

# Pinch Based Approach Graphical Targeting for Multi Period of Carbon Capture Storage and Utilization

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## ABSTRACT

Carbon capture and storage (CCS) plays an important role in mitigating carbon dioxide emissions from industrial sources. The main issue in implementing CCS is its economy due to the high investment and operating costs. To overcome the economic issue, the carbon capture and utilization (CCU) provides an alternative option to CCS by converting some of the CO<sub>2</sub> captured to commercial products. The CCU has the advantage of generating revenue that offsets the cost of CCS. In this work, the integration of the CCS and CCU into a single system of carbon capture storage and utilization (CCSU) will be investigated. A novel graphical technique based on pinch analysis is proposed to address CCSU planning and targeting problems. The new definition of economic criteria are introduced to assess the CCSU system performance. Several utilization options such as methanol, dimethyl carbonate (DMC), and enhanced oil recovery (EOR) are applied to evaluate the feasibility of the CCSU system. The hypothetical case study is used to elucidate the proposed method. Among the case studies, the CO<sub>2</sub> utilization into DMC gives the best economic criteria, while the EOR provides the best CO<sub>2</sub> reduction criteria. The paper shows that the proposed technique gives the new insight for CO<sub>2</sub> emissions reduction planning and the new definition of economic criteria is a promising indicator for the CCSU targeting.

**Keywords:** pinch, carbon capture, carbon dioxide, enhanced oil recovery

## 1. INTRODUCTION

Around 15 million tons/year of CO<sub>2</sub> has been emitted by the power plant and other industrial sources worldwide. The international energy agency has projected to reduce carbon dioxide emissions to be around 20.1 Gt in 2030 [1]. The strategies to achieve the desired emission level come from CCS and CCU. Carbon capture and storage have been widely considered as key technology for mitigating climate change. The deployment of CCS at power plants and industrial sources has a significant barrier, mainly from relatively high costs [2]. Carbon capture and utilization give an additional option to carbon storage by utilizing the concentrated CO<sub>2</sub> from the capture as a feedstock to produce various valuable chemicals [3]. CCU has an opportunity to overcome the economic deficit resulting from the high cost of CCS.

The term CCS is now often replaced by CCUS. The CO<sub>2</sub> utilization technology is expected to play a major role in climate change mitigation strategies. However, the maturity of the technology of several CCU options

still in the developing stage. Only a few chemical processes utilizing CO<sub>2</sub> as a feedstock are currently identified as proven technology. Chauvy et al. (2020) proposed the method to select the most promising carbon dioxide utilization products. They found that methanol, methane, and dimethyl carbonate are the most promising CO<sub>2</sub>-based products to implement in short to mid-term industries [4]. Currently, the CCS is considered the most reliable technology to mitigate greenhouse gas emissions. The CCS is widely implemented worldwide and gives high-performance respect to engineering and environmental aspects.

The combination of CCS and CCU has gained significant attention from researchers and important players in the energy industry. More than 3000 patents are identified, including EOR, ECBM, chemical, and fuel [5]. The use of pinch analysis in the CCS and CCU applications has been explored in more recent work. The graphical approach based on the material recovery pinch diagram (MRPD) which became the basis for the subsequent works of CCS planning. El-Halwagi et al. (2003) was

introduced an MRPD. This is a graphical approach for mass targeting to minimize the use of fresh resources through material recycle/reuse technique [6]. The later work on MRPD was conducted by Prakash and Shenoy (2005). They proposed a method for freshwater targeting in the water network with a fixed contaminant load. The proposed method analogous to composite curve pinch diagram in heat exchanger networks [7].

The various graphical techniques have been developed for the planning of CCS system. Tan and Foo (2007) was developed Carbon Emissions Pinch Diagram for carbon targeting in the energy sector [8]. Ooi et al. (2013) proposed a graphical tool that complement with the grand composite curve (GCC) for CCS planning and scheduling [9]. The improvement of pinch analysis method for CCS planning was proposed by Diamante et al. (2014). They used cascade table for CCS targeting [10]. Handogo (2018) was proposed a method to design a CCS network based on pinch design method which is represented by a grid diagram [11]. Thengane et al. (2019) was proposed an algebraic technique for CCUS targeting. They used the Grand Composite Curve (GCC) to verify the actual targets of CCUS [12]. The later improvement of CCS planning was conducted by Mualim et al. (2021). They used the economic parameter based on the capital-carbon trade-off to evaluate the CCS system performance [13].

