the parameter definitions and input data. Thus, the pipeline connections achieved by six other cost models are determined by assuming the three representative states of CO_2 to identify the optimal state for minimizing the costs. Key parameters for deriving pipeline cost functions are the pipeline diameter, pipeline length, and CO_2 flow rate. The diameter, in particular, is the function of inlet and outlet pressure, friction factors, CO_2 density, viscosity, CO_2 flow rate, pipeline roughness factors, and so on.

3.1.3 Operations and maintenance (O&M) cost

McCollum and Ogden [3] do not define pipeline cost models exactly in accordance with the state of CO_2 transport. We assume the percentage of the cost, such as that reflecting the adiabatic process. The proportion of the cost in each process is cited by Kang [1] and Fig. 2 illustrates the component ratio.

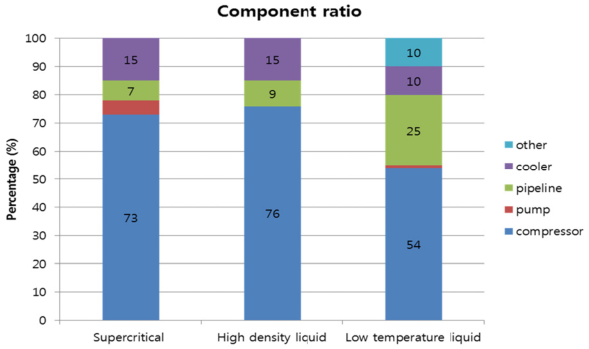


Fig. 2. Component ratio of each state of CO_2

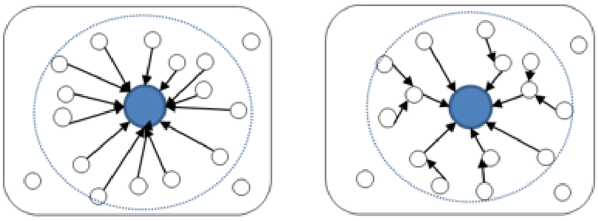
3.2 Pipeline connection network

We describe four network topologies based on the connections between the pipelines in the CCS system; star network, tree network and backbone network. Description for network topologies are in bellow Table 4.

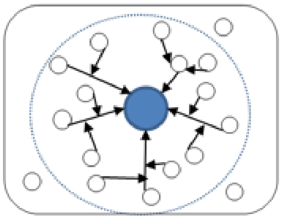
Table 4. Description for nework topologies

Network Topology	Description
Star network	- One-to-one connection in which all CO_2 emission source nodes are connected to the central hub node. - Easy to add or remove nodes. - It works well when CO_2 source nodes are scattered. - If a source node goes down, none of the other CO_2 emission source nodes will be affected. - If the hub node goes down, the entire network will suffer degraded performance or complete failure.
Tree network	- Combination of two or more star networks - It works well when CO_2 source nodes are in groups. - It is easy to add or remove CO_2 emission source nodes from each star network. - A hierarchical form
Backbone network	- A part of a network infrastructure that interconnects various pieces of network. - A backbone is a larger transmission line that carries CO_2 gathered from the smaller lines. - At the local level, a backbone is a line or set of lines that local area networks connect to for a wide area network connection, or within a local area network to span distances efficiently

As Fig. 3 shows the connectivity of whole CO_2 emission source nodes around hub node.



(a) Star network (b) Tree network



(c)Backbone network

Fig. 3. Network topologies of the pipeline connection

The purpose of this study is not solely to minimize the overall network connection costs which are trade-off between the connection cost to the CCS systems and the penalty cost, but also to maximize the throughput (total amount of CO_2) by the CCS systems.

4. SIMULATION RESULTS

4.1 Data set

CO_2 storage facility costs are composed of lots of cost factors such as capital cost (fixed cost) for storage facilities, unit storage cost (operating cost), CO_2 collection cost, and etc. To calculate the cost of intermediate storage hubs, we consider the storage capital costs and CO_2 unit storage costs shown in Table 5.

