Carbon Capture and Storage (CCS) Network Planning Based on Cost Analysis Using Superstructure Method in Indonesian Central Region

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Abstract. Today global warming is a serious threat to living things and the earth, according to WMO, 2019 is the second hottest year after 2016. The average temperature for the last 10 years has reached its highest point. CCS technology is a series of activities that start from capturing \( \text{CO}_2 \) from sources of \( \text{CO}_2 \) emissions, namely the industrial sector and electricity generation. After being captured, \( \text{CO}_2 \) is transported through pipelines or ships to the \( \text{CO}_2 \) storage location in the appropriate storage, it can be geological or ocean storage. Each CCS project will use the most suitable method to transport \( \text{CO}_2 \) and pay attention to planning, health and safety regulations. These problems can be overcome by a method, a Superstructure method. A problem with CCS may occur when the source and sink locations are not necessarily in a single region, so it is possible that the CCS process can occur in a multi-region where the source and sink locations are far apart and with many regions. The development of multi-region studies was carried out in this research, namely with the boundaries of the regions of Kalimantan, Sulawesi and East Java with a total of 4 sources and 2 sinks. Development is carried out by making mass transfer scenarios using superstructure method and cost calculations based on Total Annual Cost (TAC) then optimized with optimization software to get the minimum cost. In this study, the optimum CCS network has been determined in Kalimantan, Sulawesi and East Java regions with specific TAC US$ 11,126,782.2/Mt.

1. Introduction

Currently, global warming is a serious threat to living things and the earth. According to WMO [8], 2019 is the second warmest year after 2016. The average temperature for the last 10 years has reached its highest point. Since 1980, every decade has increased the temperature of the earth compared to the previous year. According to analysis by WMO, the annual global temperature in 2019 was 1.1 °C warmer than the average temperature of 1850-1900 before the industrial revolution. This trend is expected to continue due to the rate of heat capture by greenhouse gases in the atmosphere. Greenhouse gases are emissions in the form of carbon monoxide (CO), carbon dioxide (\( \text{CO}_2 \)), sulphur dioxide (\( \text{SO}_2 \)), nitrogen monoxide (\( \text{NO}_x \)), and several other gases. The greenhouse effect itself is the result of activities carried out by humans such as: the use of electricity, oil and coal which are the energy sources for most power plants. This has contributed greatly to global warming. The use of
transportation is also a cause of the greenhouse gas effect. Fossil fuels are fuels that are widely used in all forms of transportation systems, with the increasing use of private vehicles resulting in an increase in carbon dioxide gas in the atmosphere. Other causes are industrial and household waste, industrial waste such as cement factories, fertilizers, and coal mining and petroleum which produce a lot of greenhouse gases such as carbon dioxide. Household waste produce carbon dioxide and methane gases which are produced from waste decomposing bacteria. The use of fossil fuels in Indonesia is increasing over time. This increase occurred from 1990 to 2013, from 53.4 Mton to 154.93 Mton, and it is estimated that in 2050 it will increase to 690 Mton. This increase in fossil fuel consumption goes hand in hand with an increase in the amount of CO₂ emissions. In 2013, CO₂ emission was 133.9 Mton and it is estimated that it will be 1000.6 Mton by 2050. The countermeasure taken to reduce the effect of greenhouse gases is to mitigate greenhouse gases. Carbon capture and storage (CCS) is one of the greenhouse gas mitigation technologies. CCS has an important role in limiting the temperature increase to 2 ° C better than the pre-industrial level. The large amount of CO₂ gas emissions from the industrial sector and power generation, makes CCS a specific problem solver to support the use of fossil fuels in these 2 sectors. CCS technology is a series of activities starting from CO₂ capture (capture) of CO₂ emission sources, namely the industrial sector and power generation. Once captured, carbon dioxide is transported via pipelines or ships to a CO₂ storage location in suitable storage. Indonesia is already planning the creation of a CCS network. With many industries that are sources of CO₂ emissions (source), in 2012, LEMIGAS has estimated the potential areas as storage (sinks) with a capacity of 640 Mton from former oil and gas mines, namely in Kutai, Tarakan, and South Sumatra [3]. One source of CO₂ emissions is the Kalimantan area, mostly from hydrocarbon production. The biggest emitter is the Bontang LNG plant. Emission volume is still unknown. The largest contribution of flue gas from power plants, followed by LNG and petrochemical plants [4].

