Evaluation of Efficient CCUS System Design from Chemical Industry Emission in Indonesia

Vibianti Dwi Pratiwi[1], *Renanto* Renanto[1,*], *Juwari* Juwari[1], *Rendra* Panca Anugraha[1], and *Rizal* Arifin[1]

[1]Department of Chemical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia

Abstract. Carbon dioxide (CO_2) emissions from industry significantly contribute to increasing CO_2 in the atmosphere as the main cause of the Green House Gas (GHG) effect and climate change. CO_2 emissions cause the need for evaluation in finding emission reduction systems. The CCUS (Carbon Capture Utilization and Storage) system is one of the most studied emission reduction systems. This study aims to obtain an intuitive and quantitative CCUS network design framework using GAMS (General Algebraic Modeling System) software with a mathematical approach. Several sources of CO_2 emissions and potential absorbers are scattered in several regions in Indonesia. A mathematical approach was developed to optimize the amount of CO_2 stored and utilized by varying the minimum time difference (dt min) between source and sink from 0, 3, 5, 8, to 10 years. The economic potential of the source-sink pair decreases with the change in dt with an average of 6.50×10^6 USD. Based on the potential economic value, the CCUS system with industrial CO_2 emission sources has a positive value that can be applied in Indonesia.

1. Introduction

Increased carbon dioxide (CO_2) atmospheric emissions significantly impact the global climate. Therefore, there is an urgent need to measure and reduce the impact of carbon dioxide emissions on global climate change [1]. CO_2 emissions from burning fossil fuels in power plants, and other industrial processes cause climate change [2]. CO_2 emissions have increased rapidly in several countries, along with the increasing consumption of fossil fuels. Indonesia is among the countries with high levels of greenhouse gas emissions [3]. The role of carbon removal in meeting climate change prevention is emphasized by the Intergovernmental Panel on Climate Change (IPCC), including net-zero emissions, which requires several carbon removal approaches such as Carbon Capture Utilization and Storage technology [4]. CCS/CCUS is one of the climate change mitigation technologies that can potentially reduce large-scale CO_2 emissions from burning fossil fuels [5].

The strategies to achieve the desired emission level come from CCS and CCU. The concept of CCS is the reduction of emissions from large industrial sources by capturing the CO_2 emission from the exhaust gases and subsequently storing it in appropriate geological storage sites or using for utilization options such as enhancing oil recovery (EOR) and converting to methanol [6, 7, 8, 9]. Three major elements are involved in this technology, each of which has significant investment costs, namely, CO_2 capture, transport, and storage. The proper CO_2 transportation design can reduce investment costs [10, 11]. Technologies that enable

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[*]Corresponding author: renanto@chem-eng.its.ac.id

CO_2 capture, transport, storage, and storage are still stable, so researchers are working to develop more cost-effective CCS technologies [12].

Indonesia is actively developing CCS/CCUS to reduce CO_2 sources and increase CO_2 storage capacity. The natural gas industry in Indonesia offers the potential for CCS/CCUS to reduce CO_2 emissions, especially from the oil and gas, power, and industrial sectors [13, 14]. Java and Sumatra are the largest contributors to CO_2 emissions in Indonesia, at 60 Mt/year and 25 Mt/year. Kalimantan and Sulawesi contribute 5 ton/year [3,15]. Also, Indonesia has several sedimentary basins for geological storage, such as depleted oil and gas fields. More than 600 Mt of CO_2 can be stored in depleted oil and gas reservoirs such as the Sukowati field, Tangguh, and several areas spread across Indonesia [2, 3, 16-18].

The development of CCS systems takes several decades for various reasons, such as finding new geological sinks, the availability of carbon transportation infrastructure, plans for introducing new carbon sources, and geological sinks that only become available later. These factors lead to matching sources and sink with time considerations [2, 3, 8]. Previous researchers made designs related to CCS/CCUS based on pinch analysis [3, 5, 8, 19 – 26]. Researchers also developed CCS/CCUS designs using mathematical modelling to obtain economical designs [7, 27-31].

