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ORIGINAL RESEARCH PAPER

Multi Region Carbon Capture and Storage Network in Indonesia Using Pinch Design Method

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Abstract

Global warming, a rise in global temperatures average, is caused mainly by carbon dioxide (CO_2). Carbon capture and storage (CCS) technology is one of the best solution to mitigate CO_2. This technology is a series of activities starting from capturing CO_2 (source), transporting it, and storing it to the suitable geological sink (sink). In the CCS process, matching between source and sink may face some obstacles, such as time availability, capacity limit, and location. These problems can be solved by pinch design method. The development of multi region CCS process was conducted in this study, with of South Sumatra and East Java as boundary area with a total of five sources and six sinks. The development was done by calculating capturable CO_2 and cost needed using simultaneous and sequential method with time difference (Δt_{min}) 0, 5, and 10 years. The result of this research shows sequential method of CCS can capture the biggest amount of CO_2 with 93.86% in Δt_{min} 0 years, while simultaneous method can capture 83.94% of CO_2 in Δt_{min} 0 years. The least total annual cost is found in simultaneous method with Δt_{min} 4.6 years, which is US$ 159,259,000, compared to sequential method with Δt_{min} 4.5 years, which is US$ 166,667,000. Sequential method is best used if the CCS design prefers quantity of capturable CO_2 over the cost needed.

Keywords Carbon capture and storage · Pinch design method · Multi region · Simultaneous · Sequential

Introduction

Global warming is a phenomenon that is indicated by increasing of average temperature of earth surface. Global warming is mainly caused by high level of carbon dioxide (CO_2) in the atmosphere. In a period between January and September 2016, average temperature of earth surface is 0.88 °C higher than average temperature in a reference period between 1961 and 1990 (WMO 2016).

The 2014 global fossil-fuel carbon emission estimate, 9855 million metric tons of carbon have been released to the atmosphere. Globally, liquid and solid fuels accounted for 75.1% (7397 million metric tons of carbon) of the emissions from fossil-fuel combustion and cement production. Combustion of gas fuels (e.g., natural gas) accounted for 18.5% (1823 million metric tons of carbon) of the total emissions from fossil fuels in 2014 and reflects a gradually increasing global utilization of natural gas. The remaining emissions, at least 6.4% from cement production (568 million metric tons of carbon in 2014) and gas flaring, which accounted for less than 1% of global fossil-fuel releases (Boden et al. 2015; Global CCS Institute 2015).

ASEAN countries were considered as a rapid developing region where the energy demand projected to keep rising. Especially in the four countries such as Indonesia, The Philippines, Thailand, and Vietnam, they have been among the fastest growing economies in the world, and such growth projected to continue. Rapid economic growth, development, increased industrialization, and improved energy access have led to strong growth in the energy demand of these four countries.

The increase in energy use has been met through the consumption of fossil fuel. Commensurate with increased fossil fuel consumption, CO_2 emission have grown sharply across all four countries. Indonesia has the highest greenhouse gas (GHG) emission rate among the four countries. Its GHG levels grew 5.3% annually between 2000 and 2005 to reach 1760 Mt CO2e.

The International Energy Agency (IEA) projects for CCS in Southeast Asia reported that the initial estimates of CO_2 storage capacities of these four countries approximately 54

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Gt. It is enough to store 200 Mt CO_2/year for over two centuries. Of the estimated storage capacity, 88% is located in saline aquifer. (ADB 2013).

Figure 1 shows CO_2 emission in Indonesia in 2009. Java and Sumatra are the biggest contributors of CO_2 emission, with 60 million and 25 million tonnes (Mt) per year respectively. Kalimantan and Sulawesi contribute as much as five million tonnes per year each of CO_2 emission.

Some solutions have been proposed to reduce CO_2 emission. There is a proposed solution to convert captured CO_2 to another chemical substance, such as methanol (Putra et al. 2017). Although converting carbon dioxide looks promising, it needs complex design and planning and can take a long time before a conversion plant can be started. The other solutions focus on how to replace fossil fuel with a more renewable fuel, which also needs a long time and an intensive research to be implemented.

One of the best solution to mitigate high level of CO_2 emission in short time and in huge scale is carbon capture and storage (CCS) technology. This technology is a series of activity, which includes reducing emission from industries (source), such as natural gas processing and power plant, by capturing CO_2 from its source. The captured CO_2 is then transported and stored to a suitable geological storage (sink), such as depleted oil or gas reservoir. According to the Ministry of Energy and Mineral Resources of the Republic of Indonesia, CCS is one of the technologies that has a potential to mitigate CO_2 emission.

Harkin et al. (2009) have investigated reducing the energy penalty of CO_2 capture and storage using pinch analysis. Integration of CO_2 capture and storage into coal-fired power stations is seen as a way of significantly reducing the carbon emissions from stationery sources.

Moh Nawi et al. (2016) had used pinch analysis targeting for CO_2 total site planning. They combined the CO_2 capture and storage with CO_2 capture and utilization. Therefore, the integration of CO_2 capture and storage and CO_2 capture and utilization was introduced.

Ladislav et al. (2016) had used pinch point analysis of heat exchanger for supercritical carbon dioxide with gaseous admixtures in CCS system. Chen (2016) had used pinch point analysis and design considerations of CO_2 gas cooler for heat pump water heaters. Olson et al. (2017) had used pinch analysis for industrial organic Rankine cycles.

However, the work of investigators had not given clear analogy with the basic integration for heat exchanger networks given by Robin Smith. A grid diagram for pairing between source and sink is not explained in detail. An overall process integration was chosen to pinpoint the maximum recovery that can be obtained instead. Therefore, a method to find out how the pairing can be made is introduced in this work. Hence, an analogy as given by heat exchanger networks can be built.

According to Fig. 2, it is estimated that in Indonesia, there are some sinks available; most of them are depleted oil and gas reservoir. Sumatra is estimated to have 373 million tonnes storage space, while Java has 105 million tonnes storage space. By looking to those numbers, it can be assumed that there are a lot of space to store CO_2 emission. Therefore, in practice, there is a possibility that the availability of source and

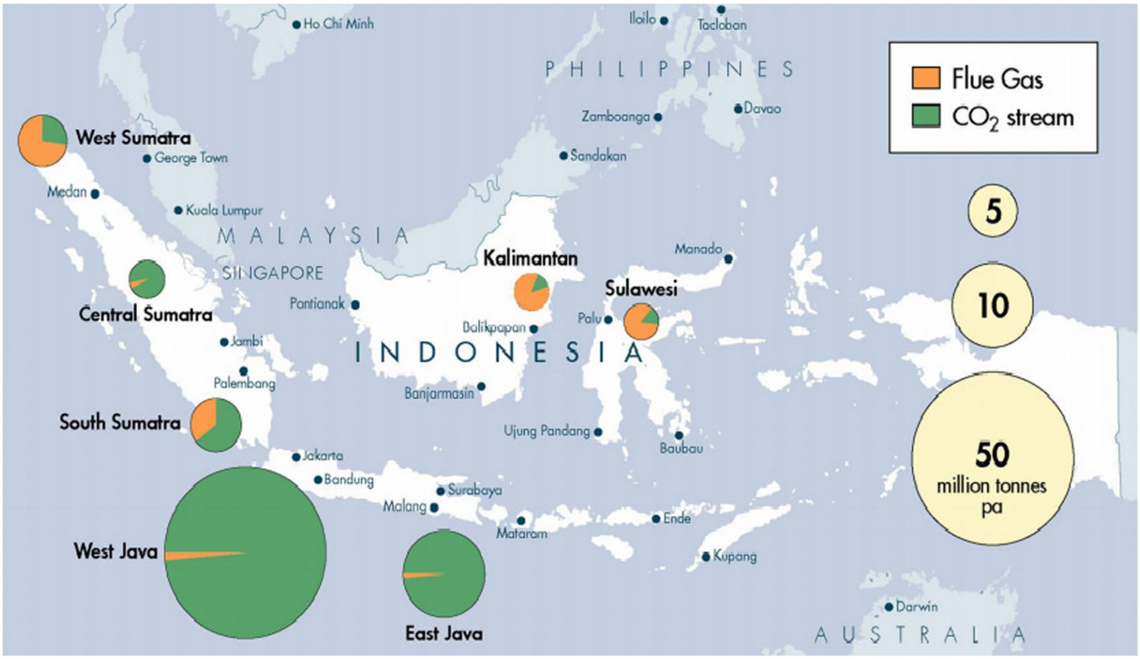


Fig. 1 Carbon dioxide emission in Indonesia (LEMIGAS 2009)

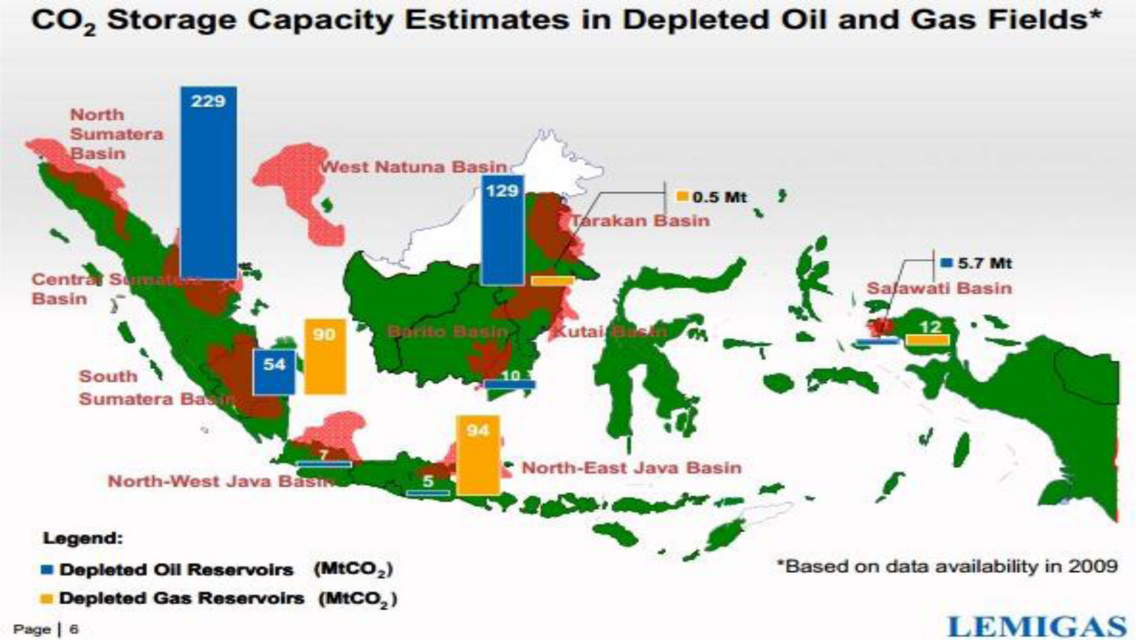


Fig. 2 Estimated location of sinks in Indonesia (Iskandar 2009)

sink is not matched, which means sink is not ready while source is already operated, or vice versa, so that it can be a problem in planning of CCS.

Beside time availability problem, another problem that can arise is a location problem. There is a possibility that source and sink are not in the same region and the capacity of the sink is not enough to store all the CO_2 emission from the same region. Because of those problems, it is possible that CCS can be done in multi region, where the location of source and sink is far apart.