There are several studies that learning about how to optimize the pairing between sink and source in CCS network. Uzorh,A.C et al. were doing research about supply chain transportation management optimization [7]. David Licindo et al. were doing research about the optimization of CCS network in single region by using mathematical approach [2]. Pinch analysis also can be used to optimize CCS network. Aditya Anugerah Putra et al. were doing research about optimization of multi region CCS network in Indonesia that also calculate Total Annual Cost (TAC) from the formed network [1]. Renanto Handogo et al. also developing pinch design method optimization for CCS network that cover central part of Indonesia [5]. However, in previous studies there are no CCS network development in Indonesia using superstructure method by considering Total Annualized Cost (TAC).

Therefore, in this work CCS network in Indonesia middle part will be using superstructure method by considering TAC. The limitation in this study are: using superstructure method, region under review are Borneo and Sulawesi for source CO₂ and East Java and Borneo (Tarakan) for sink CO₂, the distribution system using piping, CCS pairing system assumes one source can only go to one sink, and single period exchange studied in this study.

2. Methodology

2.1. Data Compilation

In this study, the CCS network are developed in a multi-region and single period system. This study will be used data from the study by Handogo et al [5]. Three regions are selected for this study, namely East Kalimantan, South Sulawesi, and North East Java. The sources that will be used in this study are represented by fertilizer plant, cement plant, and LNG plant. The carbon reservoir, hereinafter referred to as the sink, originates from two places, East Kalimantan and North East Java. The source and sink data used were listed in table 1 and table 2. Single region in this case is only containing data source and sinks in East Kalimantan region, meanwhile Multi region is containing data sources in South Sulawesi region and sinks in North East Java region and East Kalimantan.

The available time, operating life and flow rate of each source and sink point should be known as network design parameters. The start time source is the time when the industry starts carrying out the
CO₂ capture process for the first time to the end of production, while the time for sink to start is the time when CO₂ is first injected into the sink to full capacity. The start time and end time for a source is assumed based on the consideration that each source cannot start the capture process simultaneously, because planning for CO₂ capture is different for each source. The available time for sinks is based on the assumption that planning CO₂ injection can be carried out at the same time because part of the CO₂ storage is ready to use. Distance is also affected the calculation of TAC. The distance data were listed in table 3.

### Table 1. Source characteristic in Indonesian central region

| Code    | Industrial Source | Start time (year) | End time (year) | CO₂ Emission Rate (Mt/year) | CO₂ Load (Mt) |
|---------|-------------------|-------------------|-----------------|-----------------------------|---------------|
| Source 1 | Pupuk Kaltim      | 5                 | 30              | 2.403                       | 60.075        |
| Source 2 | Badak LNG         | 5                 | 20              | 5.514                       | 82.71         |
| Source 3 | Semen Bosowa      | 7                 | 27              | 1.575                       | 31.5          |
| Source 4 | Semen Tonasa      | 8                 | 28              | 3.791                       | 75.82         |
|         |                   |                   |                 |                             | 250.105       |

Total production CO₂

### Table 2. Sink characteristic in Indonesian central region

| Code | Geological Sink           | Start time (year) | End time (year) | CO₂ Injection Rate (Mt/year) | Storage Capacity (Mt) |
|------|--------------------------|-------------------|-----------------|-----------------------------|------------------------|
| Sink 1 | Kutai-Tarakan basin   | 5                 | 35              | 4.65                        | 139.50                 |
| Sink 2 | East Java basin        | 5                 | 30              | 3.76                        | 94.0                   |
|       |                         |                   |                 |                             | 233.5                  |

Table 3. Source to sink distance

| Source | Rate (Mt/year) | Source name | Destination | Distance (km) |
|--------|----------------|-------------|-------------|---------------|
| 1      | 2.403          | Pupuk Kaltim| Sink 1      | 358           |
|        |                |             | Sink 2      | 887           |
| 2      | 5.514          | Badak LNG   | Sink 1      | 518           |
|        |                |             | Sink 2      | 735           |
| 3      | 1.575          | Semen Bosowa| Sink 1      | 968           |
|        |                |             | Sink 2      | 716           |
| 4      | 3.791          | Semen Tonasa| Sink 1      | 956           |
|        |                |             | Sink 2      | 721           |

