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Optimization of Network Carbon Capture and Storage System (CCS) Using Mathematical Approach

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Abstract

Carbon capture and storage (CCS) is one of the technologies to reduce greenhouse gas emissions (GHG) to capture of CO_2 from the flue gas of a power plant that typically use coal as a Source of energy and then store it in a suitable geological storage (in specific locations). In practice, these sites may not be readily available for storage at the same time that the Sources (GHG producing) are operating which gives rise to multi – period planning problems. This study presents a mathematical approach by considering constraints limit flowrate received by Sink, various time availability of Sink and Source and calculation with the purpose to determine the minimum cost network which is getting the maximum load that is exchanged from Source to Sink. Illustrative case studies are given to demonstrate the application of mathematical models to obtained with the exact result of the exchange network from Source to Sink. Derived from network obtained from the calculation of the Maximum Load Source to Sink and results may vary in accordance with the limitations that exist in the mathematical model. The case study has been prepared with 2 cases, first 6 Source and 3 Sink with value of Source Load is greater than the amount available on the Sink. Also, second case is 2 Source and 5 Sink with value of Source Load is smaller than the amount available on the Sink. In addition, Case Studies to minimize the cost of pipeline construction and distribution of CO_2 by plant and storage location determination in Java. Flowrate restriction factor that goes into Sink, Source and Sink establishment time and cost are taken into account can affect the networks that can be exchanged from the Source to the Sink.

Keywords: carbon capture and storage system, mathematical approcah, source-sink, optimization, carbon capture

1. Introduction

1.1 Introduce the Problem

Today the issue of global warming is getting warm to talk about. Over the last few years, all human activity is causing the greenhouse effect is increasing. Carbondioxide (CO_2) is one component in the amount of greenhouse gases in the atmosphere at most. The industrial sectoris the largest contributor to carbon emissions. One of the possible solutions is to use carbon capture and storage technology system (CCS). The concept of CCS in general is the reduction of emissions from large industrial sources by capturing the CO_2 from the exhaust gases and subsequently storing it in appropriate geological storage sites. The storage sites may be depleted oil and gas fields, saline acquifers, coal seams and other similar formations (Davison et al., 2001; Pires et al., 2011).

The International Energy Agency (IEA) has indicated that to reach a target emissions level of 14 Gt/y by 2050, CCS will have to contribute 19% of the reductions (approximately 9 Gt/y of CO_2 reductions out of 48 Gt/y) (IEA, 2010). Geological reservoirs worldwide have been evaluated and it is estimated that there is a potential storage capacity of 236 Gt of CO_2, or approximately three decades of storage (Strangleand 2007).

In practice, these sites may not be readily available for storage at the same time or when the source operates before operating sources which gives rise to multi-period planning problems. At the same time the Source and Sink can be grouped geographically to minimize the need (cost) for CO_2transport over long distances.

1.2 Recent Research

Lately, optimal planning for CO_2 transport infrastructure to match the flow source, such as power plants and industrial facilities with proper Sink or storage sites, is recognized as an important prerequisite for successful commercialization of CCS (Brunsvold et al., 2011). Similar work has also been done in the United States (Ambrose, et al., 2009) and developing countries such as China and India (Condor et al., 2011). At the same time, other researchers have attempted to develop a model to provide decision support for matching Source - Sink CO_2. For example, Turk et al. (1987) did early attempts to model the optimal matching Source - Sink CO_2 for EOR purposes using integer linear programming model of the pure.

More recently, a heuristic algorithm for the design of CCS pipeline proposed by Kazmierczak et al. (2009). This recursive approach allows for a gradual adjustment of the capacity of the network from time to time, but do not involve direct optimization. Middleton and Bielicki (2009) developed a model SimCCS, which uses a mixed integer linear programming (MILP) formulation which combines the decisions about infrastructure characteristics (eg, size of pipe) in a static framework. Pekala et al., (2010) describes the planning model based on the optimal energy. Diamante et al., (2013) and Tan et al., (2013) describes unification-based model injectivity with a multi-period approach presented in. In all pinch analysis approach, the quantity and quality of the sources and the sinks are determined first.

