AN INTEGER LINEAR PROGRAM FOR SOURCE-SINK MATCHING IN CARBON CAPTURE AND STORAGE SYSTEMS

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Abstract: In this study, an integer linear program (ILP) is developed to match CO_2 sources and geological sinks subject to capacity, injection rate and geographical constraints. The problem statement addressed involves carbon capture and storage (CCS) systems in multiple geographic regions in which possible connections are limited based on geographic distance. A case study is presented to illustrate the ILP model.

Key Words: CO_2 Capture and Storage; Integer Linear Programming; Optimization

1. INTRODUCTION

The reduction of CO_2 emissions to the atmosphere is one of the main objectives in addressing climate change issues. A major portion of CO_2 emissions comes from the power generation sector particularly coal-fired plants. Carbon capture and storage (CCS) is a key technology that involves capturing CO_2 from sources and transporting it to geological sinks for permanent storage (Davison et al, 2001). The development of an integer linear program (ILP) for matching CO_2 sources and sinks is important since it may not be immediately obvious which connections should be made.

Previous CCS models have been also developed to address issues in designing CCS networks. One of the earliest models is by Turk et al (1987) for presenting a modified transportation model for CCS. Middleton and Bielicki (2009, 2012a) developed a mixed integer linear program (MILP) for CCS infrastructure for a specific geographic region. MILP models have also been proposed to account for sources and sinks that are not be available at the same time (Tan et al, 2012; 2013, Lee and Chen, 2012). However, optimization for multiple regions has not been considered in previous papers. These regions are based on sinks with overlapping geographic ranges in which some connections are allowed for a particular sink.

This paper is organized as follows: Section 2 presents the problem statement that the model will address. Section 3 presents the ILP model based on the problem statement which is illustrated using a case study in Section 4. Section 5 presents the future works to be developed by the authors.

2. PROBLEM STATEMENT

In this paper, the problem statement is addressed as follows:

- The CCS system consists of *m* sources and *n* sinks. Each *i*th source is a power plant composed of N_i identically-sized units, each with CO_2 flow rate of A_i and with a definite operating life T_i. The *j*th sink is a reservoir with capacity B_j and injection rate limit of C_j.
- All sources and sinks are available at the same time. More than one overlapping regions are considered. Only sources and sinks within the same region may be linked.
- A maximum connectivity distance is established relative to a sink as a proxy constraint for pipeline cost.

3. INTEGER LINEAR PROGRAM

An ILP model is presented in this section. The total CO_2 stored to sinks is maximized:

$$\max \sum_i \sum_j A_i y_{ij} T_i \qquad (Eq. 1)$$

subject to:

$$\sum_i^m A_i y_{ij} T_i \le B_j \qquad \forall j \qquad (Eq. 2)$$

$$\sum_i^m A_i y_{ij} \le C_j \qquad \forall j \qquad (Eq. 3)$$

$$y_{ij} \le N_i x_{ij} \qquad \forall i,j \qquad (Eq. 4)$$

$$x_{ij}(D_{max} - D_{ij}) \ge 0 \qquad \forall i,j \qquad (Eq. 5)$$

$$\sum_j^n x_{ij} < 1 \qquad \forall i,j \qquad (Eq. 6)$$

$$y_{ij} \epsilon\ I \qquad \forall i,j \qquad (Eq. 7)$$
$$x_{ij} \epsilon\ \{0,1\} \qquad \forall i,j \qquad (Eq. 8)$$

where:

A_i = CO_2 flow rate per power plant unit of source *i*.

B_j = storage capacity of sink *j*.

C_j = injection rate limit of sink *j*.

N_i = number of power plant units of source *i*.

D_{max} = maximum connectivity distance between a source and a sink.

y_{ij} = number of power plants of source *i* contributing to the total CO_2 injected to sink *j*.

x_{ij} = binary variable that determines whether a connection between source *i* and sink *j* exist.

Eq. 2 represents the capacity constraint while Eq. 3 represents the injection rate limit. The term $A_i y_{ij} T_i$ represents the total CO_2 captured and stored from a particular source. Eq. 4 denotes that the number of power plants with operating CO_2 capture technology should be equal to or less than the operating power plant units. Eq. 5 restricts the connectivity of each source-sink pair based on geographic distance. Eq. 6 permits only one connection in each source.