Table 5. Capital and unit storage costs of CO_2 storage facilities [17]

	Storage facility (steel tank)
Storage capital cost($)	10,228,607
Unit storage cost ($/t CO_2)	0.72

We use Korea as a case study example. Table 6 shows the number of plants by regional groups, plant types, and the amount of emitted CO_2.

Table 6. The number of capture facilities in each administrative district and the amount of CO_2 emissions

Region	Capture Plant type	Number of plants	CO_2 emission (kton/y)	Region	Capture plant type	Number of plants	CO_2 emission (kton/y)
Seoul	A	1	620	Gyeong sangbukdo	A	2	1863
Incheon	A	7	23481		B	4	12261
	B	2	616	Daegu	A	2	2179
	C	1	7870	Busan	A	4	3537
Gyeong gido	A	7	5744		B	1	112
Chung cheongnamdo	A	11	119622	Ulsan	A	2	4257
	C	1	2986		C	1	4817
	D	3	2760		D	8	5441
Chung cheongbukdo	D	5	16008	Jeollanamdo	A	7	21506
Gangwondo	A	5	8405		C	1	6103
	D	6	27719		D	3	2601
Gyeong sangnamdo	A	1	29539	Jeollabukdo	A	3	2576

* Plant type
A: Power plant facility / B: Iron and steel plant facility
C: Oil refinery plant facility/ D: Petrochemical plant facility

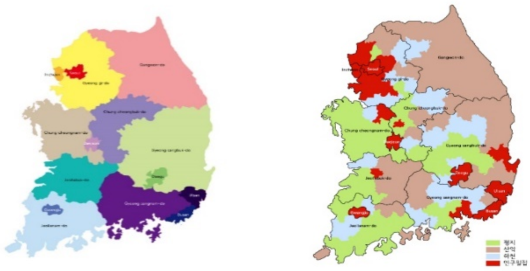
The areas of the CO_2 emission sources are estimated using a variety of terrain conditions identified by the U.S. National Energy Technology Laboratory (NETL). We classify the conditions such as mountainous, flat, river, and high population in which those are obtained by the nine categories established by NETL.

Table 7. Terrain factors

Feature	Value		Feature	Value
Waterways	10		Wetlands	15
Highway	3		Urban	15
Railroad	3		Slope	0.1-0.8
State Parks	15		Base	1
National Parks	30			

The terrain factors affect pipeline design and cost multipliers. In this case study, Korea is divided into 13 cities and provinces according to the administrative district to define the industry groups and the amounts of CO_2 they emit. Fig. 5 shows the visualization of the district and the land use in Korea case. Each district is included in one of the conditions in Table 7.

Researchers determine the locations and the number of the candidate hub nodes beforehand considering the circumstance and geological factors or other policies; the number of candidate hub nodes is assumed to be 25% (22 nodes) of the total number of CO_2 emission source nodes (88 nodes). The distribution of each node is shown in Fig. 5(c). Green circles are CO_2 emission source nodes and yellow circles are candidate hub nodes.



(a) Cities and provinces of Korea (b) Land use in Korea

(c) Distribution of CO_2 emission sources

Fig. 5. Classification of the territory using the simulator

4.2 Factor analysis

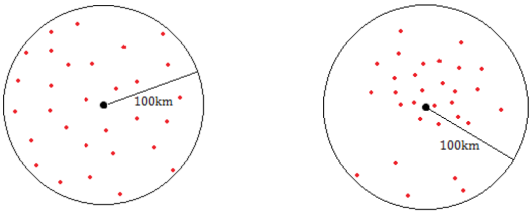
McCollum and Ogden [3] studied the relationships between pipeline length, CO_2 mass flow rate, and pipeline diameter for six cost estimation models (in Table 3). The cost is affected by the distance and the emitted amount of CO_2.

