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A Comparative Study Between Pinch Design Method and Superstructure Applied on Carbon Capture and Storage

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Carbon Capture and Storage (CCS) has become trend topic among the researcher in Indonesia due to its urgency in reducing carbon emissions. Planning of CCS optimization is important in order to achieve maximum captured CO_2. This study compares Pinch Analysis and Superstructure Modelling for CCS planning across multi-region sources and sinks in Indonesia. Focusing on three key parameters: alternative storage, captured CO_2, and unutilized storage, both approaches will be evaluated. Grid diagram will be applied to both approach (Pinch Analysis and Superstructure Modelling) to show the reliability of the calculation results. For Pinch Analysis, cascade calculations will determine optimal parameters under temporal constraints while Superstructure Modelling will employ mixed-integer linear programming (MILP) to model multi-period CCS networks. Results indicate that Pinch Analysis achieved a 7 % higher captured CO_2 compared to Superstructure Modelling, with a total of 8 pairings for Pinch Analysis and 5 pairings for Superstructure Modelling. These findings inform the comparison of hybrid frameworks between thermodynamic visualization (Pinch Analysis) and multi-objective optimization (Superstructure Modelling) to address Indonesia's cross-regional CCS challenges.

1. Introduction

Global CO_2 emissions from the energy sector increased by 1.1 % and reached 37.4 B tons in 2023 (Ayyad et al., 2024). Several mitigation strategies, such as Carbon Capture and Storage (CCS), have been developed to overcome this issue. CCS is designed to capture CO_2 from emissions sources, then transport and either store it safely or utilize it in industrial processes (Ooi et al., 2013). In short, the process begins with capturing CO_2 from exhaust gases, transporting it through pipelines, and storing it in geological reservoirs (Tapia, 2023). In Indonesia, there are many potential CO_2 sources and sinks, each with its own operational timeframe. However, selecting the appropriate method for matching sources and sinks is essential to effectively implement a CCS system and reduce the carbon footprint. These approaches are particularly valuable since CCS planning involves several complex challenges including the temporal and spatial mismatch between CO_2 sources and sinks, infrastructure limitations, and capital cost (Handogo et al., 2020). Two commonly used approaches are Pinch Analysis and Superstructure Modeling. Pinch Analysis offers a heuristic method that simplifies the matching of sources and sinks based on time compatibility and capacity constraints, making it suitable for fast evaluation (Smith, 2005). Meanwhile, Superstructure Modeling provides more comprehensive frameworks by using mathematical programming to determine the optimal configuration (Ayyad et al., 2024). Therefore, using these two approaches allows more holistic comparison of system performance. Putra et al. (2018) reported that this approach was applied to compare the effectiveness of simultaneous and sequential approaches in CO_2 capture. The results indicated that the sequential approach achieved a capture efficiency of up to 93.86 % under a zero time-difference scenario whereas the simultaneous approach achieved 83.94 %. Furthermore, this approach could reduce the system's total annual cost by up to US$ 159 M under optimal configuration. On the other hand, the Superstructure Modeling allows for the simultaneous exploration of multiple system configurations. Dwiputro et al. (2021) developed a multi-region CCS scenario for Kalimantan, Sulawesi, and East Java, demonstrating that the approach achieved 93.36 % CO_2 capture efficiency with full sink utilization

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and no unutilized storage, despite incurring higher costs compared to the Pinch Analysis. The Superstructure Modelling minimized the Total Annual Cost (TAC) to approximately US$ 2.6 B. Although previous studies have applied either Pinch Analysis or Superstructure Modelling in CCS, a direct comparison between the two under identical assumptions has not yet been explored. Prior works, such as Putra et al. (2018) and Dwiputro et al. (2021), have utilized these methods in isolation, often under differing assumptions and system constraints. However, a direct, side-by-side evaluation using consistent system boundaries and data inputs remains largely unaddressed in existing literature. To address this gap, both approaches are evaluated side by side using consistent input data, timeframes, and capacity constraints so it will become quantitative comparison that highlights the trade-offs between Pinch Analysis and Superstructure Modelling. The outcomes are expected to contribute to the development of efficient CCS systems and support emissions reduction policies in the transition towards a low-carbon economy.