2.2. *Equation and Constrains Development*

The illustration in Figure 1 illustrates a possible scenario for the distribution of CO₂ from the source to the existing sink. From here, pairing will be made between the source and sink which will produce a minimum cost. In this study, the constraints will be determined as needed in order to get the most optimal simulation results when implemented. The end result goal will influence the constraint creation. Then proceed with making a mathematical model as an algorithm to determine the pairing source and sink which results in the exchange of maximum load and minimum cost.
In this study, the desired objective function is the minimum cost of the piped transportation network configuration on the Carbon Capture and Storage (CCS) system between the available sources and sinks. Then for the equation we use is the development of equations that have been used in previous research in the supply chain. The constraint we set is the maximum amount of load that can be transferred by the source and can be accepted by the sink so that later it will get the maximum load exchange value for its optimum configuration. For cost calculation, we develop the equation we take by adding the calculation of Total Annual Cost (TAC) which includes Annual Capital Cost (ACC) and Annual Operating Cost (AOC) to get the minimum simulation results.

- **Objective Function:**
  1. Minimum transportation cost

\[
\text{Minimize } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij}X_{ij}
\]

- **Constraints used:**
  1. Parameter exchange

\[
X_{ij} \geq 0
\]

where \(x_{ij}\) is the possible exchange that occurs between an existing source and sink. The \(x_{ij}\) value is more than equal to 0 to prevent the exchange from sink to source. So the exchange of CO\(_2\) that occurs can only take place from source to sink.

2. **Load Exchange**

\[
\sum_{j} x_{ij} \leq a_i
\]

\[
\sum_{i} x_{ij} \leq b_j
\]

this constraint is used to obtain the maximum exchange rate of CO\(_2\) load. Where the variables we use here are \(a_i\) which is the amount of CO\(_2\) load produced by each source and \(b_j\) which is the amount
of CO₂ load that can be accommodated by each sink. For constraint (3), this means that the load exchange that occurs is less than the same as the load capacity produced. Meanwhile, constraint (4) means that the load exchange to each sink j is less than the same as the load capacity that sink j can accommodate.

- **Piping Transportation Cost Equation**

  \[ C_{ij} = (AOC + ACC) \]

  Defined as follows:

  1. Calculating the Annual Capital Cost (ACC) of Piping

  \[ ACC \text{ piping} = \text{construction cost factor} \times D \times \text{distance} \times \frac{i(1 + i)^n}{(1 + i)^n - 1} \]

  The diameter used in this research, simulated using the Aspen HYSYS pipe segment application

  2. Calculating the Annual Operating Cost (AOC) of Piping

  \[ AOC \text{ piping} = \text{O&M cost factor} \times \text{distance} \]

  2.3. **Cost Analysis**

  After obtaining the optimum configuration and minimum cost, it is continued with the calculation of penalty cost from the configuration that has been formed and ends with the calculation of the Total Annual Cost (TAC). Calculations to get a penalty fee and TAC:

  1. Supporting variables [6]

     Carbon tax = US$ 20.94/Mton CO₂

  2. Calculating the AOC penalty for alternative storage

     AOC penalty alternative storage = carbon tax x load alternative storage

  3. Calculating the AOC penalty for unutilized storage

     AOC penalty unutilized storage = carbon tax x load unutilized storage

  The total cost (\( \Sigma \) AOC) penalty is the amount of AOC penalty for alternative storage and AOC penalty for unutilized storage.

  Calculation Annual Capital Cost (ACC):

  \[ ACC = \Sigma ACC \text{ piping} \]

  Calculation Annual Operating Cost (AOC):

  \[ AOC = \Sigma AOC \text{ piping} + \Sigma AOC \text{ penalty} \]

  Calculation TAC:

  \[ TAC = ACC + AOC \]

  3. **Result and Discussion**

  3.1. **Superstructure Network Development**

  The optimum CCS network has been developed using superstructure method as shown in Figure 2. From the simulation results, objective function or the minimum cost for the configuration is US$ 2,598,103,639.0533. For maximum load exchange from the configuration is source 1 send 60.076 Mt CO₂ to sink 1.
Figure 2. Optimum Network Scenario.