Based on previous research, the design of CCS/CCUS systems, especially in Indonesia, using superstructure technology and mathematical modelling, is still not optimal. So, it is necessary to conduct a configuration study to determine the design of CCS/CCUS pairs from emission sources at several factories in Indonesia that can be injected into geological storage and utilization sinks. This study will design a superstructure source and sink pair based on a non-linear program (NLP) approach with GAMS (General Algebraic Modeling System) software that is optimal and economical. The economic evaluation of the CCS/CCUS design is based on incentive costs, emission taxes, the price of CO_2 sold for utilization, and operating costs, including CO_2 purification and delivery costs from the source to the sink.

2. Methods

This research developed a non-linear programming (NLP) mathematical approach to optimize the source–sink pair design with a limited minimum difference time (dt min). Figure 1 illustrates the distribution of CO_2 emissions from the source to the geological storage. CO_2 emissions that cannot be injected into geological storage are called Total Alternative Storage (TAS) and will be sent to the Utilization Sink. Excess CO_2 emissions that cannot be sent to the Utilization Sink are called Total Alternative Sinks (TASi). The time difference between source and storage or sink will cause excess storage or sink capacity called Total Unutilized Storage or Sink (TUS or TUSi).

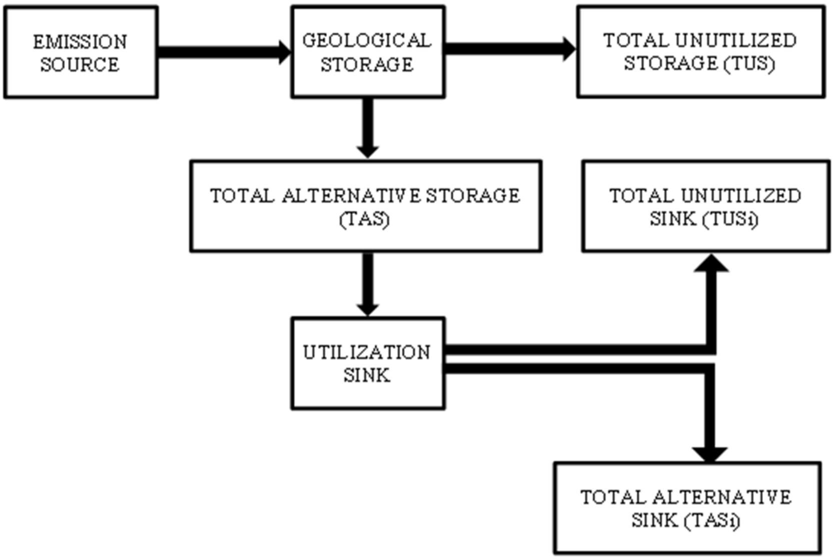

Fig. 1. Illustrates the distribution of CO_2 emissions from source to storage or sink.

2.1 Data Collection

Matching a source-storage and an alternative storage-utilization sink pair requires data such as CO_2 flow rate and time from industrial CO_2 sources. Table 1 shows the flow rate of CO_2 emissions from several factories in Indonesia [2, 3, 17, 18]. Storage capacity data and availability time are taken from [2, 3, 17, 18], while CO_2 needs for utilization sink [32] are based on data from the industry, as shown in Tables 2 and 3.

Table 1. Sources data for CCSU study in Indonesia

Code	Industrial source	Cluster	Start time (y)	Duration (y)	End time (y)	CO_2 emission rate (Mt/y)	CO_2 Load (Mt)
SR1	PLN Bukit Asam	R1 (Su)	5	25	30	1.79	44.65
SR2	RU III Plaju	R1 (Su)	7	25	32	0.62	15.48
SR3	Merbau GGS	R1 (Su)	15	25	40	0.13	3.33
SR4	Semen Batu Raja	R1 (Su)	10	50	60	0.51	25.05
SR5	Pusri Palembang	R1 (Su)	12	20	32	2.51	50.14
SR6	Pupuk Kaltim	R2 (EK)	5	25	30	2.41	60.08
SR7	Badak LNG	R2 (EK)	5	15	20	5.52	82.71
SR8	Semen Bosowa	R3 (SS)	7	20	27	1.58	31.5
SR9	Semen Tonasa	R3 (SS)	8	20	28	3.79	75.82
SR10	LNG Tangguh	R4 (WP)	5	20	25	4.31	86.04
Total CO_2 produced							**474.80**