1.3 Purpose of this Study

In this work, a simple model of programming algorithm with mathematical approach was developed to optimization models for matching Source - Sink temporal periods, the level of injectivity, and storage capacity constraints. This model requires data to be determined for both the CO_2 source (ie: rate of CO_2 from power plants with carbon capture (CC) and the start time of operation) and Sink (ie: CO_2 storage capacity, injection rate limit (absorption) of CO_2, and the time availability). By using the data input, this model can automatically determine the allocation of CO_2 networks by maximizing the amount of CO_2 that is captured and stored in the system that has been granted. The objective is to determine the minimum amount of unutilized CO_2 storage capacity by matching CO_2 sources and sinks, given these specified temporal and physical constraints. This is also equivalent to maximizing total CO_2 captured and stored with hope for the future, this model can be used for planning of CCS in Indonesia.

2. Method

The In this work, developed a mathematical approach to optimization models matching Source - Sink in the temporal period, the level of injectivity, and storage capacity constraints. This model requires data specified for both the CO_2 source (ie: rate of CO_2 from power plants with carbon capture (CC) and the start time of operation) and Sink (ie: CO_2 storage capacity, injection rate limit (absorption) of CO_2, and time availability). By using the data input, this model can automatically determine the network allocation to maximize the amount of CO_2 captured and stored in the system that has been given. Description of the details on the model details will be given in the following section.

3. Results

Objective function on this issue is the maximum value of the total load that can be exchanged from Source to Sink in the system. Defined as follows:

$$max \sum_i Source\ i$$

$$Source\ i = \sum_j (t_{ij\ end} - t_{ij\ start}) * S_{ij} * b_{ij} \qquad \forall i,j \tag{1}$$

Where i is the number of Source and j is the amount Sink contained in the existing system. $T_{ij\ end}$ is the expiration of the Source and Sink in particular simultaneously so that the load is on Source stops distributed at the end of the year. For $T_{ij\ start}$ itself was started in a certain time of the Source and Sink simultaneously so that the existing load on the source can be distributed to the Sink. S_{ij} is the large flowrate of Source that will fit into Sink and matched with the injectivity Sink receptions on build up distribution. b_{ij} are the parameters of the exchange of Source and Sink are assumed to have a value of 1 if source can be exchanged with Sink j and is 0 if the source is not interchangeable with Sink j. As for the source i is the amount of load that is exchanged from source i to one destination Sink.

$$\sum_i (t_{ij\ end} - t_{ij\ start}) * S_{ij} * b_{ij} \leq S_j * (t_{j\ end} - t_j) \qquad \forall i,j \tag{2}$$

S_j is the injectivity of CO_2 that can be accepted by Sink j or can be called flowrate limits that go into storage (Sink) are available in the system. S_j value is the maximum value of CO_2 flowrate acceptable so flowrate entering into Sink j must be less than or equal to the flowrate limits available. $t_{j\ end}$ is the end of the their time Sink j and $t_j$is the time of the beginning of their Sink j available. Flowrate of Source that goes into Sink should not exceed the limits specified injectivity and also right in that allowed for the distribution.

$$\sum_j b_{ij} \leq 1 \qquad \forall i,j \qquad (3)$$

b_{ij} are the parameters of the exchange of Source and Sink. Assumed value b_{ij} only 0and 1. Equal to 0 when the source i is not interchangeable with Sink j. While the value of 1 means the Source i can be exchanged with Sinkj. The value of this parameter should not be more than 1 when the Source i. It is intended Source i only can be distributed to one of the existing j Sink or can not be divided or broken because when shared will add to the total cost to manufacture the piping network between Source and Sink.

$$t_{ij\,start} \geq t_j \qquad \forall i,j \qquad (4)$$

$T_{ij\,start}$ is the start time of the year so many of Source and Sink simultaneously so that the existing load on the source can be distributed to the Sink. $T_{ij\,start}$ value of more than or equal to the start time of the construction of a storage or Sink j.

$$t_{ij\,start} \geq t_i \qquad \forall i,j \qquad (5)$$

$T_{ij\,start}$ value of more than or equal to the start time of the construction of a plant producing CO_2 or Source i. This means that T_{ij} worth between or equal to t_i or t_j, taken years to so many of the greatest (both pass throughthe year). For example, if t_i is equal to the value 0 and t_j is equal to the 5th year, the T_{ij} optimum for the 5th years in since t_i also pass through the 5th year, while new t_j starting in year 5.

$$t_{ij\,end} \leq t_{j\,end} \qquad \forall i,j \qquad (6)$$

$T_{ij\,end}$ is the end time of they year so many of Source and Sink simultaneously so that the CO_2 is in the Source can stop distributed because of the age of existing storage. $T_{ij\,end}$ value of less than or equal to the expiration of a storage or Sink j.

