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Graphical Targeting Tool for the Planning of Carbon Capture and Storage

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Carbon capture and storage (CCS) is one of the interim technologies to mitigate greenhouse gas emissions from stationary sources such as power plant and large industrial facilities. CCS allows for continued utilization of fossil fuels, which are still relatively inexpensive and reliable in comparison to inherently low-carbon renewable resources (e.g. wind, solar etc.). The selection and matching of the power plants and storage sites are often an issue of optimisation due to various constraints, i.e., time of availability, injection rate, and storage capacity limits. In this work, a new graphical technique based on pinch analysis is proposed to address the planning problem of the storage of captured CO_2 from power plants into corresponding reservoirs. A case study is used to elucidate the proposed approach.

1. Introduction

Power generation from fossil fuels (e.g. coal, oil and natural gas) continues to account for a significant portion of global carbon dioxide (CO_2) emissions. To mitigate climate change impacts, increased research on efficiency improvements, fuel substitution and increased use of low-carbon energy for cleaner electricity generation have been observed (Weisser, 2007; Varun et al., 2009). However, fossil fuels are expected to remain as major contributors to the world's overall power generation mix in the near future (Quadrelli and Peterson, 2007), mainly because it is impractical to shut down existing fossil fuel-fired plants for purely environmental reasons, if these have not yet fully expended their projected economic lives. In addition, fossil fuel-fired plants rely on mature technologies and have inherently better reliability and availability than many renewable energy sources (e.g. wind, hydro, nuclear, solar power). The above factors have led to widespread interest in retrofitting existing plants with carbon capture (CC) technology, such as oxy-fuel combustion, pre- or post-combustion captures. These technologies can be used to capture 80 – 90 % of the carbon from power plant exhaust gases, and subsequently compress it for secure storage in various reservoirs, such as depleted oil wells, inaccessible coal seams and impervious geological formations. Among the factors considered during feasibility planning stage in matching of CO_2 sinks and sources is the time availability, CO_2 storage capacity and injection rate (Tan et al., 2012a). Several works based on mathematical programming were developed recently to address these factors in the context of carbon-constrained energy planning problem, utilising various models, e.g. automated targeting (Foo et al., 2010a), superstructural (e.g. Pękala et al., 2010), fuzzy (Tan et al., 2010) and continuous-time models (Tan et al., 2012b).

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In this paper, the CCS planning problem is addressed via a novel graphical pinch analysis tool, which is extended from that of the human resource management problem (Foo et al., 2010b).

2. New definition of CCS sinks and sources

A new definition for resource sinks and sources is used in this work. The availability of CO_2 storage reservoirs is defined as *storage sources* that provide “service” to CO_2 emitting power plants. In contrast, the power plants that emit CO_2 are defined as *storage sinks/demands*, are to be matched to the appropriate storage source. This new definition for the role and contribution of the sink-source is shown in Figure 1. Note that the convention used in this work where physical sources of CO_2 emission (i.e., power plants) are taken as sinks for the *service* of CO_2 disposal, and conversely the storage reservoirs which act as physical sinks are taken as sources of this service. Hence, the disposal service flows in the opposite direction as the captured CO_2 itself. This convention was proposed in the context of life cycle assessment by Tan et al. (2008). From the above description, the sink-source definition is different than the assumption made in the work of Tan et al. (2012a, 2012b) where power plants are considered as CO_2 sources while the storage as sinks.

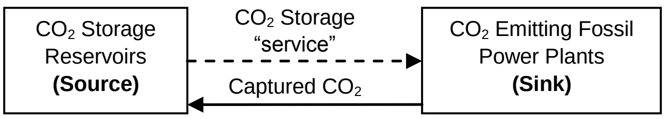

Figure 1: CO_2 Source and Sink Interpretation for CCS Planning Problem

3. Carbon Storage Composite Curve

The CCS planning problem can be handled using the *carbon storage composite curves* (CSCCs) in Figure 2. The CSCCs are plotted on a time vs. capacity diagram, where *y*-axis represents the time axis of the planning problem, i.e. storage and life span of power plants; while the *x*-axis represents the total accumulated CO_2 load (usually in Mt) involved for capturing and storage. The CSCC provides valuable insights for CCS planning problem particularly on the bottleneck of the planning problem (i.e. the *pinch* point in the CSCC). It will also be possible to identify the timing of deficiency or excess in storage capacity in the reservoirs which can be allocated for other power plants either inside or outside the geographical region. These would reflect power plants located in nearby region or areas sufficiently close in geographic proximity.