Pinch design method, which is a well-known method in heat exchanger network integration, can be applied to solve the problem. The pinch design method has already been done and proven to solve the problem that arises from planning of CCS (Ooi et al. 2012). A new graphical technique is proposed based on pinch analysis. However, the case study taken is only for single region and single time difference ($\Delta t = 0$ year) approach. In addition, graphical technique is cumbersome and therefore problem table algorithm for this work is more meaningful. Some parameters that are used in process integration using pinch design method are primarily capacity limit, location, flow rate, and time availability of both source and sink.

Sequential method of CCS can also be done other than simultaneous method, which is already a well-known method. With sequential method, it is predicted that percentage of captured CO_2 can be increased (Diamante et al. 2014). In his work, multi region and multi period of time are used to apply for the planning of CCS. They used problem table algorithm as opposed to graphical technique to calculate CO_2 capture. Pairing between specific source and sink was investigated. However, the grid diagram for multi periods of time and multi regions were not clearly illustrated and therefore this work will add to elucidate the problems on CCS planning. In the previous research, sequential method of CCS in multi region location has not been done, even though the method can overcome the problem on matching and integrating CCS network.

Because of that reason, this research focus on multi region CCS with sequential method and compare it with simultaneous method. This research also concerns about cost and several time differences ($\Delta t_{\min}$) to get the best CCS network in terms of minimum total annual cost.

Carbon Capture and Storage Technology Description

Carbon capture and storage is a technology that prevents CO_2 to be released to the atmosphere. This technology includes capturing CO_2 that is produced by industries, compressing CO_2 for transportation, and injecting CO_2 to a geological sink carefully, where it will be stored permanently (Global CCS Institute 2011).

There are some technologies to capture CO_2 from industries; those are post-combustion, pre-combustion, and oxy-fuel combustion carbon capture. Those three technologies can capture up to 90% CO_2 emission.

a. Post-combustion carbon capture

Post-combustion carbon capture technology captures CO_2 from flue gas that is released as a result of fuel combustion. This technology usually uses liquid solvent to capture CO_2 in flue gas. Ethanol amine and its derivative, such as mono ethanol amine (MEA) and diethanol amine (DEA), are used in most of the cases and can capture more than 90% of CO_2 in flue gas (Putra et al. 2016).

b. Pre-combustion carbon capture

Pre-combustion carbon capture technology captures CO_2 before combustion of fuel happens. This technology processes main fuel in a reactor to produce carbon monoxide and hydrogen, or usually called as syngas, as its main component. Additional hydrogen, together with carbon monoxide, is formed in a shift reactor, where carbon monoxide reacts with water vapor. Mixture of CO_2 and hydrogen that is produced can be separated in two streams. CO_2 stream will be captured, while hydrogen stream is used as fuel to produce heat. This system is commonly used in power plant which used integrated gasification combined cycle (IGCC) technology (IEA 2013, IPCC 2005).

c. Oxy-fuel combustion carbon capture

This system uses nearly pure oxygen, instead of ordinary air, to burn fuel. By using nearly pure oxygen, flue gas will contain mainly water vapor and CO_2, with CO_2 concentration, is higher than water vapor. Water vapor is then removed by cooling and compressing flue gas stream (IEA 2013, IPCC 2005). Theoretically, this system is very simple and cheaper than the other two technologies. However, producing nearly pure oxygen with 95–99% purity is quite expensive and needs a huge amount of energy.

Compressing and transporting captured CO_2 are important steps of the process. Generally, captured CO_2 will be transported to sink by using pipeline. CO_2 will be transported in liquid form, since it will need smaller pipe size than transporting in gas form. Even though transporting CO_2 using pipeline is the good choice, the use of ship to transport CO_2 is one of the alternative good choices, especially if the location of the sink is far apart (Leung et al. 2014).

Injecting CO_2 to sink is the last step of the process. Geological sink should be chosen carefully, since CO_2 will be stored permanently in there. Geological sink must be in stable condition and has a minimum risk of natural disaster, especially earthquake. Depleted oil or gas reservoir and deep saline are the best place to store CO_2 underground (Davison et al. 2001).

Problem Statement

Problem statements of this research are as follows:

- CCS network is determined to have five sources and six sinks. All sources are located in one region. Three sinks are located in the same region as the sources, while the other three are located in another region.
- Each CO_2 source is defined by a fixed CO_2 flowrate that can be captured from emission source. Time availability for each source, which is the time that the industry starts its first CO_2 capturing process, is defined with consideration that every source cannot start its capture process together.
- Each CO_2 sink is defined by maximum CO_2 injected to each sink. Time availability for each sink, which is the time while CO_2 is injected to sink for the first time, is defined. The time that CO_2 sink starts receiving the injection of CO_2 is different for each sink.
- The starting time and the end time for CO_2 source and CO_2 sink are the same for each pair and for 0 year of time difference. However, the starting time for CO_2 source always lags by the given time difference with respect to CO_2 sink.
- The aims of this work are to minimize the amount of unutilized and alternative storage and thus to maximize the CO_2 capture that is emitted from the source. It also tries to pair between source and sink available using sequential and simultaneous methods with 0, 5, and 10 years of time difference.
- Total annual cost which consists of annual capital cost and operating cost for each network will be calculated. By using annual capital and operating costs for each time difference, the minimum total annual cost is obtained.

Research Methodology

Data Collection

Data collection is one of the most important steps in this research. Accuracy of data collected will affect the actual result while implementing CCS in the real world. Some data that are needed for this research are source and sink of CO_2, time availability, operation lifetime, and capacity and flow rate for both source and sink.

Since this research will focus on multi region CCS, two regions are selected for this research, namely West Sumatra and East Java. Source will come from five industries in West Sumatra, namely PLN Bukit Asam, RU III Plaju, PT Merbau GGS, PT Semen Batu Raja, and Pusri Palembang, while sink comes from six places, three of them are coming from West Sumatra, namely Site I2, H2, 3, and the other three come from East Java, namely Banyu Urip, Sukowati, and Mudi (Usman et al. 2014, Satyana and Purwaningsih 2003).

Time availability for source is the time that the industry starts its first CO_2 capturing process from its emission, while time availability for sink is the time while CO_2 is injected to sink for the first time. Time availability for source is assumed based on consideration that every source cannot start its capture process together, because planning of capturing CO_2 is different in every source.

Operation lifetime is the duration of operation for source and sink. Operation lifetime for source is gathered from previous research, while operation lifetime for sink is based on assumption that duration of every CCS process cannot be done in exactly the same time, so that lifetime of the sink should be different for every sink.

Flow rate of CO_2 is the amount of CO_2, in mass, that can be captured from source emission or can be injected into sink on yearly basis. Flow rate of CO_2 has a strong relationship with total CO_2 load for every source and total CO_2 storage capacity for every sink.

Data that are already collected for this research is shown in Table 1 for source and Table 2 for sink.

This research uses minimum time difference ($\Delta t_{\min}$) as a parameter, because there is possibility that operation time of CCS is delayed. Delay of the process can happen because of some reasons, such as sink is not ready to be injected with CO_2. CO_2 sinks usually are provided after the CO_2 source starts to operate. The values of minimum time difference used are 0, 5, and 10 years. This variable will affect in optimum time that can be implemented in CCS, and the amount of alternative storage and unutilized storage needed.

Generating Cascade Table

Pinch design method, which was introduced by Linnhoff and Hindmarsh (1983), is used as a guideline to calculate CCS network pairing. Originally, pinch design method is dominated by heat exchanger network design to obtain minimum energy cost. In this research, that method will be used to obtain minimum alternative and unutilized storage. While heat exchanger network has hot and cold stream that can be exchanged, this research will use source and sink flow rate as exchanged stream. Pinch point will also be used in this research as a time where there is no mass transfer between source and sink.

Similar to heat exchanger network, generating cascade table is the first step to calculate CCS network. Cascade table is used to calculate the amount of minimum alternative storage needed and unutilized storage and pinch point that will be used for generating grid diagram. Generating cascade table is done in several steps (Diamante et al. 2014). A table with the following column name is written first: t (it means lifespan time), source, sink, Δt (it means time interval), flow rate CO_2, load CO_2, infeasible, and feasible cascade. Then, stream lines for source and sink in appropriate year are plotted in the same graph. Δt column is time difference between the CO_2 source and CO_2 sink. Flow rate CO_2 column is $SK - SR$. Load CO_2 column is flow rate CO_2 times Δt. Calculation on the amount CO_2 transferred in the CO_2 cascade column for different minimum time different Δt is done by adding the amount of CO_2 from the top to bottom for each interval. The source and sink pinch years are found from the column where there is no flow between the year interval.

Generating Grid Diagram

Grid diagram is the design of CCS network. Grid diagram will be made in two ways, simultaneous and sequential. In simultaneous method, there is no consideration about which region do source and sink belong; every source and sink can be paired without any region limitation. In sequential method, region limitation of source and sink is considered. As stated before, sources are assumed to be in one region, which is West Sumatra, while sinks are assumed to be separated in two regions, West Sumatra and East Java. In sequential method, source and sink which belong to the same region, which is West Sumatra, are paired first. The alternative storage that arises from single region pairing is then transferred to another region, so that some amount of CO_2 that needs alternative storage can be paired with sink from another region, in this case East Java.

Table 1 Sources data for carbon capture and storage in West Sumatra

Code	Source place	Start time (year)	Duration (year)	End time (year)	Average CO_2 production rate (Mt/year)	CO_2 produced (Mt)
SR1	PLN Bukit Asam	5	25	30	1.786	44.65
SR2	RU III Plaju	7	25	32	0.619	15.475
SR3	PT. Merbau GGS	15	25	40	0.133	3.325
SR4	PT. Semen Batu Raja	10	50	60	0.501	25.05
SR5	Pusri Palembang	12	20	32	2.507	50.14
Total CO_2 produced (Mt)						138.64