4. CASE STUDY

The model was implemented in Lingo 12.0 for the case study that follows. The case study is composed of four sources and two sinks. The maximum distance allowed for connection is 500 km.

Table 1. Source data

Source	No of Power Plant Units, N_i	Flow Rate (Mt/y), A_i	Time of Operation (y), T_i	Total CO_2 emitted (Mt)
i =1	3	0.8	20	48
i = 2	4	0.8	30	96
i =3	2	1.0	20	40
i =4	2	0.8	25	40

Table 2. Sink data

Sink	Capacity (Mt) B_i	Injection Rate Limit (Mt/y) C_i
j =1 (A)	150	15
j =2 (B)	150	15

Table 3. Distances between source-sink pair

	Distance (km)	
Source	Sink 1	Sink 2
1	**480**	**400**
2	1100	**250**
3	**350**	**300**
4	**450**	650

The optimal solution for this case is shown below. The dotted lines represent one geographic region based on a 500-km radius around a particular sink.

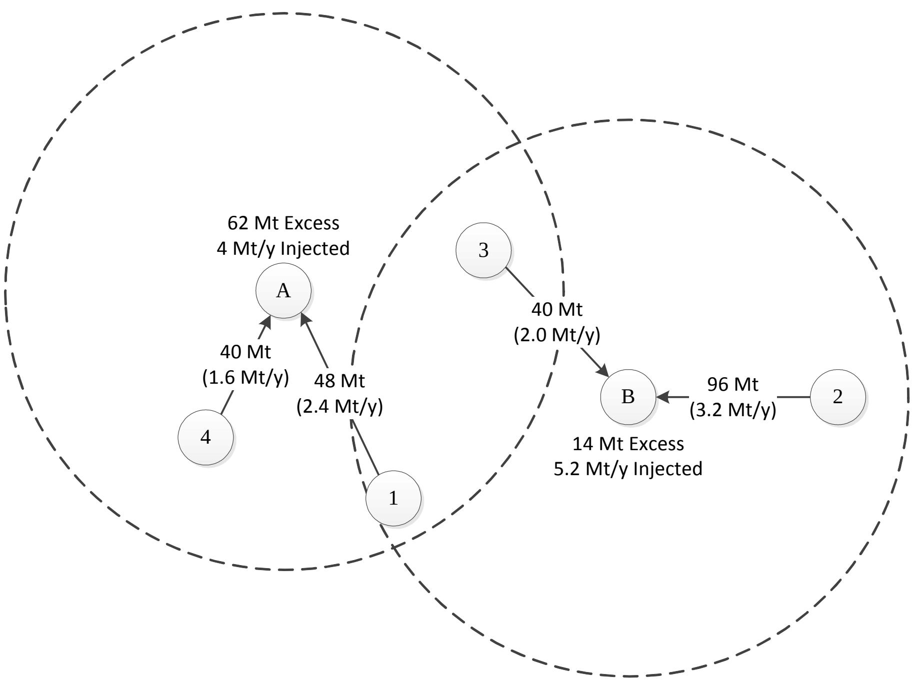

Figure 1: Optimal CCS Network for the case study.

In Figure 1, it shown that 74.6% of the total capacity is utilized by all CO_2 captured from the sources. Sink A has a higher spare capacity than Sink B with 62 Mt available. The total spare capacity is equal to 76 Mt and at least 9.8 Mt/y can be injected for both sinks. All power plant units in this case contribute to the total flow rate of the sources.

5. CONCLUSIONS AND RECOMMENDATION

An ILP model was developed based on capacity, injection rate and geographic constraints. The model is applicable for two or more overlapping regions. The characteristic of the candidate sources is the typical point source with multiple power plant units in which a single capture plant can be installed and the pipeline costs for a CCS network is mathematically represented by a maximum connectivity distance. Future works by the authors includes extensions of this model which incorporates total costs of capture and robust optimization of multiple scenarios.

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