Table 2. Geological Storage data for CCSU study in Indonesia

Code	Geological Storage	Cluster	Start time (y)	Duration (y)	End time (y)	CO_2 injection rate (Mt/y)	CO_2 Capacity (Mt)
SK1	Sakakemang	R1 (Su)	25	15	40	29.4	441

SK2	Site 3	R1 (Su)	2	50	52	0.96	48
SK3	Kutai Basin	R2 (EK)	5	30	35	4.65	139.5
SK4	Salawati Basin	R4(WP)	5	20	25	0.885	17.7
Total CO_2 Capacity							**646.20**

Table 3. Utilization of Sink data for CCSU study in Indonesia

Code	**Utilization Sink**	**Cluster**	**Start time (y)**	**Duration (y)**	**End time (y)**	**CO_2 injection rate (Mt/y)**	**CO_2 Capacity (Mt)**
SK5	EOR – attaka field	R2 (EK)	10	20	30	5.853	117.06
SK6	EOR – handil field	R2 (EK)	10	20	30	8.119	162.38
SK7	Methanol	R4(WP)	5	25	30	1.2	30
Total CO_2 Capacity							**309.44**

2.2 Algorithm

Emission rate data in Table 1 and storage capacity in Table 3 will be inputted to GAMS to obtain the maximum recovery that can be injected from source to storage. Then, Total alternative storage that cannot be injected into storage will be paired with a utilization sink. The aim is to determine maximum recovery by matching CO_2 sources and storage or sinks. The maximum recovery is also equivalent to maximizing the total CO_2 captured and utilized with the hope that, in the future, this model can be used for CCUS planning in Indonesia. Maximum recovery can be defined in Equation 1 as follows:

$$\max \sum_i \text{source } i = \sum_i (t_{ij\ end} - t_{ij\ start}) \text{ x } S_{ij} \qquad \forall_{ij} \qquad (1)$$

Where i is the number of sources and j is the amount of storage or sink available on the system ($\forall_{ij}$). Tij end is the end time of the Source and Storage or Sink simultaneously so that the load on the source stops being injected at the end of the year. Tij start is the starting time for the source and storage or sink simultaneously so that the load on the source can be paired with the sink. Sij is the amount of Source discharge injected into the storage or sent to the sink and adjusted to the receipt of Sink Injectivity Capacity [7].

$$S_{ij} \text{ x } (t_{ij\ end} - t_{ij\ start}) \leq D_j\ (t_{j\ end} - t_{ij\ start}) \qquad \forall_{ij} \qquad (2)$$

Dj is the CO_2 injection rate that Storage or Sink j can receive, or it can be called the debit limit that goes into the storage or utilization sink available in the system, as shown in Table 2 and Table 3. Sij value is the maximum recovery of CO_2 discharge that can be accepted so that the discharge entering Sink j must be less than or equal to the available discharge limit. Tj end is the end time Sink j, and Tj start is the first time Sink j is available. Source debits injected into Storage or Sink may not exceed the specified and appropriate injectivity limits allowed for distribution [7].

2.3 Economic Analysis

The economics of the CCUS network design is analyzed based on the carbon management hierarchy. The economics of the CCUS network design is calculated from the four cost components as the economic target: carbon taxes, carbon sales, carbon incentives, and carbon costs [2]. The CCUS system has three main elements related to carbon costs: carbon capture, transportation, and storage or injection. Excess CO_2 emissions that cannot be recovered or alternative sinks will be subject to a carbon tax. CO_2 emissions that can be recovered under the CCS system or converted under the CCU scheme will be given carbon incentives. Also, CO_2 emissions sent to sink utilization can be sold as carbon sales. Carbon incentives and carbon sales from the CCU scheme are expected to provide positive economic value because they reduce costs arising from carbon taxes and carbon costs [2]. An illustration of potential economic evaluation in a grid diagram is shown in Figure 2.