Table 2 Sinks data for carbon capture and storage in West Sumatra and East Java

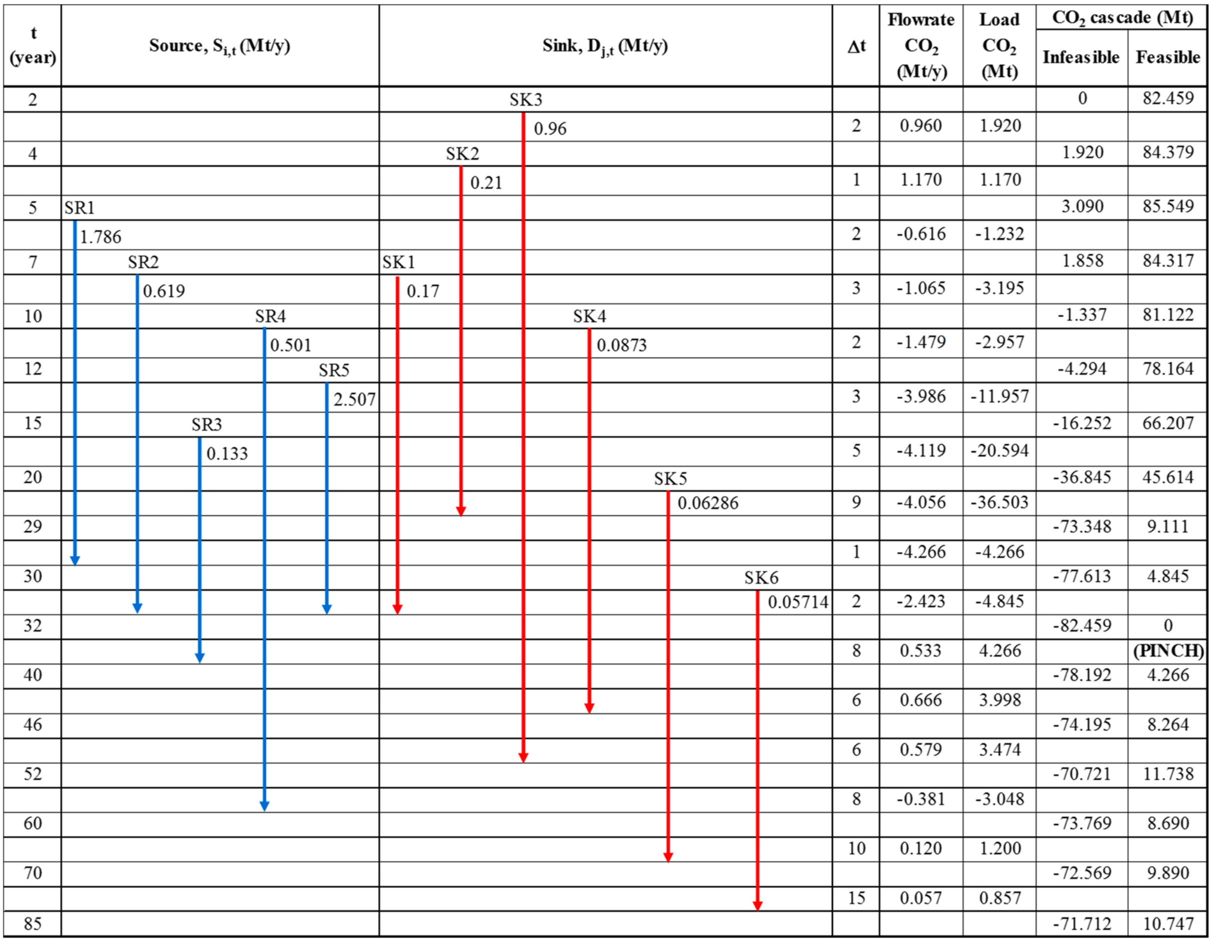
Code	Sink place	Region	Start time (year)	Duration (year)	End time (year)	Average CO_2 injection rate (Mt/year)	CO_2 injected (Mt)
SK1	Site I2	West Sumatra	7	25	32	0.17	4.25
SK2	Site H2		4	25	29	0.21	5.25
SK3	Site 3		2	50	52	0.96	48
SK4	Banyu Urip	East Java	10	36	46	0.0873	3.14
SK5	Sukowati		20	50	70	0.06286	3.14
SK6	Mudi		30	55	85	0.05714	3.14
Total CO_2 injected (Mt)							66.92

Steps for generating grid diagram are described below (Smith 2005):

For simultaneous grid diagram:

1. A vertical line is drawn as pinch point line.
2. Horizontal lines are also drawn, in which each line represents each source and sink. Line direction is drawn from the left (starting operation year) to right (end operation year).
3. Calculation for shifted year is done by substracting pinch point time of sink by 0, 5, and 10 years for the source and sink pinch year.
4. Grid diagram consists of two zones, below pinch (left side of the pinch line) and above pinch (right side of the pinch line). There are some rules for designing integration process between source and sink regarding below and above pinch zone.

Table 3 Cascade table for $\Delta t_{\min}$ equals 0 year using simultaneous method



t (year)	Source, $S_{i,t}$ (Mt/y)	Sink, $D_{j,t}$ (Mt/y)	Δt	Flowrate CO_2 (Mt/y)	Load CO_2 (Mt)	CO_2 cascade (Mt)	
						Infeasible	Feasible
2		SK3				0	82.459
		0.96	2	0.960	1.920		
4		SK2				1.920	84.379
		0.21	1	1.170	1.170		
5	SR1					3.090	85.549
	1.786		2	-0.616	-1.232		
7	SR2	SK1				1.858	84.317
	0.619	0.17	3	-1.065	-3.195		
10	SR4	SK4				-1.337	81.122
	0.501	0.0873	2	-1.479	-2.957		
12	SR5					-4.294	78.164
	2.507		3	-3.986	-11.957		
15	SR3					-16.252	66.207
	0.133		5	-4.119	-20.594		
20		SK5				-36.845	45.614
		0.06286	9	-4.056	-36.503		
29						-73.348	9.111
			1	-4.266	-4.266		
30		SK6				-77.613	4.845
		0.05714	2	-2.423	-4.845		
32						-82.459	0
			8	0.533	4.266		(PINCH)
40						-78.192	4.266
			6	0.666	3.998		
46						-74.195	8.264
			6	0.579	3.474		
52						-70.721	11.738
			8	-0.381	-3.048		
60						-73.769	8.690
			10	0.120	1.200		
70						-72.569	9.890
			15	0.057	0.857		
85						-71.712	10.747

- Mass transfer in below pinch zone, flow rate source ≥ flow rate sink, while in above pinch zone, flow rate source ≤ flow rate sink.
- Mass transfer is started from pinch point.
- Below pinch zone, there should be no unutilized storage and above pinch zone, there should be no alternative storage.

5. Pairing process between source and sink also concerns about the minimum time difference between paired source and sink. Find pairing that has the same or close to minimum time difference. To obtain suitable time difference, there is possibility that source and sink stream has to be split. Some rules for splitting stream are as follows.

   - Splitting process is only being done if pairing stream does not meet the requirement of pinch rules.
   - Splitting process is done by dividing one stream of source and sink to several streams with appropriate values.
   - Start and end year of the stream are not changed.

6. If pairing process has been done, but there is still unutilized storage below pinch zone and alternative storage above pinch zone, the additional pairing can be done without following the rule that has been stated before.

For sequential grid diagram:

1. Grid diagram is made using simultaneous method for single region only.
2. Alternative storage that is needed is then transferred to sinks that are located in the other region, in this case East Java.
3. Multi region pairing also considers about minimum time difference between paired source and sink, just like single region pairing process.
4. Multi region pairing does not follow the pinch rules.

Optimizing Based on Total Annualized Cost

In this research, calculation of total annual cost (TAC), which consists of annual operating cost (AOC) and annual capital cost (ACC), based on transferred load between source and sink is also calculated. Some of main costs that are calculated in determining TAC are transportation cost and penalty fee. Based on geographical location of each source and sink,

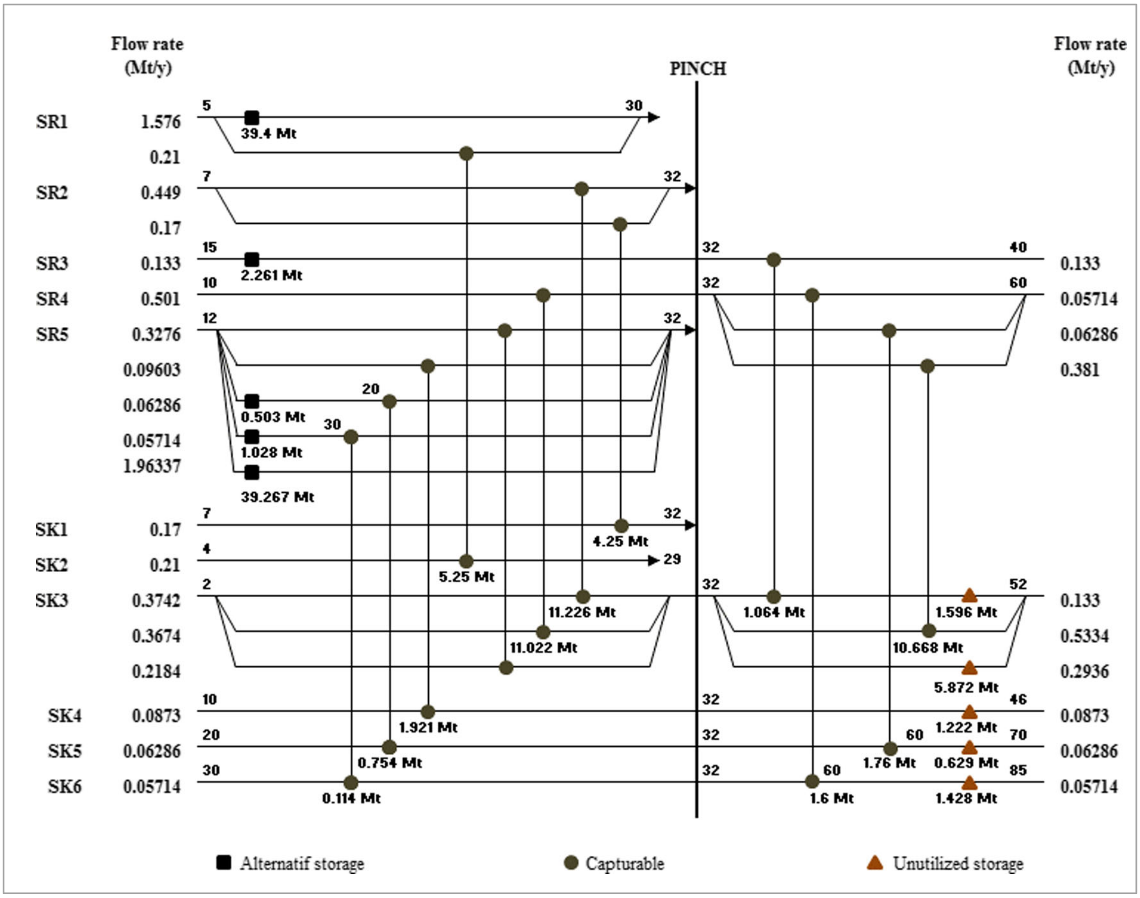


Fig. 3 Grid diagram for $\Delta t_{\min}$ equals 0 year using simultaneous method

transportation system is decided to use both piping and shipping. Shipping consists of three elements, ship cost, port storage cost, and loading cost, while penalty fee consists of alternative storage and unutilized storage penalty. Therefore, there are some calculations to calculate TAC, which are ACC (piping and shipping) and AOC (piping, shipping, and penalty).

For Piping ACC and AOC Calculation

1. Some variables to calculate ACC and AOC for piping system are as follows:

$P_{in} = 152$ bar, $P_{out} = 103$ bar, $T = 25$ °C, $\rho = 884$ kg/m^3, $\mu = 0.0000606$ Ns/m^2, surface roughness (ε) = 0.00015 m (galvanized iron), construction cost factor = US$ 826,338.58/m km, and O&M cost factor = US$ 3100/km (Heddle et al. 2003).