This study considers a planning method to mitigate carbon dioxide emissions through the integration of CCS and CCU. The CCS is placed at first hierarchy to reduce CO<sub>2</sub> emissions, followed by CCU. Therefore, in this study, the term CCUS is interchanged by CCSU. In this paper, The CCSU planning problem is addressed via graphical procedure based on the material recovery pinch diagram (MRPD) and algebraic technique that complement each other.

In addressing the planning of CCSU, the formal problem statement was given below:

- The system consists of  $m$  CO<sub>2</sub> sources and  $n$  CO<sub>2</sub> sinks
- Utilization sinks are identified as a fixed time sink, and storage sinks are recognized as a fixed capacity sink.
- The CO<sub>2</sub> recovered through storage sinks is considered the primary solution, and the CO<sub>2</sub> recovered through utilization sinks is regarded as a second alternative solution.
- The objective is to determine the target, i.e., the minimum amount of alternative storage equivalent to minimum CO<sub>2</sub> utilized for chemical products and EOR.

- Pinch-based sensitivity analysis will be performed to determine the influence of changing the sinks or demand on the system target.

## 2. METHODS

The methods to obtain feasible targeting for a CCSU system is described here. The targeting procedure is based on a material recovery pinch diagram (MRPD) [6]. The methods uses the graphical technique referred to as the carbon capture storage pinch diagram (CCSPD) and the algebraic technique referred to as the carbon capture storage cascade analysis (CCSCA). The main steps for targeting are given as follows:

- Perform the targeting for CCS first through composite curve and CCSCA. The unrecovered CO<sub>2</sub> from alternative storage can be utilized later with several utilization options.
- Draw the composite curve using the cumulative CO<sub>2</sub> load as the horizontal axis and the operating time as the vertical axis. The source-composite curve must stay above and to the left of the sink composite curve. The target can be determined by shifting the sink composite curve to the right until the pinch point is met.
- Plot the graphical tool (GCC of the system) based on the CCSCA table [12]. The preliminary target of the system can be obtained from the CCSCA or the composite curve, whereas the actual target of the CCSU system can be determined from the graphical technique of GCC.

## 3. RESULTS AND DISCUSSIONS

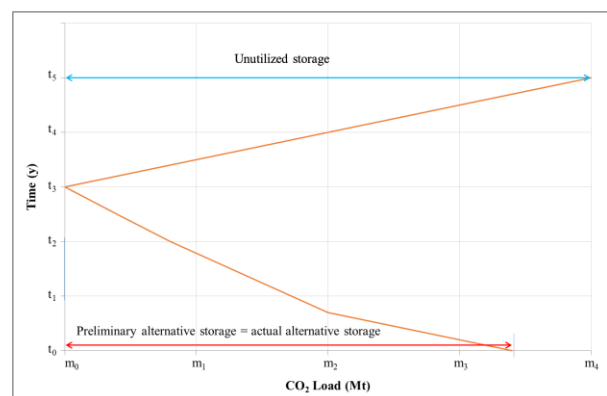
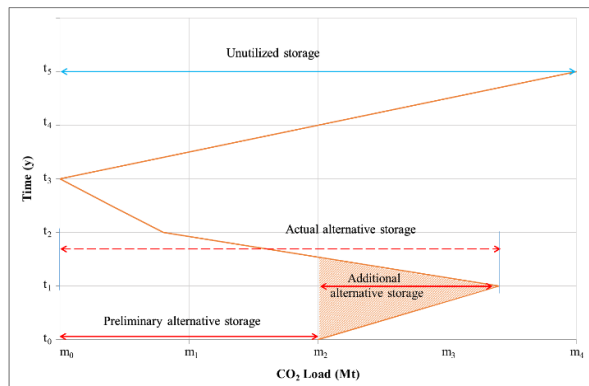


Figure 1. GCC without pocket..