2. Method

The following paragraph outlines the basis data related to CO_2 source and existing potential sinks in Indonesia, detailing the procedures for conducting Pinch Analysis and Superstructure Modelling.

2.1 Basis Data

Table 1 and Table 2 show data on the sources and sinks that will be utilized in this study. This data was adopted from Handogo et al. (2020), which includes four sources and two sinks. These specific facilities were selected due to their high emissions profiles and proximity to identified storage sites, as well as the availability of complete temporal and emissions data. In this study, the term ‘alternative storage’ will be used to indicate CO_2 from sources that cannot be captured by sinks and can be utilized as chemical products. Conversely, ‘unutilized storage’ will be used to indicate inactive sinks since they do not receive any CO_2 from sources.

Table 1: Source Data

No.	Source	Start of Operation (y)	End of Operation (y)	Average CO_2 Emissions Rate (Mt/y)	Total CO_2 Emitted (Mt)
1.	Pupuk Kaltim	5	30	2.403	60.075
2.	Badak LNG	5	20	5.514	82.71
3.	Semen Bosowa	7	27	1.575	31.5
4.	Semen Tonasa	8	28	3.791	75.82
			Total CO_2 Emitted		250.105

Table 2: Sink Data

No.	Sink	Start of Operation (y)	End of Operation (y)	Average CO_2 Injectivity (Mt/y)	Total CO_2 Capacity (Mt)
1.	Kutai-Tarakan Basin	5	35	4.65	139.5
2.	North East Java	5	30	3.76	94
			Total CO_2 Capacity		233.5

2.2 Pinch Analysis

Referring to Handogo et al. (2020), the cascade table for Pinch Analysis is constructed by initially listing unique operational time points (t_1 to t_n), followed by recording CO_2 flow rates for sources and sinks during their operational time. This are illustrated as directional arrows inside the second and third column. Time intervals (Δt) between adjacent time points are then determined, and the net CO_2 flow rate for each interval is calculated as the difference between total sink and source flow rates. Next, the net CO_2 load for each interval is computed, followed by the cumulative CO_2 load starting from zero (infeasible cascade). Finally, the feasible CO_2 cascade is established, using the absolute value of the most negative infeasible cascade to identify the pinch point and alternative storage, with the final row indicating unutilized storage.

2.3 Superstructure Modelling

Development of the Superstructure Modelling consist of three general steps: determination of the objective function, formulation of the mathematical model, and optimization approach (Yang et al., 2022). Matlab R2019b software will be used to facilitate the optimization requirements.

2.3.1 Objective Function

In this case, maximization of CO_2 transfer between source to sink will be chosen as objective function using the following formula:

$$maximize \sum_i \sum_j Q_{(i,j)} \tag{1}$$

With $Q_{(i,j)}$ is the total CO_2 transfer from source-i to sink-j (Mt).

2.3.2 Overall Material Balance

Total CO_2 transferred from source to sink must satisfy the material balance rule according to the following equation:

$$\mathrm{CO_2\ emissions\ rate}_{source-i} * (\mathrm{t}_{\mathrm{end}\,source\,\mathrm{i}} - \mathrm{t}_{\mathrm{start}\,source\,\mathrm{i}}) = \sum\nolimits_{\mathrm{j}} \mathrm{Q(i,j)} + \mathrm{Alternative\ Storage} \tag{2}$$

$$\mathrm{CO_2\ injectivity}_{sink-\mathrm{j}} * (\mathrm{t}_{\mathrm{end}\,sink\,\mathrm{j}} - \mathrm{t}_{\mathrm{start}\,sink\,\mathrm{j}}) = \sum\nolimits_{\mathrm{i}} \mathrm{Q(i,j)} + \mathrm{Unutilized\ Storage} \tag{3}$$

where t_{start} and t_{end} refer to start and end time of each source and sink (y). Additionally, the total CO_2 transferred from source to sink must not exceed the minimum capacity of either the source or the sink, as follows:

$$\mathrm{Q(i,j)} \leq \mathrm{min[CO_2\ emitted\ by\ source - i, CO_2\ capacity\ of\ sink - j]} \tag{4}$$