$$t_{ij\,end} \leq t_{i\,end} \qquad \forall i,j \qquad (7)$$

$T_{ij\,end}$ value of less than or equal to the time of the end of the completion of a plant producing CO_2 or Source i. This means that the end T_{ij} worth between or equal to t_i or t_j, taken so many years to the smallest (both pass through the year). For example, if the value is equal to $t_{i\,end}$ to the year-end 30 and t_j is equal to the 50^{th} (if the start of the same year 0) then t_{ijend} optimum lies in the 30th year since t_j also passed the 30th year, while t_i ended in 30th year and it was not until the 50th.

$$S_{ij} \leq S_j \qquad \forall i,j \qquad (8)$$

S_{ij} is a large amount of CO_2 flowrate distributed from the Source and Sink. S_{ij} value of less than or equal to limit CO_2 injectivity of Source that goes into Sink j.

$$S_{ij} \leq S_i \qquad \forall i,j \qquad (9)$$

S_{ij} value of less than or equal to the flowrate of CO_2 at a plant producing CO_2 or Source i. This means that S_{ij} worth between or equal to S_j or S_i, taken large flowrate is the smallest that can be entered into the storage (flowrate magnitude does not exceed a predetermined). For example, if the value of S_i equal to10 Mt/year and S_j is equal to 5 Mt/year of the S_i optimum that can be exchanged at 5 Mt/year because of restrictions flowrate entering into Sink j at 5Mt/year.

$$\sum_i S_{ij} * b_{ij} \leq S_j \qquad \forall i,j \qquad (10)$$

The value of the amount of CO_2 that can be distributed flowrate from various source i to the Sink j (S_{ij}) is less than or equal to the value of the injectivity of CO_2 that can be accepted by Sink j. This means that the CO_2 Sink j can receive in accordance with the restrictions set to get in on the j Sink. For example, if the Source 1 produces CO_2 of 5 Mt/year and Source 2 produces CO_2 of 3 Mt/year in the same year. Then Sink 1has a limit incoming flowrate of 10 Mt/year in the same year as the source, then the CO_2 from the Source 1 and Source 2 can be accommodated by Sink 1 because the value of the Source 1 and Source 2 is less than the limits acceptance CO_2 flowrate at Sink 1.

$$\left(t_{ij\,end} - t_{ij\,start}\right) \geq t^{min} * b_{ij} \qquad \forall i,j \qquad (11)$$

The distance in between $T_{ij\,end}$ or the expiration of the distribution of CO_2 from Source to Sink with $T_{ij\,start}$ or the initiation of distribution Source to Sink must be greater than t^{min} with b_{ij} factors. t^{min} is the minimum time given distance. In this case t^{min} used is equal to 0 so that the distance $T_{ij\,end}$ and$T_{ij\,start}$ must be greater than 0. Not the same as possible if the distance is worth less than 0 or negative.

For the analysis of cost calculation, its objective function changed as follows:

$$min \sum_i Source\ i$$

$$Source\ i = \sum_j \left(\left(t_{ij\,end} - t_{ij\,start} \right) * S_{ij} * capture\ cost + distance_{ij} * pipeline\ cost \right) * b_{ij} \vee i,j \quad (12)$$

With capture cost equals with $/Mt$_{captured}$. Added to the price of pipeline being built between the Source and Sink are available (pipeline cost equals with $/km). And added the correction factor:

$$\sum_i \sum_j b_{ij} \geq 1 \qquad \vee i,j \quad (13)$$

$$\sum_i \sum_j b_{ij} \leq smax \quad \vee i,j \quad (14)$$

Where smax isthe total number of available source. The results obtained later is the maximum flowrate or large objective function that can be distributed from Source to Sink at the appropriate time. Also obtained the most optimal network in the distribution Source Sink i to j so that it can be made after the grid diagram of the system.

To use the model above, use the following assumptions:

1. CCS system consists of m Source CO_2 and n Sink CO_2. Source and Sink can begin to operate at any time in the planning.
2. Each i Source CO_2 (i=1,2,...,m) is characterized by CO_2 capture flowrate corresponding to the maximum potential of the exhaust gas removal plant. In addition, the operation of each source i, also defined.
3. Each j Sink CO_2 (i=1,2,...,n) is characterized by the upper limit for CO_2 storage capacity, the maximum rate at which CO_2 can be injected into any given Sink. Both of these characteristics are based on the geological characteristics of the storage site.
4. Source and Sink located in one geographical area.