**Figure 2.** GCC with pocket

Figure 1 and 2 show the GCC, where time is plotted as the vertical axis, and feasible CO<sub>2</sub> load is plotted as a horizontal axis. The opening at the lower section of GCC corresponds to alternative storage that indicates the feasible amount of CO<sub>2</sub> that can be utilized. To verify the target, perform the inspection on GCC. If the GCC contains a pocket, the preliminary target is not valid. The CO<sub>2</sub> storage sink is not thoroughly utilized in a certain time interval. The sink may be unutilized if no source present in an earlier time interval or the total amount of CO<sub>2</sub> from the sources is less than the total capacity of sinks in a certain time interval.

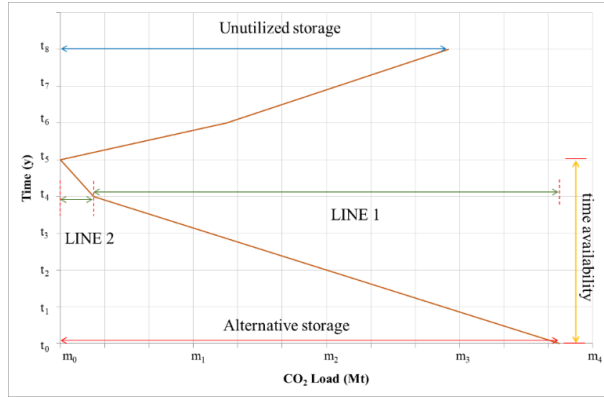
The line segment with a negative slope indicates that the storage sinks cannot be used to store CO<sub>2</sub> captured. Only the line segment with a positive slope may be considered as an actual target. The time availability of alternative storage refers to an actual target. The actual feedstock for utilization options is estimated from the actual alternative storage. The lower section of GCC may contain several line segments with different slopes. Select the line segment with the longest constant positive slope as a basis of the CO<sub>2</sub> feed rate for the utilization options. The CO<sub>2</sub> utilization, particularly for chemical processes, requires a constant feed rate for a certain time interval. The line segment with a high slope may not be feasible to utilize. The high slope indicates a little CO<sub>2</sub> feed rate.

Figure 3 shows the segment of GCC below the pinch. The alternative storage was available from  $t_0 - t_5$ . There is two line segment with two different slopes. LINE 1 has a longer and lower slope than LINE 2. This condition means LINE 1 gives a greater feed rate for utilization and has a longer time duration. LINE 1 has time availability from  $t_0 - t_4$  and LINE 2 from  $t_4 - t_5$ . The CO<sub>2</sub> supply rate from alternative storage to CO<sub>2</sub> utilization can be estimated from  $\Delta m / \Delta t$  or  $1 / \text{slope}$ . The utilization options require a constant feed rate for a long time duration. Then, LINE 1 gives a feasible CO<sub>2</sub> supply for CO<sub>2</sub> utilization options.

**Table 1.** The values of the GEP components

CCSU components	Cost range or emission rate	Reference
Capture from a power plant	15 – 75 USD/ton CO <sub>2</sub> captured	[14]
Capture from gas processing or ammonia prod.	5 – 25 USD/ton CO <sub>2</sub> captured	[14]
Capture from other industrial sources	25 – 115 USD/ton CO <sub>2</sub> captured	[14]
Transportation	1 – 8 USD/tonCO <sub>2</sub> transported	[14]
Geological storage	0.5 – 8 USD/tonCO <sub>2</sub> injected	[14]
Geological monitoring	0.1 – 0.3 USD/tonCO <sub>2</sub> injected	[14]
Ocean storage	5 – 30 USD/tonCO <sub>2</sub> injected	[14]
Carbon tax	73 USD/ton CO <sub>2</sub> emitted	Estimated
Carbon incentive	10 USD/ton CO <sub>2</sub> recovered	[15]
MeOH product price	389.78 USD/ton methanol	[16]
DMC product price	1300 USD/ton DMC	[17]
Crude oil price	70 USD/bbl	[18]
MeOH emission rate	0.462 ton CO <sub>2</sub> eq/ton MeOH	[19]
DMC emission rate	0.452 ton CO <sub>2</sub> eq/ton DMC	[20]
EOR emission rate	13.9 kg CO <sub>2</sub> /bbl oil	[21]

Assess the economic targeting for the CCSU system through economic criteria, namely gross economic potential (GEP).