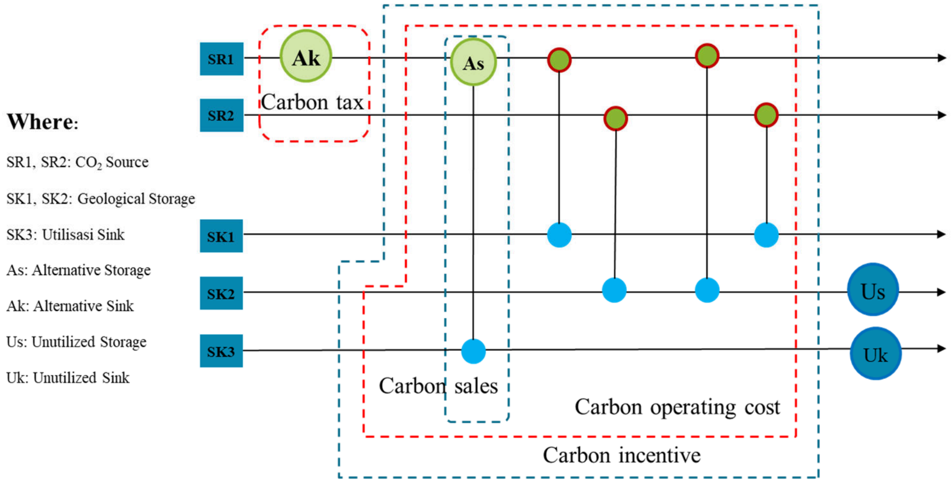

Fig. 2. Illustrates the distribution of CO2 emissions from source to storage or sink.

As shown in Figure 2, the carbon tax (CT) on the left represents a tax or fee that must be paid for excess carbon emissions that cannot be captured. Carbon sales (CS) are income from the sale of captured CO_2 emissions to sink utilization. Transferring carbon from source to sink results in two components of costs: capital costs (CC) and carbon incentives (CI). Capital costs are generated from the investment and operating costs of CCUS facilities, including CO_2 capture, transportation, injection facilities, and utilization facilities [2]. Meanwhile, carbon incentives trigger efforts or activities to withdraw CO_2 emissions through CCS or CCU. The total costs incurred in the CCUS system, along with the incentives and revenues earned, generate economic potential (EP), which is used to analyze the feasibility of the system design from an economic point of view. In general, equation 3 for calculating EP can be stated as follows:

$$EP = CI + CS - (CC + CT) \tag{3}$$

The data used in calculating the potential economy is in Table 4.

Table 4. Potential Economic Calculation Parameter Data

Parameter	**Cost (x10_6 USD/ Mt CO_2)**	**Reference**
Carbon tax (CT)	0.030	33
Carbon incentive (CI)	0.010	34
Carbon Capture (CC)	0.00456	Aspen Plus
Carbon Transport (CC)	0.0079	6
Carbon sales (CS)	0.066	35

The calculation of the economic potential for the CCUS design is observed based on the time difference (dt). Implementing a minimum time difference scenario in CCUS will affect the cost of the CCUS system [5]. The scenario used is to increase the minimum time difference at certain intervals and examine the resulting changes in economic potential. Variation of dt min will be increased from 0, 3, 5, 8, and 10 years.

3. Result and Discussion

The integration of CCS with CCU to become CCUS is projected to provide positive economic value. Industrial CO_2 sources can be equipped with CO_2 capture technology to capture and produce CO_2 with various quality levels. For example, in a power plant that uses fossil fuels, CO_2 captured from flue gas can be used to make methanol. In addition, CO_2 capture from oil or gas wells is often used as EOR injection in oil reservoirs that have experienced a decline in production [36].