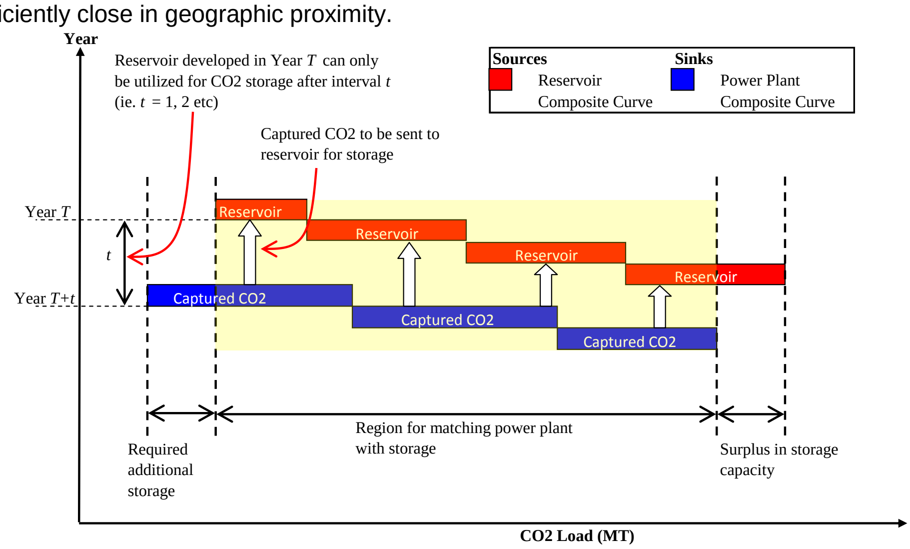

Figure 2: CSCC for CCS planning problem

4. Case Study

A case study is used to demonstrate the application of the CSCC for solving the CCS planning problem. For this case, the allocation problem will be addressed based on the overall CO_2 storage planning scenario. The objective of this case is to determine the amount of additional make-up storage (if required) and also to identify excess storage capacity (if available). Data for the problem is given in Table 1, which shows that three CO_2 storage reservoirs identified for use are Reservoirs A, B and C, each with different storage capacity. As indicated in Table 1, the total CO_2 storage capacity of the reservoirs is determined as 1240 Mt, with Reservoir A being the earliest available storage source, i.e. in Year 3.

Table 1: CO_2 storage capacity from reservoirs for case study

Storage Site	**Start to End** (yr)	**Reservoir life considered in planning horizon** (yrs)	**CO_2 Injection rate** (Mt/yr)	**Total CO_2 Capacity** (Mt)
Reservoir A	3 to 12	10	40	400
Reservoir B	8 to 18	11	60	660
Reservoir C	13 to 21	9	20	180
			Total	**1240**

Table 2 summarises the data for CO_2 load captured from power plants in consideration and to be sent for storage in the reservoirs. As shown, the total planning horizon for the case study is approximately 20 years, which is a reasonable period for energy planning. The power plant fleet is comprised of coal, natural gas and oil power plants. Two coal power plants A and B are considered in the planning horizon, with coal power plant B assumed to be a new plant constructed as replacement for coal plant A. As such, coal power plant B requires storage for captured CO_2 towards the end of the planning horizon, i.e. from year 18 onwards. Note that the availability of coal power plant B is only 4 y although realistically plant operation life is more than 20 y. However, it is assumed that the plant is constructed late, and hence exceeds the planning horizon considered for this study. The remaining operating life of plant B can be considered in the next planning horizon.

Table 2: Captured CO_2 load from power plants for case study

Power Plant	**Start to End** (yr)	**Plant life considered in planning horizon** (y)	**Average captured CO_2 rate** (Mt/yr)	**Total CO_2 load** (Mt)
Coal Power Plant A	5 to 18	14	40	560
Natural Gas Power Plant	6 to 15	10	20	200
Oil Power Plant	8 to 17	8	20	160
	16 to 18	2	40	80
Coal Power Plant B	18 to 19	2	40	80
	20 to 21	2	60	120
Total				**1200**

CSCCs for the case study are plotted in Figure 3. From Figure 3, it is observed that there are potential matching regions for offsetting, identified from the overlapping region where both source and sink are available. The source composite curve is then shifted to the left until it touches the sink composite curve on year 8 (Figure 4), which is identified as the *time pinch* for this problem. The time pinch is identified as the bottleneck that determines the availability of the storage sites for storing the captured CO_2 required to be disposed from the power plants in operation.