2. Piping ACC calculation

- Pipe diameter calculation

Calculation is done based on pressure drop and friction factor in turbulent flow (Geankoplis 2003). Pipe diameter calculation is done by using iteration, in which Reynold number is calculated first after assuming the value of D.

$$\mathrm{Re} = \frac{4\dot{m}}{\pi \mu D} \tag{1}$$

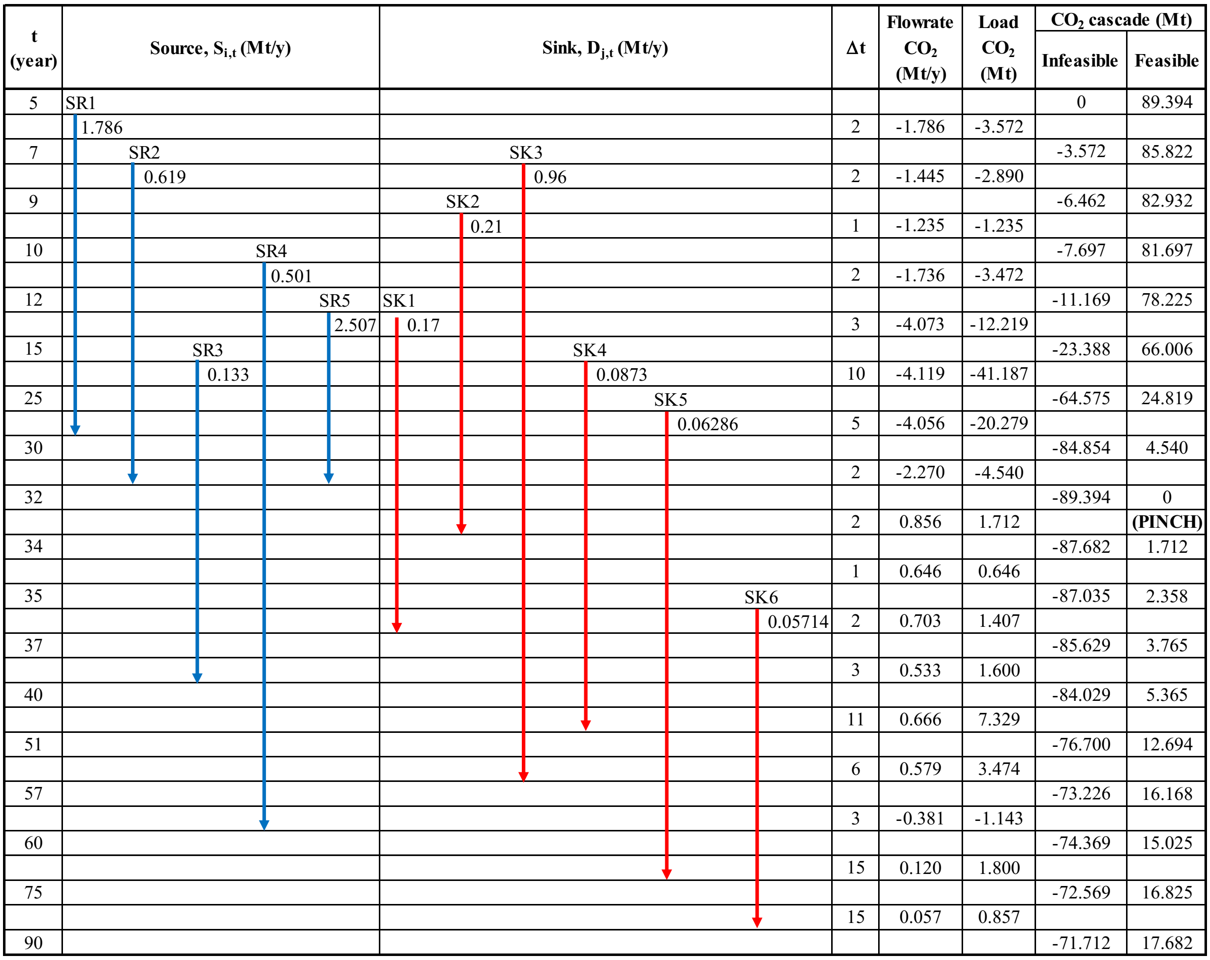
$\dot{m}$ is CO$_2$ flow rate, which is obtained from grid diagram. After that, looking up fanning friction (f) based on correlation between Reynold number and friction factor in Moody's graph (Perry and Green 2008).

$$f = \frac{\varepsilon}{D} \tag{2}$$

Then, calculating new value of D by using equation below.

$$D^5 = \frac{32 f \dot{m}^2}{\pi^2 \rho \left(\frac{\Delta P}{\Delta L}\right)} \tag{3}$$

Table 4 Cascade table for Δt_{min} equals 5 years using simultaneous method



t (year)	Source, $S_{i,t}$ (Mt/y)	Sink, $D_{j,t}$ (Mt/y)	Δt	Flowrate CO$_2$ (Mt/y)	Load CO$_2$ (Mt)	CO$_2$ cascade (Mt)	
						Infeasible	Feasible
5	SR1					0	89.394
	1.786		2	-1.786	-3.572		
7	SR2	SK3				-3.572	85.822
	0.619	0.96	2	-1.445	-2.890		
9		SK2				-6.462	82.932
		0.21	1	-1.235	-1.235		
10	SR4					-7.697	81.697
	0.501		2	-1.736	-3.472		
12	SR5	SK1				-11.169	78.225
	2.507	0.17	3	-4.073	-12.219		
15	SR3	SK4				-23.388	66.006
	0.133	0.0873	10	-4.119	-41.187		
25		SK5				-64.575	24.819
		0.06286	5	-4.056	-20.279		
30						-84.854	4.540
			2	-2.270	-4.540		
32						-89.394	0
			2	0.856	1.712		**(PINCH)**
34						-87.682	1.712
			1	0.646	0.646		
35		SK6				-87.035	2.358
		0.05714	2	0.703	1.407		
37						-85.629	3.765
			3	0.533	1.600		
40						-84.029	5.365
			11	0.666	7.329		
51						-76.700	12.694
			6	0.579	3.474		
57						-73.226	16.168
			3	-0.381	-1.143		
60						-74.369	15.025
			15	0.120	1.800		
75						-72.569	16.825
			15	0.057	0.857		
90						-71.712	17.682

The calculation above is repeated until constant value of D is obtained

- Pipe ACC calculation

After diameter of pipe is obtained, ACC of pipe is calculated using the equation below.

$$\text{Piping ACC} = \text{construction cost factor} \times D \times \text{distance} \times \frac{i(1+i)^n}{(1+i)^n - 1} \quad (4)$$

Total piping ACC is the summation of overall individual piping ACC.

3. Piping AOC calculation

Calculation of piping AOC is determined using the equation below.

$$\text{Piping AOC} = \text{O\&M cost factor} \times \text{distance} \quad (5)$$

Total piping AOC is the summation of overall individual piping AOC.

For Shipping ACC and AOC Calculation

1. Some variables that used to calculate ACC and AOC for shipping are as follows:

- Ship cost

Ship capacity = 10,000 ton; ship construction cost = US$ 35,000,000; crew, insurance, maintenance (CIM) cost = 5% construction cost; and fuel cost = $ 9150/day (Mitsubishi Heavy Industries 2004).

- Port storage cost

Storage capacity = 20,000 ton, storage construction cost = US$ 30,000,000, and O&M cost = 5% construction cost (Mitsubishi Heavy Industries 2004).

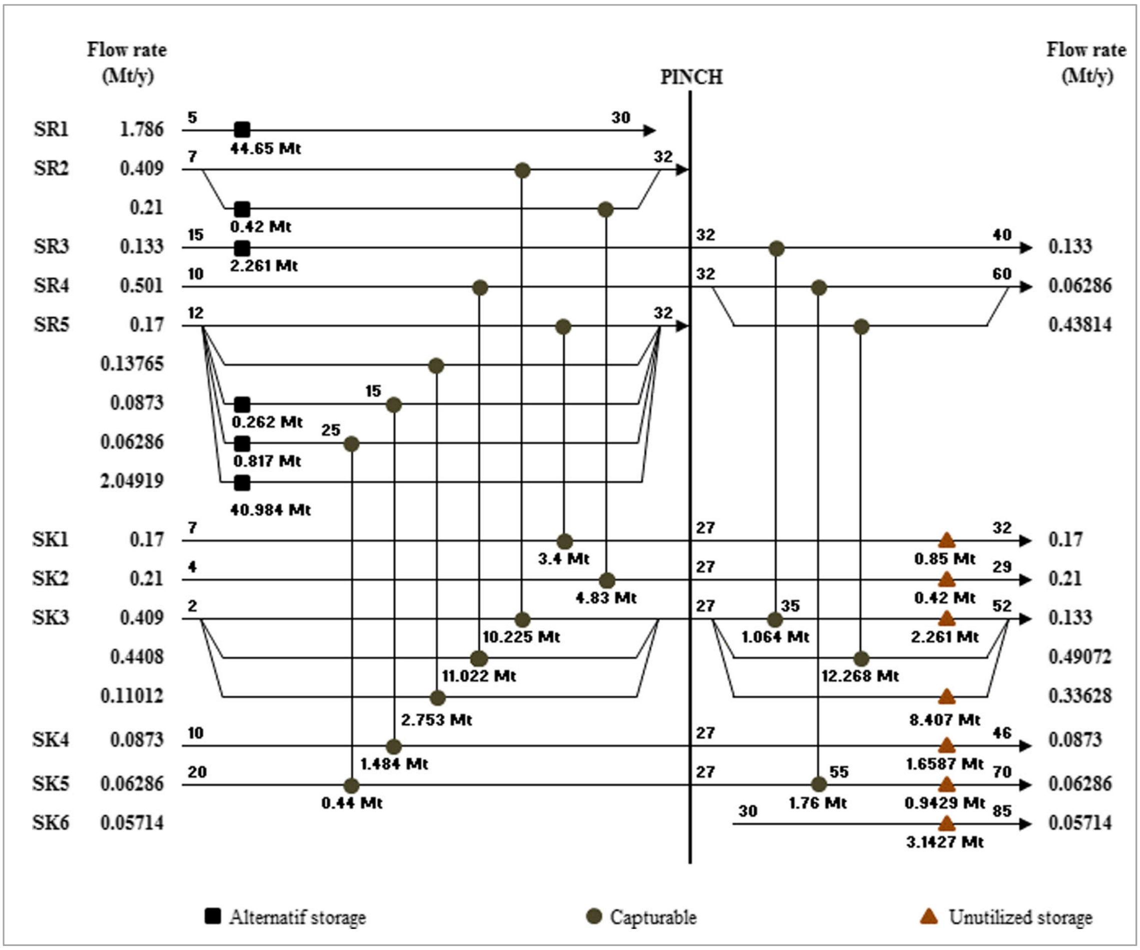


Fig. 4 Grid diagram for $\Delta t_{\min}$ equals 5 years using simultaneous method

- Loading cost

Loading capacity = 20,000 ton, loading dock construction cost = US$ 8,000,000, O&M cost = 25% construction cost, and one cycle of loading CO_2 to ship = 2 days (Mitsubishi Heavy Industries 2004).

2. Shipping ACC calculation

Calculation for each ACC calculation is done by comparing existing system with desired system using the equation below.

$$\text{ACC } A = \text{construction cost } B \times \left(\frac{\text{capacity } A}{\text{capacity } B}\right)^{0.6} \times \frac{i(1+i)^n}{(1+i)^n - 1} \tag{6}$$

A is the desired system, which is obtained from the total CO_2 flow rate transferred to sink in East Java each day, while *B* is the existing system. Total shipping ACC is the summation of ship cost, port storage cost, and loading cost.