Integrating CO_2 sources, CO_2 capture technology, utilization, and storage site selection are among the main problems in the large-scale deployment of CCUS. Other main problems include reducing energy requirements for CO_2 capture, choosing the right utilization technology, and the problem of uncertainty about the characteristics of geological storage [9]. In addition, other problems arose when the CCUS components were integrated, such as the mismatch between operating times and flow rates of the CCUS components. Because the components in the system are generally in the form of refineries operated by different companies, it is necessary to have facilities that can be used together, such as piping for CO_2 transportation [6].

In this study, the design of the CCS/CCUS pair will be evaluated based on the potential economic value of making the design of the CCUS partner in reducing CO_2 emissions from the industry. Before determining the economic potential of each design, it is necessary to find a partner between the source and storage or sink first. Based on the data in Table 1, several CO_2 sources are obtained with flow rates and CO_2 emission availability periods. The data is injected into geological storage first, and then the remaining CO_2 that is not injected will be used or sold to the industry or utilization sink. The results of the pairing between sources originating from factory emissions and geological sinks are shown in the grid diagram of Figure 3 below;

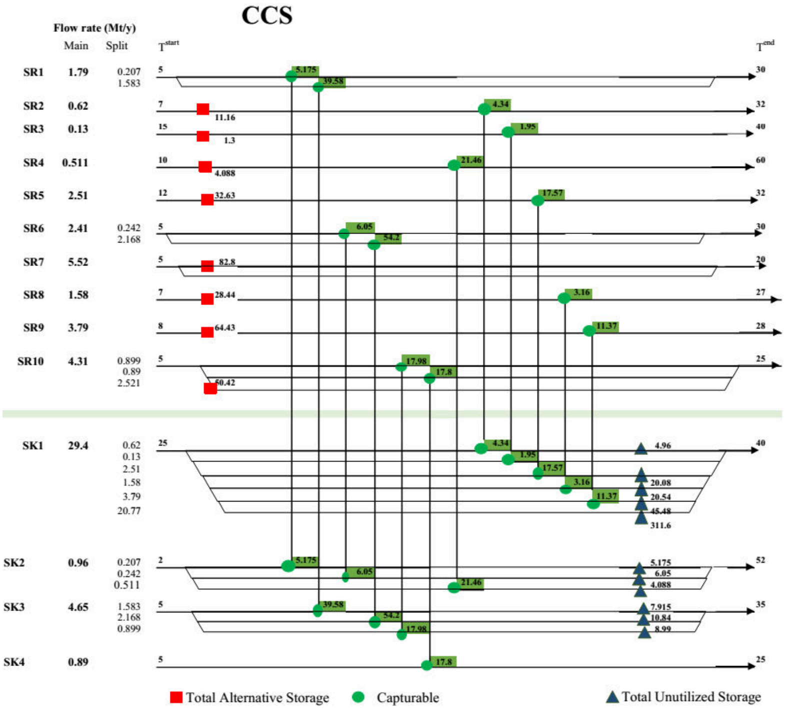

Fig. 3. Grid Diagram for Design of CCS Pairs

The CCS design in Figure 3 above shows that the maximum CO_2 that can be paired with geological storage in Table 2 is 200.63 Mt. Based on equations 1 and 2 to get maximum recovery or CO_2 Capture, SR1 and SR6 need to be split so that the entire CO_2 flow rate can be paired with SK 2 and SK3. This is based on the CO_2 flow rate and timespan between source and storage matching the specified constraints. Meanwhile, SR2, SR3, SR4, SR5, SR7, SR8, SR9, and SR10 each leave CO_2 emissions that cannot be injected into storage. Alternative storage that cannot be injected is 275.3 Mt CO_2. The initial and final duration difference between source and storage results in CO_2 emissions that cannot be injected into geological storage. The remaining 275.3 Mt of CO_2 emissions or excess CO_2 not paired with geological storage will be delivered with a utilization sink, as shown in Figure 4.