**Figure 3.** GCC line segment.

In this study, the GEP can be formulated as follows:

$$GEP = CR - CC + CI - CT \quad (1)$$

Where  $CR$  is carbon revenue from  $CO_2$  utilization,  $CC$  is carbon cost from overall facilities of CCSU system,  $CT$  is a carbon tax, and  $CI$  is carbon incentive. The values of the GEP components and indirect  $CO_2$  emissions from utilization options are given in Table 1.

In this study, three utilization options are selected, namely Methanol (MeOH), Dimethyl carbonate (DMC) and Enhanced oil recovery (EOR). The procedure above will be illustrated with examples which are discussed in the following section. The data for the examples are given in table 2 and 3. There are four  $CO_2$  sources and two  $CO_2$  sinks. The sinks are identified as storage sinks with a fixed capacity. The sources generate 850 Mt of  $CO_2$  throughout the entire planning period, while the storage sink capacity is 800 Mt.

**Table 2.** Source characteristics for illustrative example

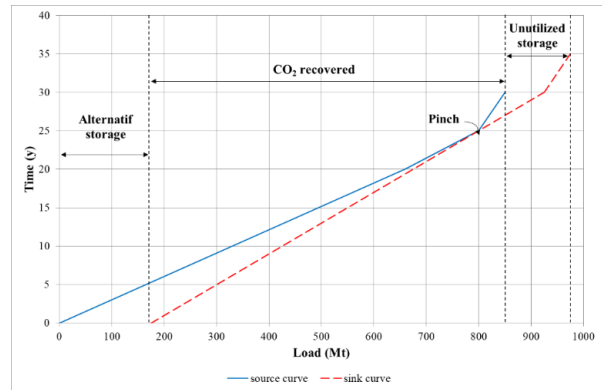
Source	Start time (y)	End time (y)	$CO_2$ Emission rate (Mt/y)	$CO_2$ load (Mt)
SR1	0	25	8	200
SR2	0	25	10	250
SR3	0	30	10	300
SR4	0	20	5	100
Total $CO_2$ produced				850

**Table 3.** Sink characteristics for illustrative example

Sink	Start time (y)	End time (y)	$CO_2$ injection rate (Mt/y)	$CO_2$ load (Mt)
SK1	0	30	15	450
SK2	0	35	10	350
Total storage capacity				800

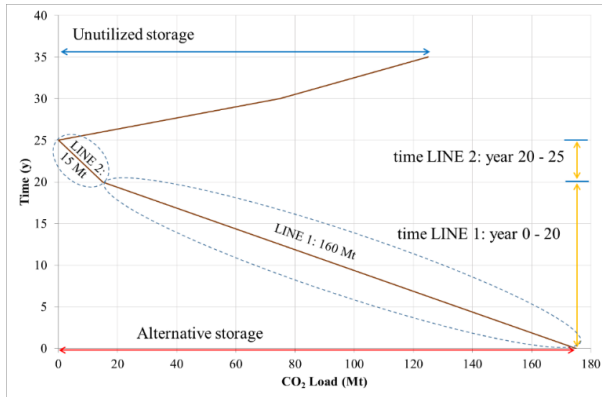
### 3.1 Initial CCSU targeting

In this example, an optimal solution for CCS targeting can be found by plotting the CCSPD in Figure 4.



**Figure 4.** CCSPD for example 1.

The result shows that pinch occurs at year 25, with 675 Mt of  $CO_2$  can be recovered, 175 Mt of alternative storage, and 125 Mt of unutilized storage. The alternative storage is an excess  $CO_2$  emission that cannot be captured and stored. The  $CO_2$  from alternative storage can be used as a feedstock for  $CO_2$  utilization. For initial assessment, 175 Mt of alternative storage is used as a preliminary target for  $CO_2$  utilization. The feasibility of  $CO_2$  supply from alternative storage is assessed by GCC plotting by following the procedure outlined in the methodology. The actual feed rate can be estimated based on the feasible GCC line. Figure 5 shows the GCC of the CCS system, for example 1. The GCC can be generated from CCSCA and may also be used to verify the various targets, i.e., alternative storage, unutilized storage, and pinch point.