Sink 1 can still receive 79.425 Mt. Then source 2 send 79.425 Mt to sink 1, therefore sink 1 is at full capacity. Source 3 send 31.5 Mt CO\(_2\) to sink 2, that sink 2 can still receive 62.5 Mt CO\(_2\). Source 4 send 62.5 Mt CO\(_2\) to sink 2, therefore sink 2 is at full capacity. So, the total of CO\(_2\) exchanged is 233.5 Mt. Source 2 and 4 have not fully captured, that need alternative storage at 16.605 Mt. There is no unutilized storage in this configuration. Percentage of captured CO\(_2\) is 93.36%.

Table 4. Optimum Mass Exchange Results on Superstructure Method CCS Network

| Alternative Storage (Mt) | Unutilized Storage (Mt) | Capturable (Mt) | \% CO\(_2\) Capture |
|--------------------------|-------------------------|-----------------|--------------------|
| 16.605                   | 0                       | 233.5           | 93.36              |

After get this configuration, calculate the Annual Operating Cost penalty that cover alternative storage and unutilized storage with carbon tax US$20.94/Mt. From this calculation the AOC penalty is US$ 347,708.7. Then sum the AOC penalty cost with minimum cost from configuration to calculate the Total Annual Cost. The Total Annual Cost is US$ 2,598,103,986.762.

3.2. Grid Diagram Network

Grid Diagram network gives general illustration for the source and sink pairing of CCS network. Figure 3 shows the grid diagram network of CCS network of multi region in central part of Indonesia. From this figure, Sink 1 could receive CO\(_2\) from source 1 and source 2 with the value of 60.075 Mt.
and 79.425 Mt, respectively. Sink 2 could receive from source 3 and source 4 with the value of 31.5 Mt and 62.5 Mt, respectively. However, source 2 and source 4 were still requiring alternative storage with value of 3.285 Mt and 13.32 Mt, respectively. There are no unutilized storage in this case which mean that all sink streams were fully stored.

3.3. Comparison with pinch method
From this simulation, we compare with pinch method with the same case with zero time difference.

**Table 5. Comparison Results of TAC and Mass Exchange of CO$_2$ between Superstructure and pinch method**

|                     | Pinch      | Superstructure |
|---------------------|------------|----------------|
| TAC (US$)           | 556.48 million | 2.598 Billion |
| Alternative Storage (Mt) | 58.572      | 16.605         |
| Unutilized Storage (Mt)  | 28.017      | 0              |
| Capturable (Mt)       | 163.516     | 233.5          |
| % CO$_2$ Capture      | 65.38       | 93.36          |
| Specific TAC (US$/Mt) | 3,403,214.36 | 11,126,782.2   |

From the comparison of the data in the 2 tables above, it can be seen that the pinch method produces a lower cost than the superstructure. However, the mass exchange of CO$_2$ from the superstructure method is more optimal where all sinks can be fully filled. From this comparative analysis, many factors can influence the calculation. For the pinch method itself, it is done by calculating the maximum exchange rate of CO$_2$ load first and then continuing the calculation of the Total Annual Cost (TAC) of the load exchange configuration that is formed. As for the method we use, namely superstructure, we immediately try it in one equation with the help of simulation in software to get these 2 things, namely the maximum load and minimum cost in one step. Then the thing that can be influential is the constraints used. In this experiment, the constraints we use are the exchange variable and load exchange constraints. This is very influential on the calculation of costs where the constraints that we can input during the simulation cause the calculated costs to be greater than the pinch method. From the simulation we have done, it can be seen the advantages, namely the small cost penalty due to the absence of unutilized storage or unused sinks, meaning that all sinks can be fully filled. Then the percentage of CO$_2$ that can be captured is 93.36% greater than the pinch method which can only capture 65.38%. For the Specific TAC value, the pinch method is less than the superstructure method, with a nominal value of US $ 3,403,214.36 for the pinch method and US $ 11,126,782.2 for the superstructure method. From the two tables above, the minimum cost of pinch method is better than superstructure. But the mass exchange of CO$_2$ from superstructure is better.

4. Conclusion
An optimum scenario for CCS system with superstructure method has been developed. This method is more effective in determining optimum configuration. With this method, percentage of capturable CO$_2$ is 93.36% better than pinch method that can capture only 65.38%. While the specific TAC for this method is US$ 11,126,782.2/Mt, higher than pinch that only need US$ 3,403,214.36/Mt.

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