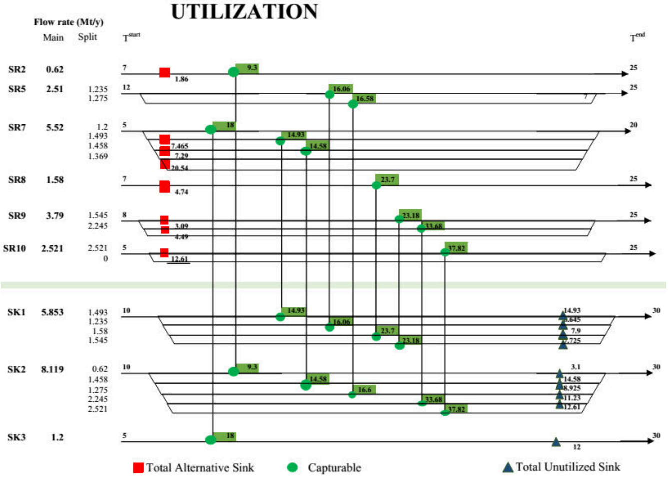

Fig. 4. Grid Diagram for Design of CCSU Pairs

Figure 4 shows that alternative storage or residual CO_2 emissions that cannot be injected into geological storage are sent to utilization sinks. Same as how to calculate source and storage pairing, source and sink pairs use equations 1 and 2. From Figure 3, SR2, SR5, SR7, SR8, SR9, and SR10, which have residual CO_2 emissions that cannot be injected into geological storage, will be paired and transferred to the utilization sink (SK1, SK2, and SK3). SR3 and SR4 cannot be paired with SK because they do not match the specified constraints, and SR5 needs to be split to be paired with SK1 and SK2. Alternative storage or CO_2 emission that can be paired with a utilization sink of 207.81 Mt. Meanwhile, SR2, SR7, SR8, SR9, and SR10 each leave CO_2 emissions that cannot be transferred to the utilization sink and leave CO_2 emissions of 67.46 Mt. Matching the Source-Storage or Sink pair for the CCUS system (dt min=0) can produce a recovery of 408.42 Mt or 86.02% of the total available storage and sink capacity.

The recovery results obtained are different when there is a dt min as shown in Table 5. Variations in dt min will affect the amount of CO_2 emissions injected into geological storage or transferred to utilization sinks. This is because the period of geological storage and sink utilization will shift along with variations in dt min, which indicates that storage and sink availability are advancing. As shown in dt min 3, the amount of CO_2 emissions injected decreases because the source and storage/sink pairs decrease due to the storage/sink timespan shifting away from the source timespan. So, CO_2 emissions (TASi) that cannot be injected into storage and transferred to sinks are getting bigger. The variations in dt min 5, 8, and 10 years in Table 5 show the same thing.

Table 5. Comparison of CCS/CCUS matches by dt min variation

dt min (y)	**CCS (Mt)**	**CCU (Mt)**	**Max CO_2 Capt (Mt)**	**TASi (Mt)**	**TUN (TUS + TUSi) (Mt)**	**% CO_2 Capture**
0	200.61	207.81	408.42	67.46	445.59	86.02
3	166.58	157.52	324.10	83.40	479.62	68.26
5	150.34	165.55	315.89	133.00	495.86	66.53
8	135.98	113.97	249.95	152.89	510.22	52.64
10	123.24	83.63	206.87	157.94	522.96	43.57

Table 5 shows that the maximum CO_2 that can be paired with geological storage and sink utilization will decrease as dt min increases. The increase of dt min is because the time span of the storage or sink changes based on availability or readiness for use in the CCUS system. Several problems arise in CCS planning, such as geographical conditions (especially for archipelagic countries like Indonesia), consideration of the distance between emission sources and geological storage, and the availability of different operating times between CO_2 capture and injection into storage. Therefore, having a shorter time difference would be more acceptable in the CCS system design [3, 5].