Therefore, we investigate the causal relationship and the factors which influence how the distribution of CO_2 emission source nodes in the cluster is affected by the network topologies of the pipeline connection. The factors in the experimental design are shown in Table 7.

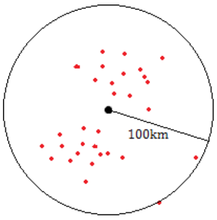
Table 7. Factors in the experimental design

Radius of cluster (km)	100km / 200km / 300km
State of CO_2	Supercritical state High density liquid state Low temperature liquid state
Network topology	Star network Tree network Backbone network
Node distribution	Random distribution One-biased distribution Two-biased distribution
Pipeline cost estimation model	Ogden model / MIT model Ecofys model / IEA GHG PH4/6 IEA GHG 2005/2 / IEA GHG 2005/3

The factors, which affect the costs while increasing the cluster's radius, are the state of the CO_2 being transported and the pipeline connection network topologies. An example is shown in Fig. 6.



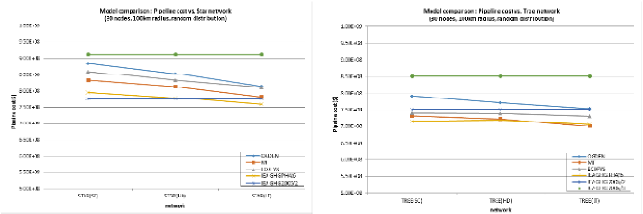
(a) Random distribution (b) One-biased distribution



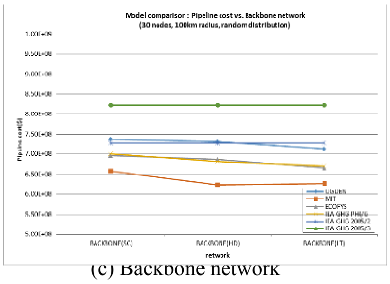
(c) Two-biased distribution

Fig. 6. Examples of experimental designs: source node distribution

The graphs in Fig. 7 describe the relationship between network topologies and the six pipeline cost models assuming 100km radius.



(a) Star network (b) Tree network



(c) Backbone network

Fig. 7. Model comparisons of pipeline and network topology: 100 km radius

Within a 100 km transport, the case of the supercritical state of CO_2 is the highest cost for all the network topologies and, conversely, the cost for the low temperature liquid state of CO_2 is the lowest. This is an important point because pressure drop is significant factor and it is strongly affected by the state of transported CO_2. Consequently, a low temperature state of liquid CO_2 is cost-effective within a 100km length of pipelines.

We extend the length of pipeline to the 300 km to compare the result with 100km cases. The result is shown in Fig. 8. The longer the distance of CO_2 transport via pipelines, the more efficient the transportation of supercritical CO_2 compared with the other states of CO_2. The results for the other five pipeline cost estimation models are the same.

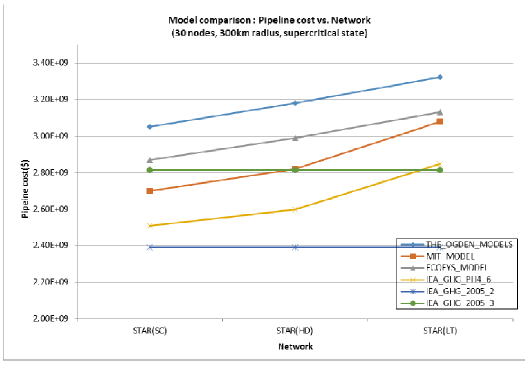
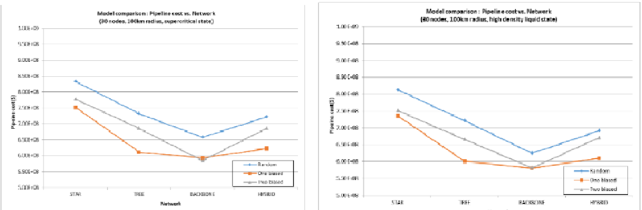