3. Shipping AOC calculation

Calculation of shipping AOC is done by the following equations:

- Ship AOC

$$\text{Ship AOC} = \text{ship CIM cost} + \text{fuel cost} \tag{7}$$

- Port storage AOC

$$\text{Port storage AOC} = \text{O\&M port storage cost} \tag{8}$$

- Loading AOC

Table 5 Cascade table for $\Delta t_{\min}$ equals 10 years using simultaneous method

t (year)	Source, $S_{i,t}$ (Mt/y)	Sink, $D_{j,t}$ (Mt/y)	Δt	Flowrate CO_2 (Mt/y)	Load CO_2 (Mt)	CO_2 cascade (Mt)	
						Infeasible	Feasible
5	SR1					0	96.845
	1.786		2	-1.786	-3.572		
7	SR2					-3.572	93.273
	0.619		3	-2.405	-7.215		
10	SR4					-10.787	86.058
	0.501		2	-2.906	-5.812		
12	SR5	SK3				-16.599	80.246
	2.507	0.96	2	-4.453	-8.906		
14		SK2				-25.505	71.340
		0.21	1	-4.243	-4.243		
15	SR3					-29.748	67.097
	0.133		2	-4.376	-8.752		
17		SK1				-38.500	58.345
		0.17	3	-4.206	-12.618		
20		SK4				-51.118	45.727
		0.0873	10	-4.119	-41.187		
30		SK5				-92.305	4.540
		0.06286	2	-2.270	-4.540		
32						-96.845	0
			7	0.856	5.993		**(PINCH)**
39						-90.852	5.993
			1	0.646	0.646		
40		SK6				-90.205	6.639
		0.05714	2	0.836	1.673		
42						-88.533	8.312
			14	0.666	9.328		
56						-79.205	17.640
			4	0.579	2.316		
60						-76.889	19.956
			2	1.080	2.160		
62						-74.729	22.116
			18	0.120	2.160		
80						-72.569	24.276
			15	0.057	0.857		
95						-71.712	25.133

$$\text{Loading AOC} = \text{O\&M loading cost} \tag{9}$$

Total shipping AOC is the summation of those three equations.

For Penalty AOC Calculation

1. Variable used to calculate AOC for penalty fee is as follows:

Carbon tax = US$ 20.74/ton CO_2 (Sofyan 2010).

2. Alternative storage penalty AOC

$$\text{Penalty AOC} = \text{carbon tax} \times \text{alternative storage flow rate} \tag{10}$$

3. Unutilized storage penalty AOC

$$\text{Penalty AOC} = \text{carbon tax} \times \text{unutilized storage flow rate} \tag{11}$$

Total penalty AOC is the summation of both alternative and unutilized storage penalty AOC.

For Total Calculation

1. Total annual capital cost (TACC) calculation

$$\text{TACC} = \sum \text{piping ACC} + \sum \text{shipping ACC} \tag{12}$$

2. Total annual operating cost (TAOC) calculation

$$\text{TAOC} = \sum \text{piping AOC} + \sum \text{shipping AOC} + \sum \text{penalty AOC} \tag{13}$$

3. Total annual cost (TAC) calculation

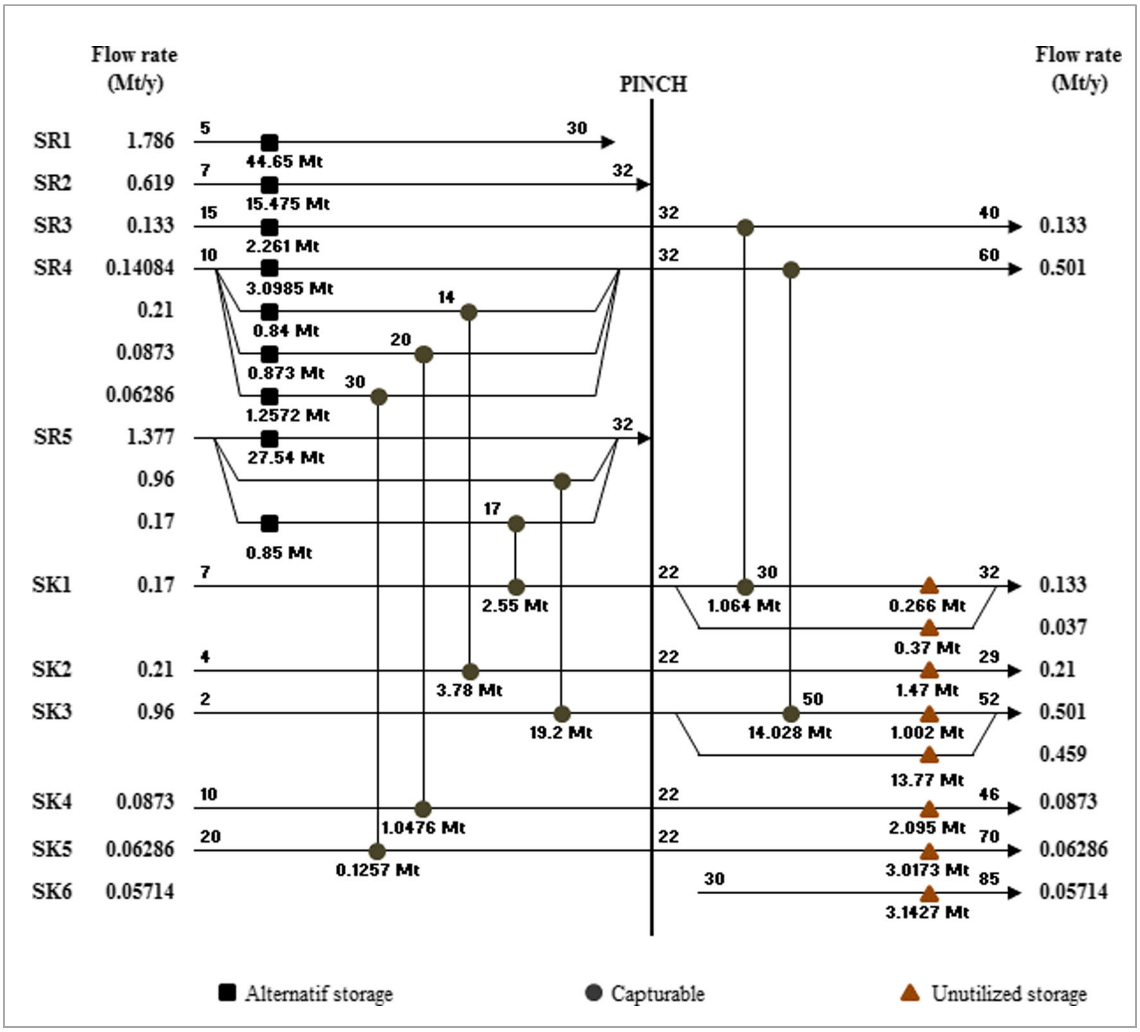


Fig. 5 Grid diagram for $\Delta t_{\min}$ equals 10 years using simultaneous method

$$TAC = TACC + TAOC \quad (14)$$

Discussion

Carbon Capture and Storage Network Using Simultaneous Method

Cascade table, as described before, is made to determine the amount of alternative and unutilized storage needed of the system and to determine the pinch point of the system. Generating the correct cascade diagram is crucial, since the result of cascade table will be used for creating grid diagram later on. Cascade table for time difference 0 years is shown in Table 3.

From Table 3, we can see that the pinch point of the system is obtained in year 32. This is the source pinch year. The sink pinch year is also in year 32. It is shown also that in Δt_{min} equals 0 year, the alternative storage needed is 82.549 Mt while the unutilized storage of the system is 10.747 Mt. From data that are obtained from cascade table, grid diagram of the CCS network can be made and is shown in Fig. 3.

As shown in Fig. 3, pinch point is divided in the grid diagram into two zones: below pinch point, where CO_2 needs storage, and above pinch point, where there is excess sink. Those phenomena are a common problem that will happen in real life, and therefore needs to be minimized.

It is shown in Fig. 3 that SK1 receive CO_2 from SR2 from year 7 until year 32 with the amount of CO_2 is 4.25 Mt, while CO_2 from SR1 is transported to SK2, which will end in year 29, with the amount of CO_2 transferred is 5.25 Mt. The other pairings are shown in Fig. 3. Grid diagram above gives exactly the same amount of alternative and unutilized storage as cascade table that has been made before. Alternative storage needed comes from SR1, SR3, and SR5 with 39.4, 2.261, and 40.798 Mt of CO_2 need alternative storage respectively, while all CO_2 comes from SR2 and SR4 is stored in available sink.

Table 6 Single region cascade table for Δt_{min} equals 0 year

t (year)	Source, $S_{i,t}$ (Mt/y)	Sink, $D_{j,t}$ (Mt/y)	Δt	Flowrate CO_2 (Mt/y)	Load CO_2 (Mt)	CO_2 cascade (Mt)	
						Infeasible	Feasible
2		SK3				0	85.248
		0.960	2	0.960	1.920		
4		SK2				1.92	87.168
		0.210	1	1.170	1.170		
5	SR1					3.09	88.338
	1.786		2	-0.616	-1.232		
7	SR2	SK1				1.858	87.106
	0.619	0.170	3	-1.065	-3.195		
10	SR4					-1.337	83.911
	0.501		2	-1.566	-3.132		
12	SR5					-4.469	80.779
	2.507		3	-4.073	-12.219		
15	SR3					-16.688	68.56
	0.133		14	-4.206	-58.884		
29						-75.572	9.676
			1	-4.416	-4.416		
30						-79.988	5.26
			2	-2.630	-5.260		
32						-85.248	**0**
			8	0.326	2.608		**(PINCH)**
40						-82.64	2.608
			12	0.459	5.508		
52						-77.132	8.116
			8	-0.501	-4.008		
60						-81.14	4.108

Unutilized storage comes from SK3, SK4, SK5, and SK6 with 7.468, 1.222, 0.629, and 1.428 Mt of storage is unutilized respectively.

Cascade table for $\Delta t_{\min}$ equals 5 years is shown in Table 4. The amount of alternative storage needed for the system is 89.394 Mt, while unutilized storage is 17.682 Mt. Pinch point for the system remains the same from $\Delta t_{\min}$ equals 0 year, which is year 32. However, the sink pinch year is in year 27. From cascade table that has been generated, grid diagram for the system is made as shown in Fig. 4.

It is shown in Fig. 4 that there are some differences between grid diagram for Δt equals 0 and 5 years, especially in grid line. In grid diagram for $\Delta t_{\min}$ equals 0 year, grid line for SK1 and SK2 is below pinch point, while in grid diagram $\Delta t_{\min}$ equals 5 years, line of SK1 and SK2 crosses pinch point, because of the time difference. Some notable pairings are all of CO_2 from SR1, which is 44.65 Mt, is not captured at all. SK1 receives 3.4 Mt of CO_2 from SR5, and SK2 receives 4.83 Mt of CO_2 from SR2. Because of the time difference, there are unutilized storage from SK1 and SK2. The other pairings are shown in Fig. 4. Alternative storage comes from SR1, SR2, SR3, and SR5, with 44.65, 0.42, 2.261, and 42.063 Mt of CO_2 needs alternative storage respectively. Unutilized storage comes from all of the sink, with 0.85 Mt of CO_2 from SK1, 0.42 Mt of CO_2 from SK2, 10.668 Mt of CO_2 from SK3, 1.6587 Mt of CO_2 from SK4, 0.9429 Mt of CO_2 from SK5, and 3.1427 Mt of CO_2 from SK6.

The last cascade table for simultaneous method, which is Δt equals 10 years, is shown in Table 5. As predicted before, the amount of alternative storage needed and unutilized storage is increasing. For $\Delta t_{\min}$ equals 10 years, the amount of alternative storage needed is 96.845 Mt of CO_2, while the amount of unutilized storage is 25.113 Mt of CO_2. Pinch point for $\Delta t_{\min}$ equals 10 years is year 32, similar with the other time differences. However, the sink pinch year is now in year 22. Grid diagram is made based on cascade table that has been generated before and is shown in Fig. 5.