**Figure 5.** GCC for example 1.

Figure 5 shows that the GCC does not contain any pocket, and hence the preliminary alternative storage is actual alternative storage. There are two line segments of alternative storage. Line 1 is available in interval years of 0 – 20. The amount of alternatives storage in this interval is 160 Mt. This means that the CO<sub>2</sub> can be supplied from the CCS system to the CO<sub>2</sub> utilization sink with a feed rate of  $160/20 = 8$  Mt/y. Line 2 is present in the interval years of 20 – 25 with the amount of alternative storage is 15 Mt. Hence, the potential feed rate of CO<sub>2</sub> from the CCS system to CO<sub>2</sub> utilization sink is 3 Mt/y in this interval. Line 1 has a longer time duration and greater feed rate than line 2. When all of the entire alternative storage is utilized, we obtain the economic target (GEP) and the emission target of the CCSU system as given in table 4. Three utilization options were selected for this study, namely CO<sub>2</sub> utilization for EOR, CO<sub>2</sub> conversion to DMC, and MeOH. The excess CO<sub>2</sub> emissions are indirect emissions from the CO<sub>2</sub> utilization process. The results are based on the assumption that all alternative storage is utilized over the time horizon

**Table 4.** Targeting of CCSU system for example 1.

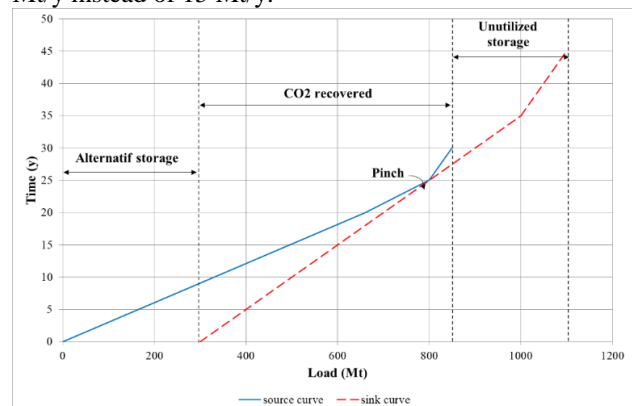
Target criterias	Value
Utilized alternative storage	175 Mt
GEP of CCS	(72,205) million USD
GEP of CCSU – MeOH	(46,301) million USD
GEP of CCSU – DMC	(16,140) million USD
GEP of CCSU – EOR	(57,038) million USD
Excess CO <sub>2</sub> emission CCSU – MeOH	58.8 Mt
Excess CO <sub>2</sub> emission CCSU – DMC	53.96 Mt
Excess CO <sub>2</sub> emission CCSU – EOR	4.05 Mt

If the CO<sub>2</sub> utilization sink requires a constant feed rate from year 0 to 25, then the possible supply of CO<sub>2</sub> feed is 3 Mt/y. In this scenario, we obtain unutilized-alternative storage with a CO<sub>2</sub> feed rate of 5 Mt/y from year 0 to 20. A number of strategy can be applied to maximize CO<sub>2</sub> utilization from alternative storage. The strategy can be performed with dynamic CO<sub>2</sub> feed rate consideration.

- Utilize 3 Mt/y of CO<sub>2</sub> from year 0 to 25 for the first utilization option, then utilize 5 Mt/y of CO<sub>2</sub> from year 0 to 20 for the second utilization option.
- Utilize 8 Mt/y of CO<sub>2</sub> from year 0 to 20 for the first utilization option, then utilize 3 Mt/y of CO<sub>2</sub> from year 0 to 20 for the second utilization option.
- Utilize 8 Mt/y of CO<sub>2</sub> from year 0 to 20 for first utilization option, continued by decrease utilize 3 Mt/y of CO<sub>2</sub> from year 0 to 20.

### 3.2 Effects of changes in sink injection rates.

The reservoirs rocks characteristic determines the maximum CO<sub>2</sub> injection rates to the sinks. The injection rates that exceed the maximum limit cause reservoir damage. Under certain conditions, the injection rate may drop due to well or reservoir maintenance. In this scenario, it is assumed that the injection rate of SK1 will be decreased from 15 Mt/y to 10 Mt/y. Based on the assumption that the storage capacity is constant, the reduction in the injection rate will cause the operating time of SK1 to be longer (45 years). The CCSPD for this scenario is given in figure 5. The sources and sinks data remain the same except for SK1, with an injection rate of 10 Mt/y instead of 15 Mt/y.