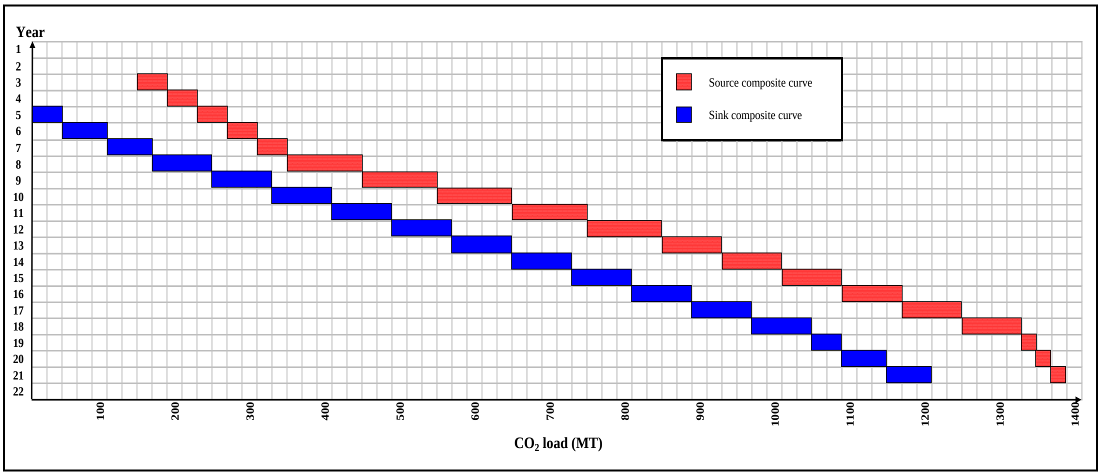

Figure 3: Plotting of CSCC for Case Study

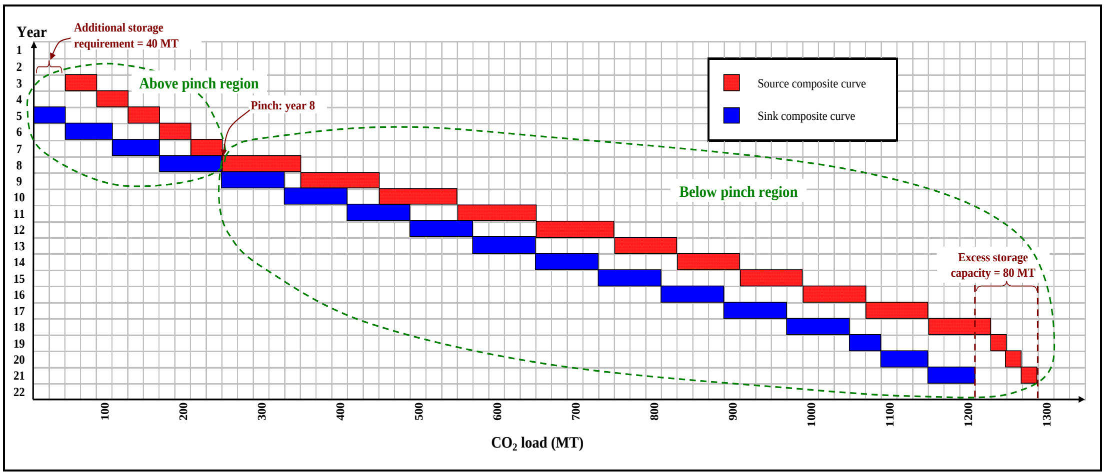

Figure 4: A feasible CSCC for Case Study

From the above pinch region, the amount of additional CO_2 storage requirement or target is 40 Mt CO_2. Additional storage can be supplied from neighbouring storage sites in the area/region to support the storage deficit identified (i.e., excess CO_2 may be exported beyond the boundaries of the geographic region). The below pinch region is used to identify the amount of excess storage capacity available from the total reservoir capacity in the planning time horizon. However, of the total excess storage capacity of 80 Mt CO_2, only 60 Mt CO_2 capacity is recoverable in the planning duration. This spare capacity can be used to accommodate CO_2 storage from other additional power plants implemented with CCS initiatives in the area/ region, or for the next planning horizon (i. e. as the external storage available prior to the start of year 22 for the case study). The remaining 20 Mt CO_2 storage capacity is only available from year 22 and beyond. Note that the storage deficit and excess capacity in this problem is conceptually similar to heat integration problem where minimum hot and cold utilities are needed (Linnhoff et al., 1982); or the resource conservation networks with external resources and waste discharge (Foo, 2012). Having to identify the storage deficit enables the country to revise its energy plan so that external storage requirement can be reduced.