In Δt equals 10 years, every stream, either source or sink, needs either alternative storage or unutilized storage. SR1 and SR2 in $\Delta t_{\min}$ equals 10 years do not transfer any CO_2 to any sinks, which leads to requirement of alternative storage as big

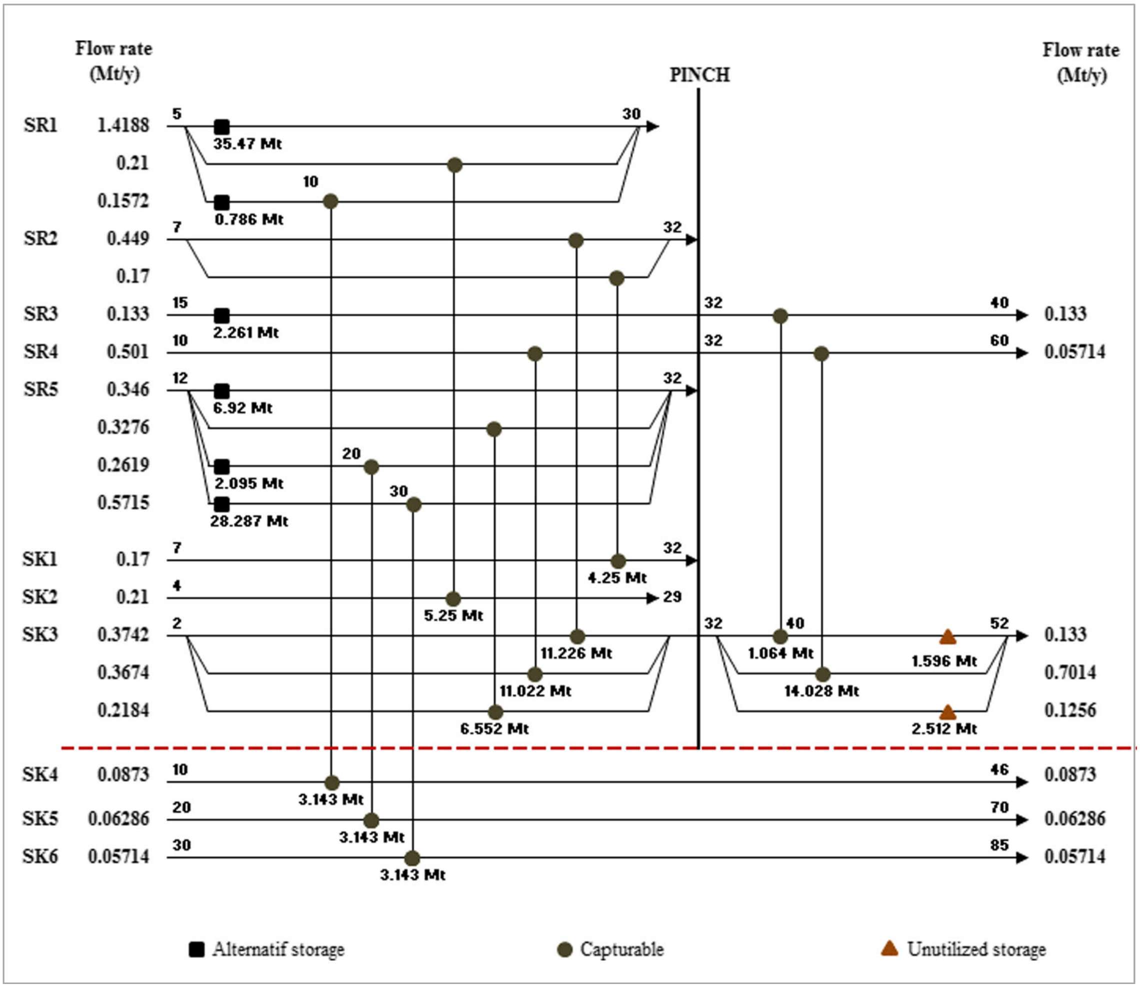


Fig. 6 Multi region grid diagram for $\Delta t_{\min}$ equals 0 year using sequential method

as 44.65 Mt of CO_2 for SR1 and 15.475 Mt of CO_2 for SR2. SK6 also does not receive any CO_2 from any sources, so there is 3.1427 Mt of CO_2 storage unutilized. The other requirements of alternative storage come from SR3, SR4, and SR5, with 2.261, 6.0687, and 28.39 Mt of CO_2 respectively. Unutilized storage comes from SK1, SK2, SK3, SK4, and SK5, with 0.636, 1.47, 14.792, 2.095, and 3.0173 Mt of CO_2 respectively.

Increasing uncaptured CO_2 and excess sink with increasing time difference, as mentioned before, is caused by the increasing possibility that sink has not been ready yet, while source of CO_2 has already started its capture process. Although $\Delta t_{\min}$ equals 0 year gives the best result in simultaneous method, it is very hard to be achieved in real world. Every aspect of CCS project needs to be perfect in order to achieve $\Delta t_{\min}$ equals 0 year. However, the presence of time difference generally acceptable, since there must be a little delay in planning of CCS project.

Carbon Capture and Storage Network Using Sequential Method

After CCS network is calculated using simultaneous method, next step is calculating mass transfer of CCS network using sequential method. This method is done by generating cascade table and grid diagram for single region, which is West Sumatra in this case, then the amount of alternative storage is transported to another region, in this case is East Java. Sequential method needs to be done in order to lower the amount of alternative and unutilized storage needed (Diamante et al. 2014).

Single region cascade table and multi region grid diagram for $\Delta t_{\min}$ equals 0 year are shown in Table 6 and Fig. 6.

Table 6 shows the cascade table for single region CCS network with $\Delta t_{\min}$ equals 0 year. Pinch point is obtained in year 32, which is the same as simultaneous method. The amount of alternative storage needed is 85.248 Mt,

Table 7 Single region cascade table for $\Delta t_{\min}$ equals 5 years

t (year)	Source, $S_{i,t}$ (Mt/y)	Sink, $D_{j,t}$ (Mt/y)	Δt	Flowrate CO_2 (Mt/y)	Load CO2 (Mt)	CO_2 cascade (Mt)	
						Infeasible	Feasible
5	SR1					0	91.318
	1.786		2	-1.786	-3.572		
7	SR2	SK3				-3.572	87.746
	0.619	0.960	2	-1.445	-2.89		
9		SK2				-6.462	84.856
		0.210	1	-1.235	-1.235		
10	SR4					-7.697	83.621
	0.501		2	-1.736	-3.472		
12	SR5	SK1				-11.169	80.149
	2.507	0.170	3	-4.073	-12.219		
15	SR3					-23.388	67.93
	0.133		15	-4.206	-63.09		
30						-86.478	4.84
			2	-2.42	-4.84		
32						-91.318	**0**
			2	0.706	1.412		**(PINCH)**
34						-89.906	1.412
			3	0.496	1.488		
37						-88.418	2.9
			3	0.326	0.978		
40						-87.44	3.878
			17	0.459	7.803		
57						-79.637	11.681
			3	-0.501	-1.503		
60						-81.14	10.178

while unutilized storage is 4.108 Mt. The CO_2 stream that needs alternative storage is then transported to another region. Results from cascade table are used to generate grid diagram, which is shown in Fig. 10.

Figure 6 shows that SR2, from year 7 to year 32 sends 11.226 Mt of CO_2 to SK3 and 4.25 Mt of CO_2 to SK1. SR4 sends 11.022 Mt of CO_2 to SK3 from year 10 until year 32 and continues sending 14.028 Mt of CO_2 to the same sink from year 32 until year 60. The other pairings are shown in Fig. 10. Alternative storage needed, based on grid diagram, is 75.819 Mt, which consists of 36.256, 2.261, and 37.301 Mt of CO_2 from SR1, SR3, and SR5 respectively. Unutilized storage needed is 4.108 Mt of CO_2, which comes from SK3.

Table 7 shows single region cascade table for $\Delta t_{\min}$ equals 5 years. Similar with simultaneous method, in sequential method, there is a tendency that alternative storage needed and unutilized storage is increasing with the increasing time difference. In $\Delta t_{\min}$ equals 5 years, the amount of alternative storage needed is 85.032 Mt of CO_2 and unutilized storage is 13.321 Mt of CO_2. Grid diagram is then generated and shown in Fig. 7.

As shown in Fig. 7, SR1 does not transfer any CO_2 to sink, which leads to 44.65 Mt of CO_2 needs an alternative storage. SR3 and SR4 transfer all of its CO_2 to several sinks and do not need any alternative storage. SR3 and SR5 transfer some of its CO_2 to sink in another region. SR3 transfers 2.261 Mt of CO_2 to SK4, while SR5 transfers 0.982 Mt of CO_2 to SK4 and 3.143 Mt of CO_2 to SK5. Besides SR1, alternative storage comes from SR2 with 0.42 Mt of CO_2 and SR5 with 39.962 Mt of CO_2. Unutilized storage in the system comes from SK1, SK2, SK3, and SK6, with 0.85, 0.42, 8.908, and 3.143 Mt of CO_2 respectively.

Single region cascade table is shown in Table 8. As predicted before, the amount of alternative storage needed and unutilized storage is increasing. Now, for $\Delta t_{\min}$ 10 years, alternative storage needed is 91.732 Mt of CO_2 and unutilized storage is 20.021 Mt of CO_2. Pinch point for this system remains the same with the other systems. Grid diagram based on cascade table for $\Delta t_{\min}$ equals 10 years is shown in Fig. 8.