The modelis implemented using commercial modeling software Lingo14.0 using a PC with a 1.7 GHz processor and 4 GB of RAM. In both cases, the solution found ignores time simulation process.

4. Discussion

For the implementation of this model, is used as a case study follows (taken by Lee et al., 2014):

Table 1. Source Data

Source	CO_2*flowrate* (Mt/y)	CO_2*Load* (Mt)	*Start Time* (y)	*End Time* (y)
1	4	120	0	30
2	5	200	0	40
3	2.5	62.5	5	30
4	8	240	10	40
5	5	200	0	40
6	3	120	10	50
Total		942.5		

Table 2. Sink Data

Sink	*Injectivity (Mt/y)*	*StorageCapacity* (Mt)	*Earliest time available* (y)
1	5	200	0
2	10	400	10
3	10	250	15
Total		850	

Figure 1 illustrates all the possibilities of the distribution of CO_2 from Source to Sink there. All probability is the Source 1 can be distributed to Sink 1, Sink 2, and Sink 3, as well as others. Determination of the maximum that can be distributed based on the mathematical model in the form of constraints that have been described above.

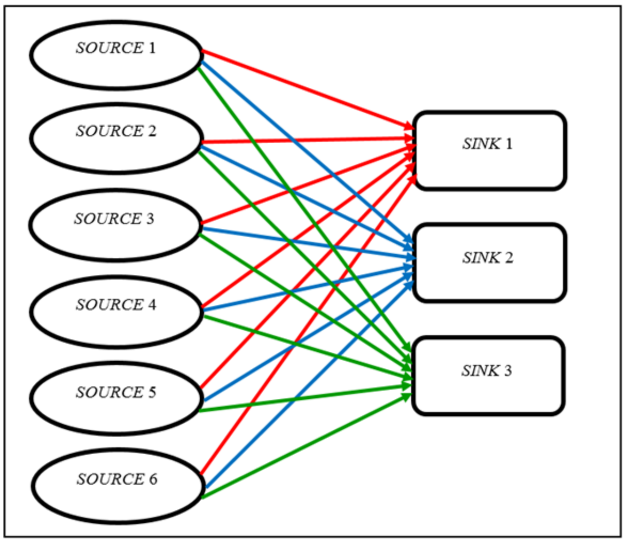

Figure 1. All possible distribution of CO_2

From the simulation results, obtained from objective function or the maximum load that can be exchanged is at 670 Mt, or 71.09% of the total generated source. Sink 1 can receive CO_2 from Source 5 of 200 Mt, so storage is not trace or fully charged. Source 5 has a flowrate of CO_2 that will be incorporated into the Sink by 5 Mt/year while the Sink 1 has a limited CO_2 injection at 5 Mt/year, so that the CO_2 out of 5 Source distributed into Sink Sink 1. While Sink 2 may receive CO_2 from Source 2 and Source 6 as much as 150 Mt and 120 Mt so the rest of this storage is at 130 Mt. Source 2 has a flowrate of CO_2 that will be injected into the Sink by 5 Mt/year while CO_2 flowrate in Source 6 have to be incorporated into the Sink by 3 Mt/year.Sink 2 has a limitation of CO_2 that goes by 10 Mt/year so that the CO_2 out of the Source 2 and Source 6 is distributed into Sink 2 because it meets the limits of CO_2 that goes in Sink 2. Sink 3 can receive the CO_2 from the Source 4 of 200 Mt and the rest of this storage is at 50 Mt.Source 4 has a flowrate of CO_2 that will be incorporated into the Sink of 8 Mt/year while Sink 3 have limitations diinjekkan CO_2 by 10 Mt/year so that the CO_2 out of the Source 4 distributed into Sink 3. The result is the most optimal results for distribution according to the CO_2 flowrate out of Source i and CO_2 acceptance limits specified in the Sink j at time availability of Source and Sink simultaneously.