Furthermore, there is a rule that the amount of alternative storage and unutilized storage must not exceed the total CO_2 available at the source or the total capacity of the sink, as follows:

$$\mathrm{Alternative\ storage} \leq \mathrm{CO_2\ emitted\ by\ source - i} \tag{5}$$

$$\mathrm{Unutilized\ storage} \leq \mathrm{CO_2\ capacity\ of\ sink - j} \tag{6}$$

2.3.3 Constraint for Stream Splitting

To demonstrate that one source can transfer CO_2 to multiple sinks, or vice versa, constraint for stream splitting shall be defined. This condition is represented by the following equation:

$$fh_{ij} * \mathrm{CO_2\ emissions\ rate}_{source-\mathrm{i}} * (\mathrm{t}_{\mathrm{end}\,source\,\mathrm{i}} - \mathrm{t}_{\mathrm{start}\,source\,\mathrm{i}}) \geq \sum\nolimits_{\mathrm{j}} \mathrm{Q(i,j)} \tag{7}$$

$$fc_{ij} * \mathrm{CO_2\ injectivity}_{sink-\mathrm{j}} * (\mathrm{t}_{\mathrm{end}\,sink\,\mathrm{j}} - \mathrm{t}_{\mathrm{start}\,sink\,\mathrm{j}}) \geq \sum\nolimits_{\mathrm{i}} \mathrm{Q(i,j)} \tag{8}$$

Where fh_{ij} and fc_{ij} represent the split fractions for the source and sink, respectively, with values ranging from 0 to 1. If no pairing occurs between source-i and sink-j in stage-k, the split fraction must be zero.

2.3.4 Time Configuration

In configuring source and sink, it is necessary to consider the compatibility of operational timing between the two. The time point at each stage must also be adjusted. Source and sink can be matched each other if there is time overlap between each other. This time configuration can be observed in the following equation:

$$\mathrm{t}_{start\ overlap} = max\ (t_{start\ source-i} - t_{start\ sink\ j}) \tag{9}$$

$$\mathrm{t}_{end\ overlap} = min\ (t_{end\ source-i} - t_{end\ sink\ j}) \tag{10}$$

Eq (9) and Eq (10) indicate that CO_2 transfer can occur when there is a time overlap between the source and sink. If there is a difference in the start times of source and sink, the overlap start time is determined by the maximum value between those start time. Conversely, if there is a difference in the end times of the source and sink, the overlap end time is determined by the minimum value between those end time. This configuration determines the duration of CO_2 transfer between the source and sink.

2.3.5 Optimization

The optimization process is conducted using Matlab 2019b software. The optimization aims to obtain the total amount of CO_2 transferred for each pairing and stream splitting fraction at the optimum condition based on the mentioned objective function.

2.4 Grid Diagram Generation

In the implementation of Carbon Capture and Storage (CCS), the use of a grid diagram aims to design potential connections between available emissions sources (sources) and storage locations (sinks) (Tapia et al., 2018). This diagram provides information regarding the amount of CO_2 that can be transferred as well as the estimated time required for the process (Kim et al., 2024).