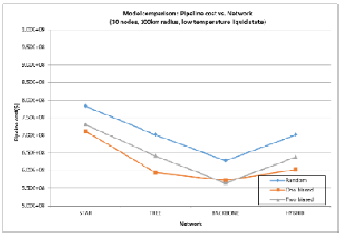
Fig. 8. Model comparison of pipeline and network topologies: 300km radius

In order to examine the effect of the network topologies and the source node distributions, the Ogden model is considered to estimate pipeline cost where the state of CO_2 is not changed in each case. Fig. 9 illustrates that pipeline cost in accordance with the different state of CO_2 shows a similar tendency and the lowest cost occurs in the case of the backbone network connection, although the source node distributions are different.



(a) Pipeline cost vs. Network: supercritical state of CO_2

(b) Pipeline cost vs. Network: high density liquid state of CO_2

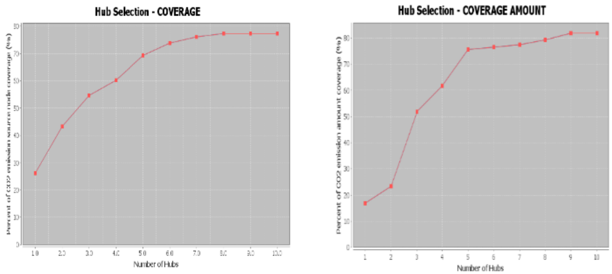


(c) Pipeline cost vs. Network: low temperature liquid state of CO_2

Fig. 9. Model comparison of pipeline and network topologies regarding the state of CO_2

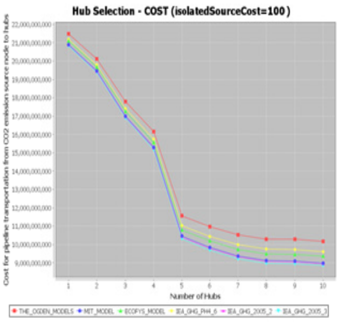
4.3 Hub selection

Lee [11] proposed a heuristic algorithm to determine the number of hubs and their locations. Fig. 10 provides the three graphs which illustrate the percentage of covered source nods, covered amount of CO_2 and the pipeline transportation cost derived from Lee's algorithm [11]. It is assumed that Ogden's pipeline model is used to calculate pipeline transportation cost. Fig. 10(a) shows the rate of the included number of CO_2 emission source nodes in the hub nodes when we increase the number of hubs. As the aim of this study is to use hub nodes to maximize coverage rates, we calculate the number of nodes every time by the increase in the number of hubs. We assume that the connected rate for the source nodes is more than 75%. This proportion value can be set based on the problem, to be determined by the researcher. In Fig. 10(a), when the number of hubs is set to more than 7, the coverage rate exceeds about 75% of the total. Thus, the minimum number of hub nodes can be set to 7. Likewise, Fig. 10(b) shows the amount of emitted CO_2 covered by the hub nodes and Fig. 10(c) reveals how the total cost changes as we increase the number of hubs.



(a) Percentage of covered nodes

(b) Percentage of covered amount of CO_2



(c) Pipeline transportation cost

Fig. 10. Coverage rates of CO_2 emission source nodes

The results reported in Fig. 11 suggest that the number of hubs giving a relatively small cost value and satisfying the three conditions described above is 8. As the pipeline costs are only calculated when the CO_2 emission source nodes are included in the hubs, we assume that the disconnected CO_2 emission source nodes generate a penalty cost (emission cost) proportional to the amount of emitted CO_2 per ton. We assume the penalty cost to be $100 per ton.