The above interpretation of the model Source 1 can not be accommodated. So also with the Source 3. This is caused because of the limits set for the entry of CO_2 Sink, thus the Sink can not receive all of the CO_2 that comes from Source despite existing storage remains. Source 2 and Source 4 can not be accommodated on the existing Sink. Source 2 in year 0 to year 10, the CO_2 from the plant can not be accommodated in storage because in the Sink 2 began in the 10th year. For Source 4 in year 10 to year 15, CO_2 can not be accommodated in the storage / Sink 3 because in that year Sink 3 has not been in operation and Sink 3 only can be used on its 15th year. So that the network according to this study is the Source 2 distributed to Sink 2, Source 4 to Sink 3, Source 5 to Sink 1, and Source 6 to Sink 2. The simulation results can be represented in the grid diagram as follows:

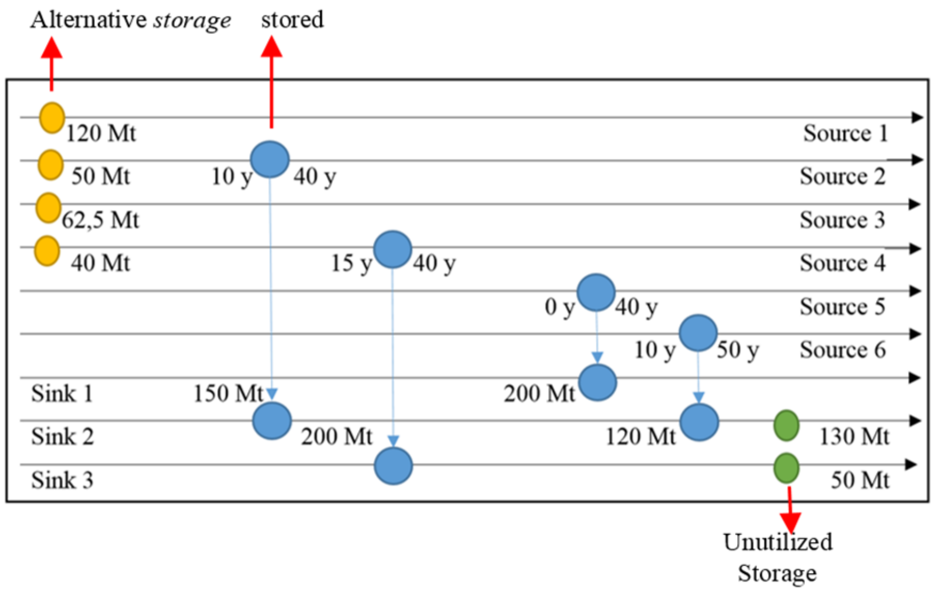

Figure 2. Grid diagram for optimal Source-Sink matching in case above

As for the implementation of cost calculation, added data in table.3. In this study, taken on site layout Sink, Sink 2, and Sink 3 respectively, Purbalingga (Central Java), Blora (Central Java), and Garut (West Java).

Table 3. Approximate Distance from Source-Sink

Source	Rate (Mt/y)	Source Name	Distance (km)	
1	4	PJB UP Muara Karang	*Sink* 1	318.03
			Sink 2	521.39
			Sink 3	174.92
2	5	Semen Gresik (Tuban)	*Sink* 1	281.25
			Sink 2	55.42
			Sink 3	443.71
3	2.5	Chandra Asri	*Sink* 1	400.02
			Sink 2	605.58
			Sink 3	248.72
4	8	PJB UP Paiton	*Sink* 1	453.6
			Sink 2	243.9
			Sink 3	618.9
5	5	PJB UP Gresik	*Sink* 1	359.96
			Sink 2	138.38
			Sink 3	525.22
6	3	Pertamina blok Cepu	*Sink* 1	309.37
			Sink 2	515.08
			Sink 3	165.69