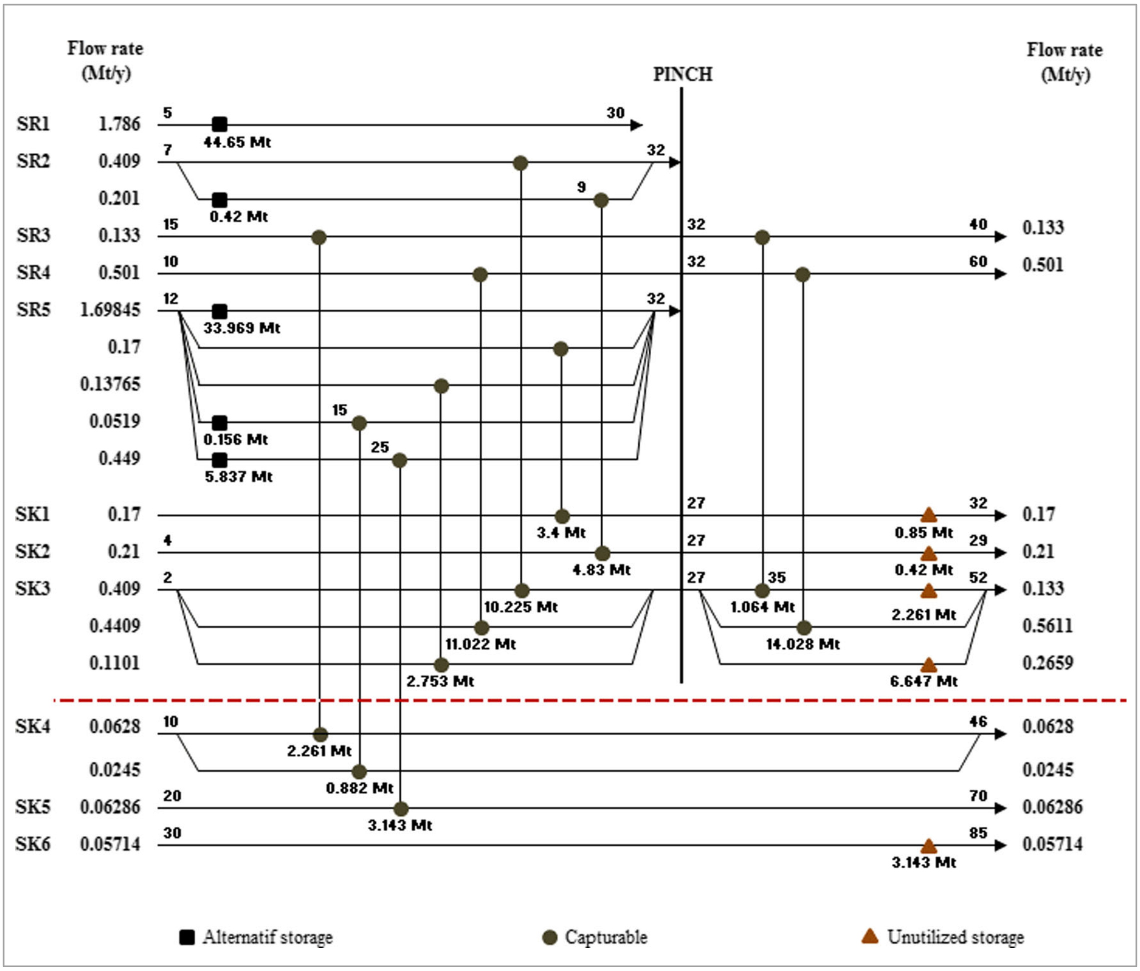
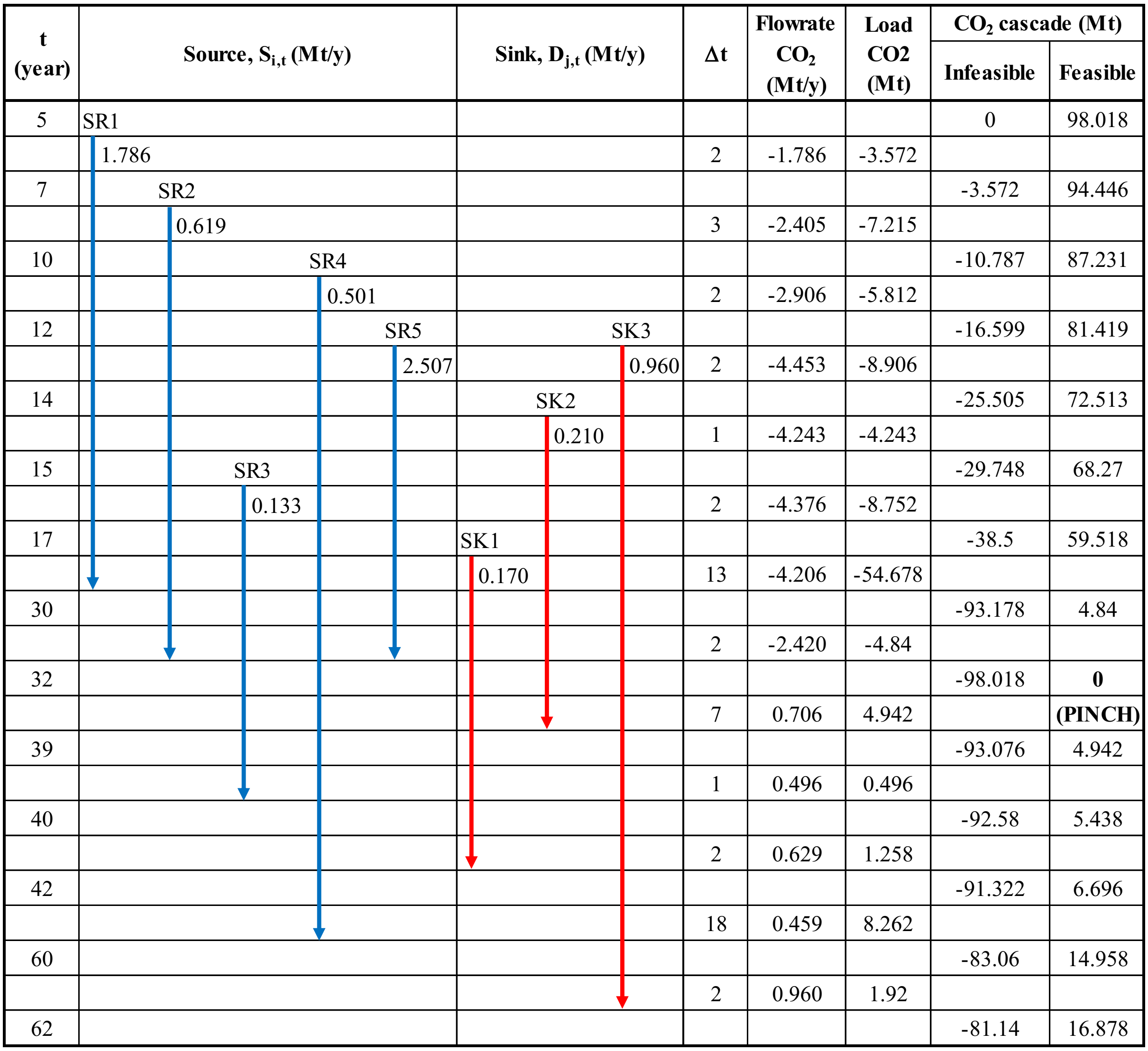


Fig. 7 Multi region grid diagram for $\Delta t_{\min}$ equals 5 years using sequential method

Table 8 Single region cascade table for $\Delta t_{\min}$ equals 10 years



t (year)	Source, $S_{i,t}$ (Mt/y)	Sink, $D_{j,t}$ (Mt/y)	Δt	Flowrate CO_2 (Mt/y)	Load CO2 (Mt)	CO_2 cascade (Mt)	
						Infeasible	Feasible
5	SR1					0	98.018
	1.786		2	-1.786	-3.572		
7	SR2					-3.572	94.446
	0.619		3	-2.405	-7.215		
10	SR4					-10.787	87.231
	0.501		2	-2.906	-5.812		
12	SR5	SK3				-16.599	81.419
	2.507	0.960	2	-4.453	-8.906		
14		SK2				-25.505	72.513
		0.210	1	-4.243	-4.243		
15	SR3					-29.748	68.27
	0.133		2	-4.376	-8.752		
17		SK1				-38.5	59.518
		0.170	13	-4.206	-54.678		
30						-93.178	4.84
			2	-2.420	-4.84		
32						-98.018	**0**
			7	0.706	4.942		**(PINCH)**
39						-93.076	4.942
			1	0.496	0.496		
40						-92.58	5.438
			2	0.629	1.258		
42						-91.322	6.696
			18	0.459	8.262		
60						-83.06	14.958
			2	0.960	1.92		
62						-81.14	16.878

In $\Delta t_{\min}$ equals 10 years, every source needs alternative storage, similar with simultaneous method for Δt equals 10 years. SR1, SR2, SR3, SR4, and SR5 need 44.65, 15.41, 1.995, 4.021, and 25.636 Mt of CO_2 alternative storage. The difference between simultaneous methods is SK4, and SK5 do not have unutilized storage. All of the storage capacity of those sinks is filled with CO_2 from SR3 and SR5. Unutilized storage from the system comes from SK1 with 0.636 Mt of CO_2, SK2 with 1.47 Mt of CO_2, SK3 with 14.772 Mt of CO_2, and SK6 with 3.143 Mt of CO_2.

Summary of results, either for simultaneous method and sequential method, are shown in Table 9.

Based on table above, CCS using sequential method gives a better result in terms of capturable CO_2. For the same $\Delta t_{\min}$, sequential method gives smaller amount of both alternative and unutilized storage. This is because in sequential method, sink in East Java region is utilized more, compared with simultaneous method. By utilizing more sink in East Java, alternative storage requirement will be lower and utilized storage will be higher, affecting amount of capturable CO_2.

Carbon Capture and Storage Network Optimization Based on Total Annual Cost

Based on CCS network design result, there are six schemes of mass transfer network that can be used. From each scheme, economic analysis based on minimum TAC is used to determine the best mass exchanger

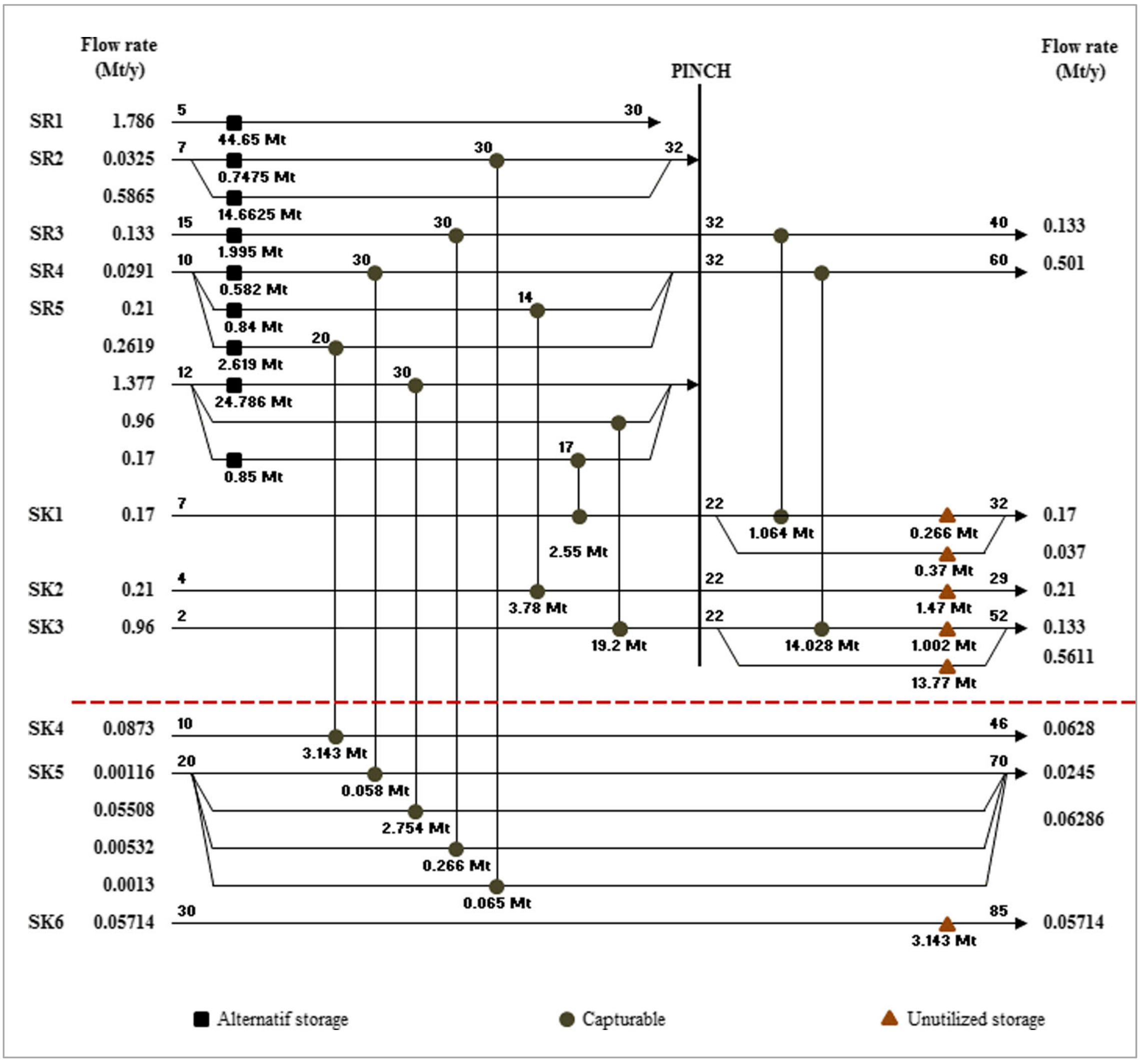


Fig. 8 Multi region grid diagram for $\Delta t_{\min}$ equals 10 years using sequential method

network. As mentioned before, calculated TAC will consist of TAOC and TACC of piping, shipping, and penalty, which will vary for each scheme. Based on formula that has been described before, calculation of TAC is shown in Table 10.