3. Result and Discussion

3.1 Pinch Analysis

Table 3 shows the cascade table for the Pinch Analysis, with the pinch point identified at year 20. In CCS, the pinch point indicates the critical time point where the cumulative CO_2 storage capacity of the sinks matches the cumulative CO_2 emissions from the sources, representing the most constrained point in the system where no further CO_2 transfer is feasible without additional storage capacity or alternative measures (Thengane et al., 2019). Furthermore, Table 3 reveals that the alternative storage amounts to 58.572 Mt, and the unutilized storage is 41.967 Mt. Based on this configuration, the total captured CO_2 is determined to be 190.54 Mt. **Errore. L'origine riferimento non è stata trovata.** illustrates the grid diagram which was derived from the results of Table 3. Eight pairings are foreseen to represent the captured CO_2. Stream splitting is applied to Badak LNG, Semen Bosowa, and North East Java to meet the criteria for the grid diagram below the pinch. Conversely, for the above-pinch region, the stream splitting rule is applied to Semen Bosowa, Kutai Tarakan Basin, and North East Java due to the number of sinks being fewer than the number of sources, necessitating the splitting of sinks. Alternative storage is observed at Semen Bosowa and Semen Tonasa, all located below the pinch, as an impact of differences in the start times of these sources relative to the available sinks and the limited capacity of sinks to accommodate CO_2. The amount of alternative storage derived from the grid diagram is consistent with the results from Table 3. On the other hand, unutilized storage is identified at Kutai Tarakan Basin start from years 20 to 35. In this duration, at years 27 and 28, Kutai Tarakan Basin was no longer received CO_2 from Semen Bosowa and Semen Tonasa. For North East Java, unutilized storage is foreseen at years 5 to 7 and years 27 to 30. This occurs because, during these periods, all CO_2 from all sources has been successfully captured (Kemp, 2007). The amount of unutilized storage obtained also aligns with the results from Table 3.

Table 3: Cascade Table for Pinch Analysis

Time (y)	Source				Sink		Δt (y)	CO_2 Flowrate (Mt/y)	CO_2 Load (Mt)	Infeasible Cascade (Mt)	Feasible Cascade (Mt)
	Pupuk Kaltim	Badak LNG	Semen Bosowa	Semen Tonasa	Kutai Tarakan Basin	North East Java					
5	2.403	5.514			4.65	3.76				0	58.572
	↓	↓			↓	↓	2	0.493	0.986		
7	↓	↓	1.575		↓	↓				0.986	59.558
	↓	↓	↓		↓	↓	1	-1.082	-1.082		
8	↓	↓	↓	3.791	↓	↓				-0.096	58.476
	↓	↓	↓	↓	↓	↓	12	-4.873	-58.476		
20	↓	↓	↓	↓	↓	↓				-58.572	0
	↓		↓	↓	↓	↓	7	0.641	4.487		(Pinch)
27	↓		↓	↓	↓	↓				-54.085	4.487
	↓			↓	↓	↓	1	2.216	2.216		
28	↓			↓	↓	↓				-51.869	6.703
	↓				↓	↓	2	6.007	12.014		
30	↓				↓	↓				-39.855	18.717
					↓		5	4.65	23.25		
35					↓					-16.605	41.967

3.2 Superstructure Modeling

Superstructure Modeling use iterative process to achieve optimal result and it does not rely on cascade table (Tan et al., 2012). Based on optimization results, derived from the applied mathematical equations, it indicate that alternative storage, captured CO_2, and unutilized storage amount to 73.095 Mt, 177.01 Mt, and 56.49 Mt, respectively. The value of captured CO_2 is lower compared to the result provided by Pinch Analysis. Pairing configuration between sources and sinks in the superstructure approach also differs from Pinch Analysis, as illustrated by the grid diagram in Figure 2. It is evident that the number of pairings between sources and sinks using the superstructure Modelling is fewer, reaching 5 pairings. Alternative storage is foreseen in Badak LNG from years 5 to 20, while unutilized storage is foreseen in the Kutai-Tarakan Basin and North East Java at varying time intervals. In the Kutai-Tarakan Basin, unutilized storage emerges in years 20, 27, 28, and 30, continuing until the basin's operational end in year 35. Similarly, in North East Java, unutilized storage appears from year 28 to 30, as all CO_2 from the sources has been successfully captured during this period.