**Figure 6.** CCSPD for example 2: effect of the decrease in sink injection rate.

Figure 6 shows that pinch time remains at year 25. The total CO<sub>2</sub> recovered decrease to 550 Mt, the amount of alternative storage and unutilized storage increase to 300 Mt and 250 Mt, respectively.



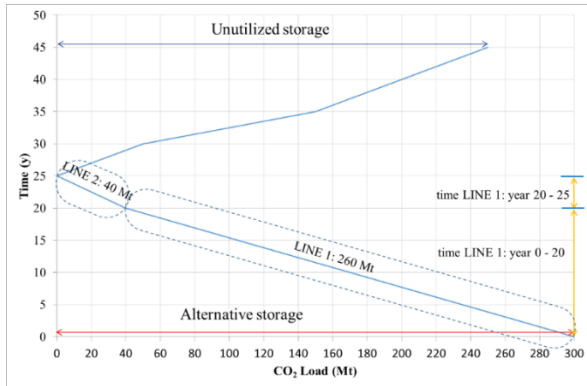


Figure 7. GCC of CCS system for example 2.

Figure 7 shows the GCC of the CCS system, for example, 2. Similar to figure 5, the GCC does not contain any pocket, and hence the preliminary alternative storage is actual alternative storage. The alternative storage section is divided into two line segments. Line 1 is available in interval years of 0 – 20. The amount of alternatives storage in this interval is 260 Mt. This means that the CO<sub>2</sub> can be supplied from the CCS system to the CO<sub>2</sub> utilization sink with a feed rate of  $260/20 = 13$  Mt/y. Line 2 is present in the interval years of 20 – 25, with the amount of alternative storage is 40 Mt. Then, the CO<sub>2</sub> can be supplied to the CO<sub>2</sub> utilization sink with a feed rate of  $40/5 = 8$  Mt/y. The economic target (GEP) and the emission target of the CCSU system, when all alternative storage is utilized, are given in table 5.

Table 5. Targeting of CCSU system for example 2.

Target criterias	Value
Utilized alternative storage	300 Mt
GEP CCSU – MeOH	(26,533) million USD
GEP CCSU – DMC	25,151 million USD
GEP CCSU – EOR	(44,958) million USD
Excess CO <sub>2</sub> emission CCSU – MeOH	100.8 Mt
Excess CO <sub>2</sub> emission CCSU – DMC	92.5 Mt
Excess CO <sub>2</sub> emission CCSU – EOR	6.95 Mt

The results show that the economic potential of CCSU by DMC utilization option is positive, while the other options give a lower negative value than example 1. The excess of CO<sub>2</sub> emissions from CCSU is getting bigger due to the increasing CO<sub>2</sub> utilized from alternative storage. Based on this scenario (reducing the injection rate), the total CO<sub>2</sub> recovered through CCS decrease to

550 Mt, and the total CO<sub>2</sub> recovered through CCU is 300 Mt.

### 3.3 Effects of changes in time difference.

The initial CO<sub>2</sub> transfer in the CCS system is determined by the readiness of the CO<sub>2</sub> sinks to receive CO<sub>2</sub> supply from the sources. The initial operating time of the sinks may be delayed due to technical and economic issues or changes in regulations. We analyze the effect of time delay or time difference of a sink. Mualim et al., (2021) use the time difference scenario to analyze the sensitivity of capital carbon trade-off of CCS system [13]. In the following scenario, the initial operating time of the sink SK2 is increased by 1 to 5 years of time difference. The CCSPD for this scenario is given in Figure 8. The sources and sinks data remain the same except for SK2, with operating times from year 5 to 40. The pinch time remains at year 25. The total CO<sub>2</sub> recovered decrease to 625 Mt, the amount of alternative storage and unutilized storage increase to 225 Mt and 175 Mt, respectively.