From the simulation results, obtained from objective function or minimum cost for the construction of piping between the Source and Sink that can be exchanged is for \$ 9,509,656 (taking assume capture cost equals \$14.55 \$/$Mt_{captured}$ and pipeline cost equals with 3100\$/km distance) with load exchanged for 650Mt or 68.97% of the total generated source.Sink 1can receive CO_2 from the Source 4 as much as 150 Mt, so this storage remaining 50 Mt. Source 4 has a flowrate of CO_2 thatwill be incorporated into the Sink of 8 Mt/year while the Sink 1 has a CO_2 injection limit at 5 Mt/year so that the CO_2 out of the Source 4 distributed into Sink 1 of 5 Mt/year and 3 Mt/year CO_2 at Source 4 can not captured or wasted. While the Sink 2 can receive CO_2 from the Source 1, Source 3 and Source 6 respectively, 80 Mt, 50 Mt and 120 Mt so the rest of this storage is at 150Mt. Source 1 has a flowrate of CO_2 that will be included in the Sink by 4 Mt/year, Source 3 of 2.5 Mt/year, while the CO_2 flowrate in Source 6 have to be put in the Sink by 3Mt/year. Sink 2 has a limitation of CO_2 that goes in by 10 Mt/year so that the CO_2 out of the Source 1, Source 3, and Source 6 distributed into Sink 2 because it meets the incoming CO_2 limits in Sink 2. Sink 3 can receive CO_2 from Source 2 and Source 5 respectively of 125 Mt and storage does not have the rest of storage. Source 2 has a flowrate of CO_2 that will be incorporated into the Sink by 5Mt/year. Likewise with Source 5. While Sink 3 have a CO_2 injection limitations by 10 Mt/year so that the CO_2 out of the Source 2 and Source 5 distributed into Sink 3. These results are the most optimal results for distribution in accordance with the flowrate of CO_2 out of the Source i and CO_2 acceptance limits specified in the Sink j at time availability of Source and Sink simultaneously, also with the most minimal cost calculation for the construction of pipelines from source i to sink j.

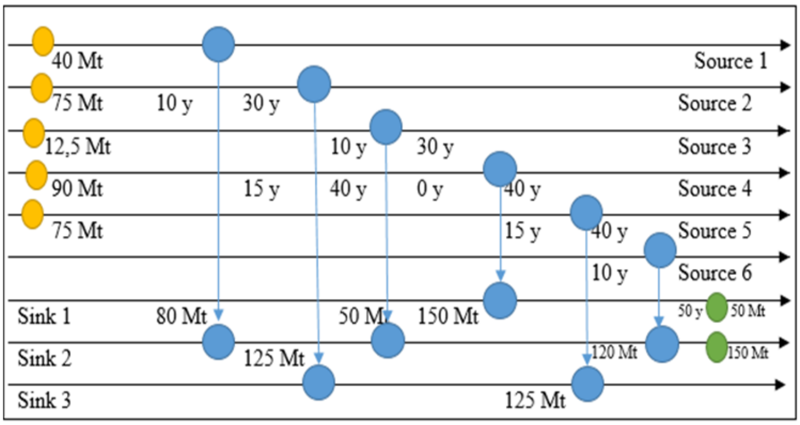

Figure 3. Grid diagram for optimal cost in Source-Sink matching

From the above interpretation of the model all Source (Source 1, 2, 3, 4 and 5) can not be accommodated on the existing Sink. Source 1 in year 0 to year 10, the CO_2 from the plant can not be accommodated in storage because in the Sink 2 began in the 10th year. Source 2 in year 0 to year 15, the CO_2 from the plant can not be accommodated in storage because in the Sink 3 began in the 15th. Source 3 in year 5 to year 10, the CO_2 from the plant can not be accommodated in storage because in the Sink 2 began in the 10th year. As for Source 4, CO_2 from the plant can not be accommodated fully into storage because flowrate constraints into the Sink 1 is at 5 Mt/year and large flowrate CO_2 out of the Source 4 is equal to 8 Mt/year so that entry into Sink 1 is at 5 Mt/year and 3 Mt/year discarded. Source 5 in year 0 to year 15, CO_2 can not be accommodated in the Sink 3 because in that year Sink Sink 3 has not been in operation and 3 can be used on its 15th year. So that the network according to this study is the Source 1 distributed to Sink 2, Source 2 to 3 Sink, Source 3 to Sink 2, Source 4 to Sink 1, Source 5 to Sink 3 and Source 6 to Sink 2. In this optimization, mathematical model and the constraint set is affecting the results obtained. Likewise with known data also affect the results obtained. Network modeling obtained at each different from one another due to differences in the specified constraints. For modeling 1is influenced by the limits of CO_2 flowrate into the Sink and Sink end time of the operation. And for modeling 2, network distribution of CO_2 from Source to Sink influenced by the minimum cost results obtained in the development of existing piping.Thus can be concluded a simple model has been developed for optimal matching of Source and Sink CO_2 in CCS systems are limited by the temporal period, the rate of injectivity, and storage capacity constraints. Two illustrative case studies have been completed and resulted in exchange efficiency of 71.09% and 68.97%. Matching generated from this model can be changed if the variable costs are taken into account.

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