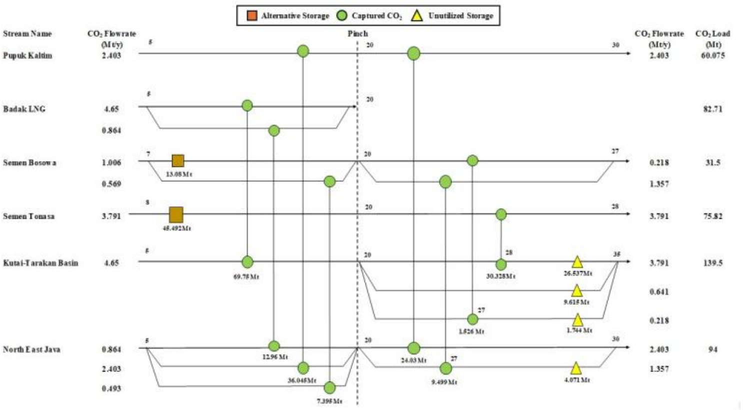

Figure 1: Grid Diagram for Pinch Analysis

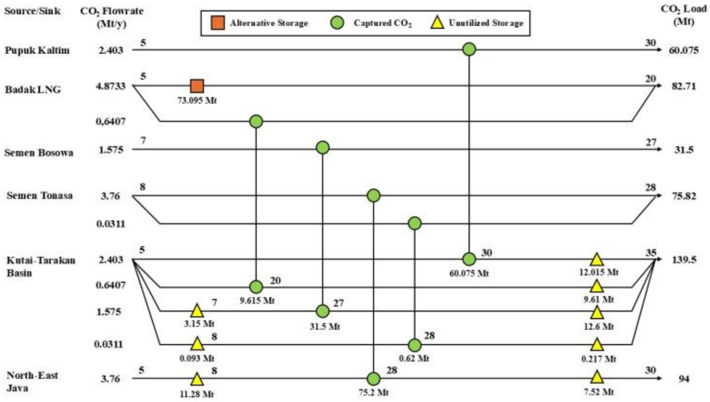

Figure 2: Grid Diagram for Superstructure Modelling

3.3 Final Pairing

Table 4: Final Result

Parameters	Pinch Analysis	Superstructure Modelling
Alternative storage (Mt)	58.572	73.095
Captured CO_2 (Mt)	190.54	177.01
Unutilized Storage (Mt)	41.967	56.49

Table 5: Final Pairing Results (P: Pinch, S: Superstructure)

Source/Sink	Pupuk Kaltim	Badak LNG	Semen Bosowa	Semen Tonasa
Kutai-Tarakan Basin	-	69.75 Mt (P)	1.526 Mt (P)	30.328 Mt (P)
	60.075 (S)	9.615 Mt (S)	31.5 Mt (S)	0.62 Mt (S)
North East Java	60.075 (P)	12.96 Mt (P)	9.499 Mt (P)	-
	-	-	-	75.2 Mt (S)

Table 4 summarizes alternative storage, captured CO_2, and unutilized storage for Pinch Analysis and Superstructure Modelling, while Table 5 presents their source-sink pairings. Pinch Analysis captures up to 7 %

more CO_2 than Superstructure Modelling. This is due to its ability to identify optimal pairings with fewer computational constraints, requiring less time (Diamante et al., 2014) and resources (Foo and Tan, 2020). While both methods yield similar pairings, Pinch Analysis uniquely pairs North East Java with Pupuk Kaltim, Badak LNG, and Semen Bosowa, whereas Superstructure Modeling pairs Pupuk Kaltim with Kutai-Tarakan Basin and Semen Tonasa with North East Java. Some pairings are infeasible in both methods due to mismatched operational time ranges, marked by "-" in Table 5.

4. Conclusion

Strategic planning in CCS development was successfully conducted using both Pinch Analysis and Superstructure Modelling. Pinch Analysis captured approximately 7 % more CO_2, due to its fast, heuristic-based source-sink matching without complex constraints, making it suitable for preliminary evaluations. Meanwhile, Superstructure Modelling offers broader optimization capabilities by evaluating multiple configurations simultaneously, which is beneficial when dealing with large-scale systems involving numerous variables and trade-offs. The variation in pairing results between the two methods further demonstrates the importance of method selection based on system complexity and data availability. Additionally, the alignment of source–sink operational periods remains a critical determinant in ensuring feasible CO_2 transfer in both approaches.

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