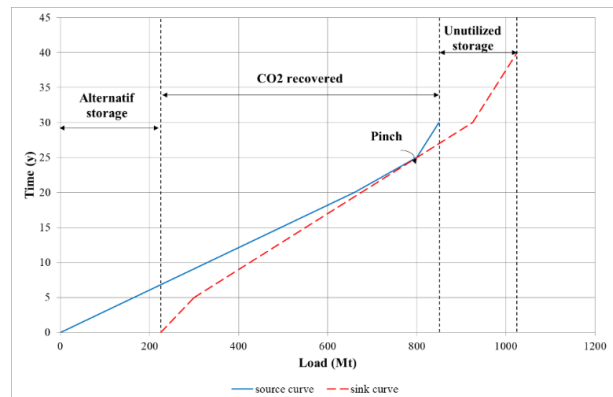


Figure 8. CCSPD for example 3: effect of the increase in time difference.

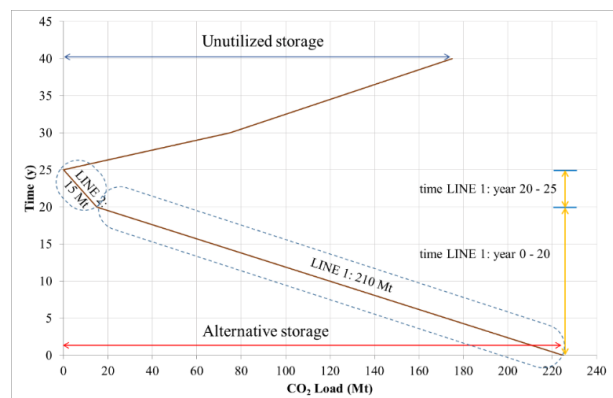


Figure 9. GCC of CCS system for example 3

Figure 9 shows the GCC of the CCS system, for example 3. Similar to figures 4 and 6, the GCC does not contain any pocket, and hence the preliminary alternative storage is actual alternative storage. The potential utilization of the alternative storage is available from years 0 to 25. The alternative storage section is divided into two line segments. Line 1 is available in years 0 to 20 with 210 Mt. Therefore, CO<sub>2</sub> can be supplied to the CO<sub>2</sub> utilization sink with a feed rate of  $210/20 = 10.5$  Mt/y. Line 2 is present in the interval of year 20 to 25 with the amount of 15 Mt. Then, CO<sub>2</sub> can be supplied to the CO<sub>2</sub> utilization sink with a feed rate of  $15/5 = 3$  Mt/y. The economic target (GEP) and the emission target of the CCSU system, when all of the alternative storage is utilized, are given in table 6.

**Table 6.** Targeting of CCSU system for example 3.

Target criterias	Value
Utilized alternative storage	225 Mt
GEP of CCSU – MeOH	(37,698) million USD
GEP of CCSU – DMC	1,080 million USD
GEP of CCSU – EOR	(51,502) million USD
Excess CO <sub>2</sub> emission CCSU – MeOH	75.6 Mt
Excess CO <sub>2</sub> emission CCSU – DMC	69.37 mt
Excess CO <sub>2</sub> emission CCSU – EOR	5.21 Mt

The results show that the economic potential of CCSU by DMC utilization option is positive, while the other options remain to give a negative value. The excess CO<sub>2</sub> emissions from CCSU are getting bigger than example 1 due to the increasing CO<sub>2</sub> utilized from alternative storage.

#### 4. CONCLUSION

A graphical pinch approach to analyzing CCSU systems has been developed. This technique is based on the pinch analysis method with such demand (sink) manipulation strategies. The technique allows determining system targets based on characteristics of storage sinks. The CO<sub>2</sub> utilization is considered the second level in the hierarchy of carbon recovered after the CO<sub>2</sub> emissions can no longer be recovered through CO<sub>2</sub> storage. Furthermore, the pinch-based technique can be used as a general technique to analyzing the sensitivity of system targets, especially in economic and emission targets. The GEP is proposed for the economics benchmark of the CCSU system. The economic performances of the CCSU system are measured by the GEP for the three CO<sub>2</sub> utilization options. The results show that the CCSU system with

DMC utilization options provides the best GEP, while the EOR provides the best CO<sub>2</sub> emissions reduction. These best criterias are obtained only when the CO<sub>2</sub> is utilized to a single utilization option. In this paper, three illustrative examples have been used to demonstrate the methodology. Two strategies were implemented in the form of reduction the CO<sub>2</sub> injection rate and increasing the time difference. Both can reduce the amount of CO<sub>2</sub> excess emissions and generate positive economic value.

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