Based on Table 4, the graph between Δt and TAOC, TACC, and TAC can be generated to find the best and optimum time difference (Figs. 9 and 10).

From Figs. 9 to 10 above, the value of TAOC is increasing for each $\Delta t_{\min}$ either for simultaneous or

Table 9 Summary of CCS network result

Δt	Alternative storage (Mt)	Capturable (Mt)	Unutilized storage (Mt)	% CO_2 capture
Simultaneous method				
0	82.459	56.181	10.747	83.94
5	89.394	49.246	17.682	73.58
10	96.845	41.795	25.133	62.45
Sequential method				
0	75.819	62.821	4.108	93.86
5	85.032	53.608	13.321	80.1
10	91.732	46.908	20.021	70.09

Table 10 TAC calculation

Δt	TAOC	TACC	TAC
Simultaneous method			
0	US$ 104,842,000	US$ 64,289,000	US$ 169,131,000
5	US$ 121,448,000	US$ 38,846,000	US$ 160,294,000
10	US$ 133,096,000	US$ 37,814,000	US$ 170,910,000
Sequential method			
0	US$ 101,303,000	US$ 129,429,000	US$ 230,732,000
5	US$ 116,179,000	US$ 54,148,000	US$ 170,327,000
10	US$ 140,776,000	US$ 180,214,000	US$ 320,990,000

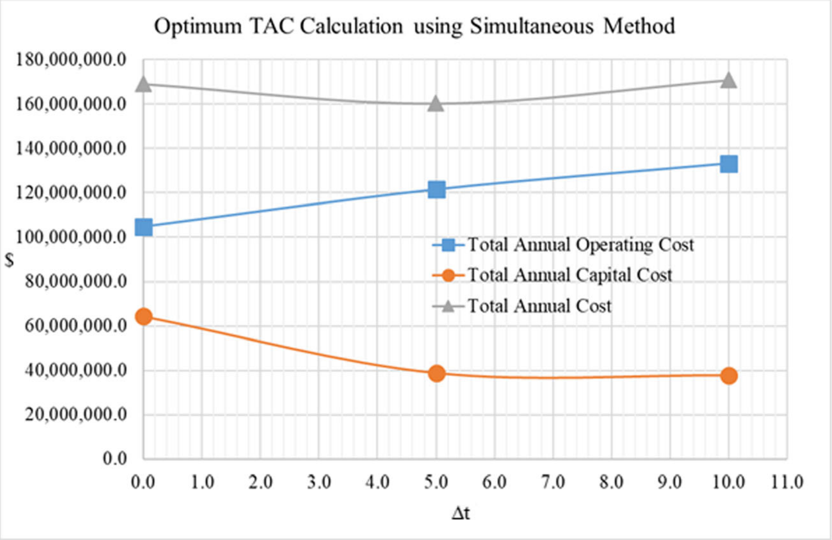


Fig. 9 Optimum TAC calculation using simultaneous method

sequential method. Increasing of TAOC is mainly caused by penalty fee. The bigger value of $\Delta t_{\min}$, the amount of alternative and unutilized storage will also increase, which will affect in the amount of penalty fee that needs to be paid as TAOC.

For TACC in simultaneous method, the longer $\Delta t_{\min}$ of the system, the amount of TACC is decreasing, while for sequential method, there is a fluctuation regarding the amount of TACC. This fluctuation happens because in $\Delta t_{\min}$ equals 10 years, CCS network has a bigger number of multi region for mass transfer and shorter time operation compared with $\Delta t_{\min}$ equals 5 years. TACC is significantly affected by capital cost of piping, the further the distance, bigger flow rate, and shorter operation time of CO_2 transportation will give bigger TACC.

Based on TAC result, it is obtained that optimum time difference for simultaneous method is 4.6 years with TAC amount US$ 159,259,000. In sequential method, although there is fluctuation in TACC result as explained before, optimum time difference is obtained in 4.5 years with TAC amount US$ 166,667,000.

Conclusion

Our works have shown that pinch design method can be used exactly as the method used in the heat exchanger networks. The pairing between sources and sink was successfully done in this work. The pairing can use minimum time difference of 0, 5, and 10 years. With the pairing analogous to the heat exchanger networks, it will make it clear to all readers how

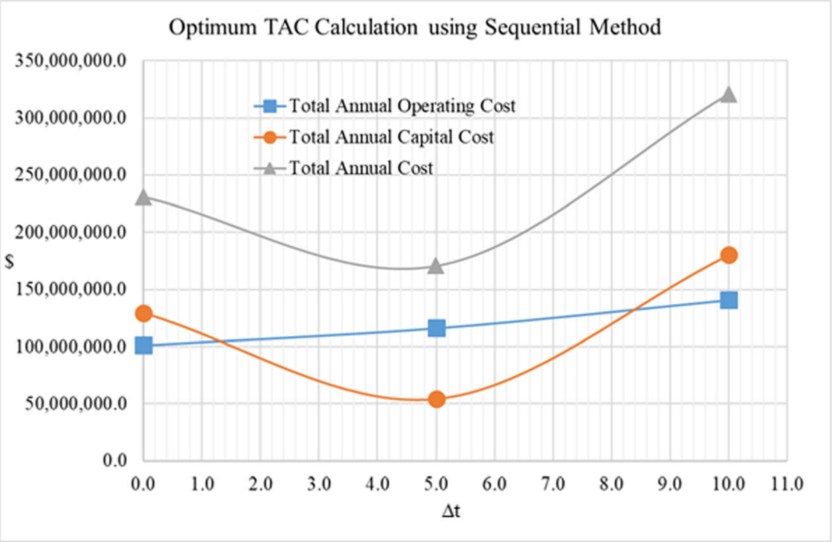


Fig. 10 Optimum TAC calculation using sequential method

to get maximum CO_2 capture in order to mitigate CO_2 emissions to the atmosphere. Two methods that are simultaneous and sequential methods were applied to problems in CCS. The results were the larger minimum time difference, the smaller the amount of captured CO_2 was, either for simultaneous or sequential method. Carbon capture and storage using sequential method is best applied if the only concern is the amount of CO_2 captured. In sequential method, maximum capturable CO_2 is 93.86%, while in simultaneous method, maximum capturable CO_2 is 83.94%. The least total annual cost is obtained in simultaneous method with time difference 4.6 years, which is US$ 159,259,000, compared to sequential method with time difference 4.5 years, which is US$ 166,667,000.

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Nomenclatures *D*, Diameter (m); ε, Surface roughness (m); *f*, Friction factor; i, Interest; ṁ, Mass flow (kg/s); n, Year; *ρ*, Density (kg/m^3); P_{in}, Inlet pressure (bar); P_{out}, Outlet pressure (bar); Re, Reynold number; T, Temperature (°C); *μ*, Viscosity (Ns/m^2)

Appendix

Problem Table Algorithm for CCS Network Calculation

Algebraic technique developed to address CCS planning problem has been conducted by Ooi et al. (2013) and Diamante et al. (2014). This method is similar to problem table algorithm, a method of calculating energy targets directly without the necessity of graphical construction and analogous to material cascade analysis for resource conservation network. The problem table algorithm method is used to find the maximum energy recovery in the heat exchanger networks (Smith 2005). The general framework for this method is shown in Fig. 11.

Table 11 shows generic cascade table for CCS system. A table consists of eight columns with following name: lifespan time (t), source (S), sink (D), time interval (Δ*t*), flow rate CO_2, load CO_2, and infeasible and feasible CO_2 cascade.

CO_2 cascade in column 7 yield the cumulative surplus/deficit CO_2 transfer. The largest deficit value represents the alternative CO_2 storage required for feasible cascade solution. Suppose $\Delta m_1 + \Delta m_2$ is the largest deficit value, then the pinch point of the system is obtained in lifespan time t equals 5 years. In lifespan time, t equals 1 year, alternative storage is $\Delta m_1 + \Delta m_2$. In lifespan time, t equals T + 1 years, the amount of

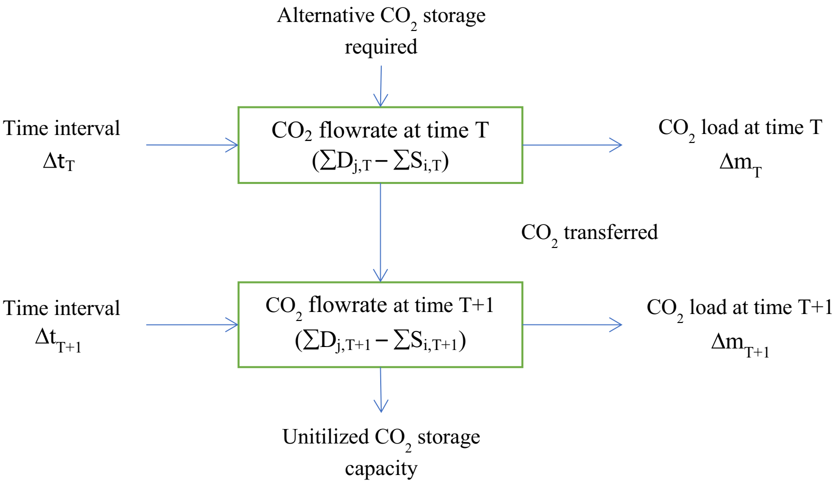

Fig. 11 General framework for CCS cascade system design

Table 11 Generic cascade table for CCS system

Lifespan Time (t)	Source, $S_{i,t}$ (Mt/y)	Sink, $D_{j,t}$ (Mt/y)	Δt	CO_2 flowrate ($\sum D_{j,t} - \sum S_{i,t}$)	CO_2 load (Mt)	CO_2 cascade infeasible (Mt)	CO_2 cascade feasible (Mt)
1	2	3	4	5	6	7	8
1	SR1					0	$\Delta m_1+\Delta m_2$
2	SR2	SK1	Δt_1	($\sum D_{j,1} - \sum S_{i,1}$)	$\Delta m_1 = (\sum D_{j,1} - \sum S_{i,1})\Delta t_1$		
3		SK2				$0+\Delta m_1$	Δm_2
4			Δt_2	($\sum D_{j,2} - \sum S_{i,2}$)	$\Delta m_2 = (\sum D_{j,2} - \sum S_{i,2})\Delta t_2$		
5						$\Delta m_1+\Delta m_2$	0
6			Δt_3	($\sum D_{j,3} - \sum S_{i,3}$)	$\Delta m_3 = (\sum D_{j,3} - \sum S_{i,3})\Delta t_3$		(PINCH)
7						$\Delta m_1+\Delta m_2+\Delta m_3$	Δm_3
	↓	↓				$\Delta m_1+\ldots+\Delta m_{T-1}$	$\Delta m_3+\ldots+\Delta m_{T-1}$
T	↓	↓	Δt_T	($\sum D_{j,T} - \sum S_{i,T}$)	$\Delta m_T = (\sum D_{j,T} - \sum S_{i,T})\Delta t_T$		
T+1						$\Delta m_1+\ldots+\Delta m_T$	$\Delta m_3+\ldots+\Delta m_T$

unutilized storage is $\Delta m_3 + \ldots + \Delta m_T$. Notice that at t equals 5 years there is no mass of CO_2 moving from the source to the sink. This is the rule for getting the maximum CO_2 capture.

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