Placement of pairs or matching between CO2 sources with appropriate storage or sinks is one of the main issues in planning a CCUS system. The right match between the source and storage or sink can help evaluate the economics of the system before carrying out a detailed engineering design [37]. In this study, the calculation of the economic potential for the CCUS design was also observed based on the minimum time difference (dt min) variation. Implementing the minimum time difference scenario in CCUS will affect the cost of the CCUS system. As shown in Table 4, the total alternative sinks or the remaining CO_2 emissions that are removed will be even greater, so it is necessary to pay taxes. CO_2 recovery that can be injected or sent to the utilization sink must incur operating costs; however, it will be given an incentive because it can reduce emissions. In addition, there is income from sending CO_2 to sink utilization through carbon sales. The economic calculation results of the dt min variations are shown in Figure 5.

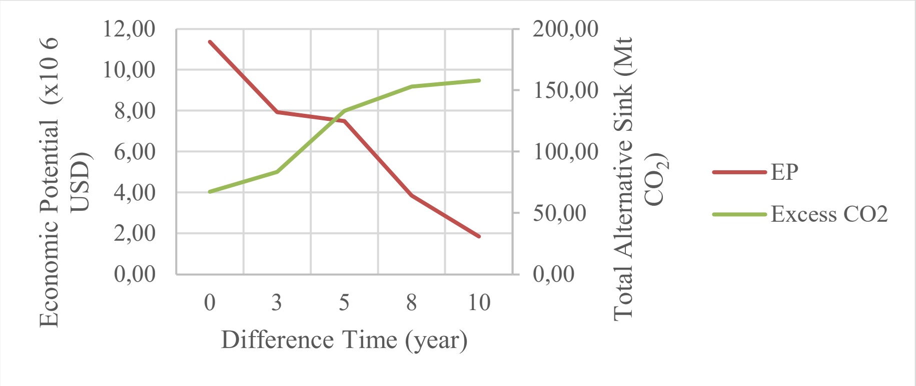

Fig. 5. Comparison of the economic potential by the minimum time difference

The scenario used is to increase dt min at certain intervals and examine the resulting changes in economic potential. The dt min will be increased from 0 to 10 years, as shown in Figure 5. In this study, the economic potential of the CCUS design from gas emissions is positive for all variations of the minimum time difference. The highest economic potential is dt min 0 of 11.36 x 10^6 USD (67.46 Mt excess CO_2), while the lowest is dt min 10 of 1.85 x 10^6

USD (157.94 Mt excess CO_2). As shown in equation 3, the CO_2 emissions that can be injected into geological storage and transferred to the utilization sink at dt min 0 variations are quite high, so the incentives and sales obtained will be high while the taxes and transportation costs paid are very low. Inversely proportional to the dt min 10 variation, where CO_2 emissions combined between source and storage/sink are the lowest.

An increase follows this decrease in economic potential in total alternative sinks or excess CO_2. This is because the greater the dt min, the less recovery of CO_2 injection and increasing the excess CO_2. The decrease in recovery will affect the income earned and an increase in spending to pay taxes due to excess CO_2. The network modelling obtained for each is different from one another due to differences in the limits set [7]. Thus, a simple model has been developed for optimal matching of CO_2 Source and Sink in a CCS system limited by temporal period, injectivity rate, and storage with capacity constraints. The matching resulting from this model can be changed if variable costs are considered.

4. Conclusion

The scenario used is to increase the minimum time difference at certain intervals and examine the resulting changes in economic potential. The highest economic potential at dt min 0 is 11.36 x 10^6 USD with 86.02% maximum CO_2 emissions that can be installed in storage or sinks. The lowest economic potential at 10 dt min is 1.85 x 10^6 USD, with 43.57% CO_2 emissions reduced from CO_2 sources. Thus, a simple model has been developed for optimal matching of the Source and Storage or Sink of CO_2 in the CCUS system in Indonesia, which is limited by the available period, injectivity rate, and storage with capacity constraints.

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