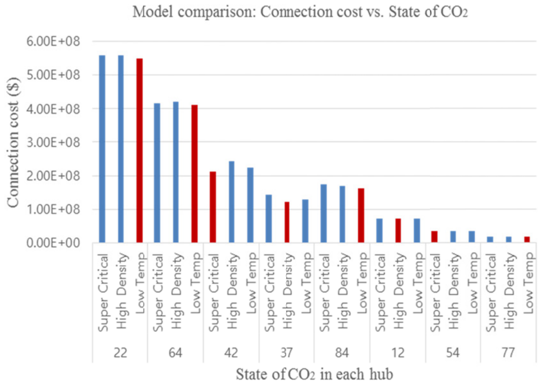


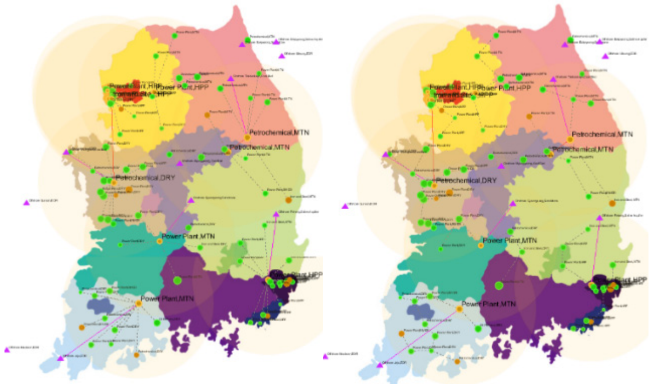
Fig. 11. Connection cost vs. state of CO_2

Table 8. Result for the state of CO_2 of each hub

Hub ID	State of CO_2
22	Low Temp
64	Low Temp
42	Super Critical
37	High Density
84	Low Temp
12	High Density
54	Low Temp
77	Low Temp

Although there is a connection between the variations in cost based on the distance from CO_2 emission source nodes to hub nodes, the distribution of the source nodes, and the amount of CO_2 transported, the transport of CO_2 in the low temperature state is largely cost-effective. One of the reasons for this result is that the maximum radius of the hub cluster assumed in the problem is 150 km. Thus, the shorter the length of the pipeline connection, the relatively lower the cost of CO_2 transport in its low temperature liquid state. It is expected that when the length of the pipeline between nodes is comparatively long, such as in the United States and China, this approach will have important implications.

Fig. 12 illustrates a linkage maps of all the nodes, connected via a cost analysis hub determined by the parameters with the assumptions. Most of the cost factors using in the paper which consist total cost of CO_2 pipeline transportation are assumed to estimate and compare the effect of properties. For the sake of uncertainty, the visualizations of three network connections using Lee's simulator [11] are proposed as in Fig. 12(a)-(c) instead of optimizing the cost model.



(a) Star network (b) Tree network

(c) Backbone network

Fig. 12: Linkage map of pipeline connection network

5. CONCLUSION

CCS is a technology for capturing, transporting, and storing/sequestrating emitted CO_2 from fuel combustion at some isolated site. A significant amount of research has focused on the infrastructural technologies involved in each step of this process. Although some empirical studies have integrated these steps, the literature remains insufficient.

Previous studies have focused on pipeline design parameters, which can influence the cost of designing CO_2 pipeline cost estimation models based on the various problems' definitions and assumptions. In this study, we focused on not only pipeline cost models, but also the connectivity of the pipeline networks from CO_2 emission source sites to the sequestration plants. Thus, when applying the conditions assumed for this study, we considered how these assumptions affected the CO_2 pipeline cost estimation models. These conditions are the state of the CO_2 being transported, the distribution of the CO_2 emission sources, and the network connectivity.

The purpose of this study was to provide a network configuration to minimize the cost of pipeline network design while increasing the overall use of the CCS system. A heuristic algorithm for placing the intermediate storage hub was proposed. This was not only cost efficient for transporting CO_2 to the sequestration plant located on the coast, but was also a realistic algorithm, especially for the inland provinces. Thus, we proposed an algorithm to determine the number and positions of hubs. We developed a simulator for the decision-making process involved in determining the locations and number of hubs. It also handled how the parameters worked within the program and provided an informatics analysis.