5. Detailed allocation and matching of CO_2 sources with storage reservoir

Following the identification of planning targets, the hypothetical example is revisited to determine the allocation of storage sinks and sources. The CSCC in Figure 4 is further refined by breaking down the sink and source composite curves into their individual constituents (i.e., power plants of coal, natural gas and oil; Reservoirs A, B and C), instead of plotting for total storage capacity and requirement. To determine a possible pairing combination, the individual source and sink for each time interval will be rearranged to ensure that once a power plant is paired to a reservoir, the plant will continue sending captured CO2 load to the same reservoir unless limited by the reservoir storage capacity, or operating life. This will ensure an economically viable pairing option to be identified, as setting up CCS facilities between a plant and storage site often entails costly facilities (e.g. pipeline and booster compressors). As such, limiting the number of routes from a plant to a reservoir (where possible) will be the primary approach adopted when determining possible permutation options in pairing.
One of the possible pairing options is shown in Figure 5. As shown, CO_2 captured from coal power plant A will be sent to reservoir A for storage from year 5 to year 13 until the end life of reservoir A after which alternative reservoir B is required for storage of remaining captured CO_2 from coal power plant A (each with CO_2 flowrate of 40 Mt/yr). Captured CO_2 from natural gas power plant will be sent to reservoirs A, B and D (additional make-up storage) throughout the operating life of the plant. Also, captured CO_2 from oil power plant will be sent for storage in reservoir B, reservoir C and reservoir D from year 8 to year 17. Captured CO_2 from coal power plant B will be sent to reservoirs B and C when it starts operation in year 18. Since the planning horizon considered in this study is only 20 y, the storage strategy for coal power plant B from year 22 onwards will be considered in next planning horizon (assuming that coal power plant B, reservoirs B and C are still available in the new planning horizon). Note that the spare storage capacity is observed for reservoir B from year 8 to year 10 to accommodate additional captured CO_2 from the power plants or new plants located in the region.

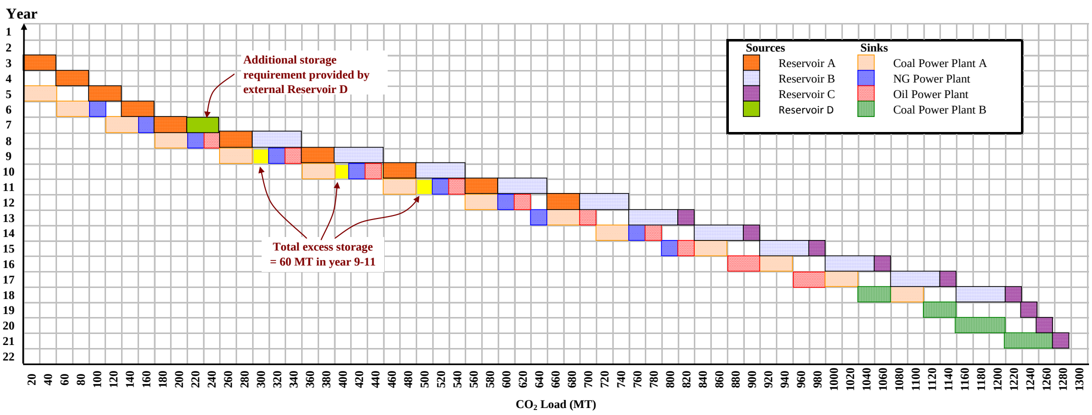

Figure 5: Detailed CSCC for matching of CO_2 sources with storage reservoir

6. Conclusion

The newly developed graphical tool of carbon storage composite curves (CSCC) serves as a valuable decision support tool for the CCS planning problem. It identifies the amount of additional CO_2 storage requirement as well as the excess storage capacity available from the total reservoir capacity in the planning time horizon. Having to identify the storage deficit enables the country to revise its energy plan so that external storage requirement can be reduced. Further development is needed to match the storage sinks and sources that fulfil the identified targets.

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