REFERENCES

[1] B. J. Kang, *Economic Analysis & Optimization of Carbon Capture Storage Pipeline Transport Network System*, Ph.D. Thesis, Seoul National university, Seoul, Republic of Korea, 2012.

[2] C. B. Farris, "Unusual design factors for supercritical CO2 pipelines," Energy Progress, Vol. 3, 1983, pp. 150-158.

[3] D. L. McCollum and J. M. Ogden, *Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage and Correlations for Estimating Carbon Dioxide Density and Viscosity*, Institute of Transportation Studies, University of California, Davis, 2006.

[4] Zhang Dongjiea, Wang Zhea, Sun Jiningb, Zhang Lilic, and Li Zhenga, "Economic evaluation of CO2 pipeline transport in China," Energy Conversion and Management, vol. 55, 2012, pp. 127-135.

[5] E. S. Rubin, "IPCC special report on carbon dioxide capture and storage," RITE international workshop on CO_2 geological storage, 2006.

[6] E. S. Rubin, "Understanding the pitfalls of CCS cost estimates," International Journal of Greenhouse Gas Control, vol. 10, 2012, pp. 181-190.

[7] G. H. Heddle, H. J. Herzog, and M. Klett, "The economics of CO_2 storage," MIT LFEE 2003-003 RP, 2003.

[8] International Energy Agency, World Energy Outlook 2009, 2009, pp. 10-19.

[9] J. H. Han and I. B. Lee, "Development of a scalable infrastructure model for planning electricity generation and CO2 mitigation strategies under mandated reduction of GHG emission," Applied Energy, vol. 88, 2011, pp. 5056-5068.

[10] J. H. Han, Y. C. Ahn, and I. B. Lee, "A multi-objective optimization model for sustainable electricity generation and CO_2 mitigation (EGCM) infrastructure design considering economic profit and financial risk," Applied Energy, vol. 95, 2012, pp. 186-195.

[11] Ji-Yong Lee, "Development of a Simulator for the Intermediate Storage Hub Selection Modeling and Visualization of Carbon Dioxide Transport Using a

Pipeline," Journal of the Korea Contents Association, vol. 16, no. 12, 2016.

[12] J. R. MacFarland and H. J. Herzog, "Incorporating carbon capture and storage technologies in integrated assessment models," Energy Economics, vol. 28, 2006, pp. 632-652.

[13] J. U. Lee, J. H. Han, and I. B. Lee, "A multiobjective optimization approach for CCS infrastructure considering cost and environmental impact," I&EC, vol. 51, 2012, pp. 14145-14157.

[14] S. T. McCoy, *The economics of CO_2 transport by pipeline and storage in saline aquifers and oil reservoirs*, Ph.D. Thesis, Carnegie Mellon University, Pittsburgh, 2008.

[15] Michael Nimtz, Matthias Klatt, Bernd Wiese, Michael K¨uhn, and Hans Joachim Krautz, "Modelling of the CO_2 process- and transport chain in CCS systems-Examination of transport and storage processes," Chemie der Erde Geochemistry journal, vol. 70, suppl. 3, 2010, pp. 185-192.

[16] M. M. J. Knoope, W. Guijt, A. Ramirez, and A. P. C. Faaij, "Improved cost models for optimizing CO_2 pipeline configuration for point-to-point pipelines and simple networks," International Journal of Greenhouse Gas Control, vol. 22, 2014, pp. 25-46.

[17] Rickard Svenssona, Mikael Odenbergera, Filip Johnssona, and Lars Strömberg, "Transportation systems for CO2 application to carbon capture and storage," Energy Convention and Management, vol. 45, no. 15-16, 2004, pp. 2343-2353.

[18] Z. X. Zhang, G. X. Wang, P. Massarotto, and V. Rudolph, "Optimization of pipeline transport for CO_2 sequestration," Energy Conversion and Management, vol. 47, 2006, pp. 702-715.

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