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Region-Wide Source-Sink Models for Carbon Dioxide Capture, Utilization, and Storage Systems

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A large fraction of anthropogenic CO_2 emissions comes from point sources such as power plants, petroleum refineries, and other large industrial facilities. Carbon capture, utilization, and storage (CCUS) is one of various strategies for carbon management that captures carbon dioxide emissions from point sources and either reuses or stores it. It is also an important component technology for regional low-carbon development. A mixed integer nonlinear programming (MINLP) model for carbon management network of regional CCUS system is proposed here for planning regional CCUS networks. The optimization objective is to minimize the total annual cost of the carbon management network (CMN). According to carbon life cycle metabolism analysis, region-wide source-sink models are developed. Various emissions point sources are considered. Alternative capture methods (pre-combustion capture, post-combustion capture, and oxy-combustion) and transportation using pipelines are included in the model. Four utilization sinks (greenhouse, urea production, methanol production, and enhanced oil recovery) are also considered. With the consideration of different regional carbon neutrality goals, potential utilization sites and CMN alternatives are investigated. The case in an assumed city in China is used to illustrate the optimization of regional CCUS schemes. For the given case study, the results show that the CMN and costs vary with CO_2 reduction targets.

1. Introduction

In 2021, the United Nations Climate Change Conference reached a resolution to "control the global temperature rise by 1.5 °C" as one of the goals to ensure that human beings can survive on earth. Limiting warming to around 2 °C would still require global greenhouse gas emissions to peak by 2025 at the latest and cut by a quarter by 2030. Accelerating equitable climate action in mitigating and adapting to the impacts of climate change is critical to sustainable development (IPCC, 2022).

Due to the increased anthropogenic activities, it is very difficult to maintain the CO_2 concentration in the atmosphere at acceptable levels. Most of the research aimed at addressing this problem has been through carbon dioxide capture, utilization, and storage (CCUS) techniques (Gambhir et al., 2019). CCUS, refers to the process of separating CO_2 from industrial processes, energy utilization or the atmosphere, and directly using it to achieve permanent CO_2 emission reduction. It includes four parts: CO_2 capture, CO_2 transport, CO_2 utilization, and CO_2 storage. The International Energy Agency (IEA) highlights that to successfully maintain the global temperature rise to less than 2 ° C, global CCUS technology must contribute 94 Gt of cumulative CO_2 emission reductions from 2013 to 2050, which accounts for about 12 % of global CO_2 emission reduction. USA, China, Japan, Australia, Germany, Canada, Netherlands, and United Kingdom are leading the research and development of CCUS technologies (Liu et al., 2017).

Till today, several studies have been performed related to CO_2 supply chain optimization. Hasan et al. (2014) designed a CCUS supply chain network with minimum cost to reduce stationary CO_2 emissions and their adverse environmental impacts in the United States. Al-Mohannadi and Linke (2016) proposed an approach for

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low-cost carbon integration network system design in industrial parks through a comprehensive analysis of carbon sources, utilization and storage options, and capture, separation, compression, and transmission options. Zhu et al. (2019) analyzed the optimal geographical matching relationship between sources and sinks by evaluating emissions from large-scale fixed CO_2 sources and the CO_2 storage potential in Jiangsu Province. Wang et al. (2020) proposed a source–sink matching model to optimal CCUS deployment in China's CFPPs to achieve the 2 °C target. Fan et al. (2020) established an optimization model that does not consider CCUS cost constraints and determined the CO_2 emission reduction potential of existing CCUS coal-fired power plants in China from the perspective of source-sink matching. Kegl et al. (2021) proposed a conceptually simplified model for the optimization of combined CO_2 supply networks and capture and utilization technologies by the MINLP approach. The objective is to maximize the profit of CCUS technologies, considering chemisorption using MDEA as a capture technology and conversion of CO_2 to CH_3OH as a utilization technology.
To plan the regional CCUS network, a MINLP model for the carbon management network of the regional CCUS system is proposed. This model is like the MINLP proposed by Al-Mohannadi and Linke (2016) for the design of low-cost carbon-integrated network systems in industrial parks. The rest of this paper is organized as follows. Section 2 gives the formal problem statement, while Section 3 gives the MINLP model formulation. Section 4 illustrates the use of the model with an assumed case study. Finally, Section 5 presents conclusions and briefly discusses directions for future work.

2. Problem Statement

There are s number of carbon emissions sources being considered for the CCUS system and t number of treated sources, u number of untreated sources, and K number of carbon emissions sinks. Each carbon source has known type, location, annual CO_2 emissions, CO_2 composition in the flue gas, and pressure; each sink has known type, location, annual CO_2 demand or storage estimate, CO_2 price; each of the untreated and treated emission sources can be allocated to any sink of CO_2 that may exist. The problem is to determine the flow and allocation of CO_2 under different emission reduction targets to minimize the total annual cost of the CMN. The carbon dioxide network representation with multiple sources and sinks is illustrated in Figure 1.

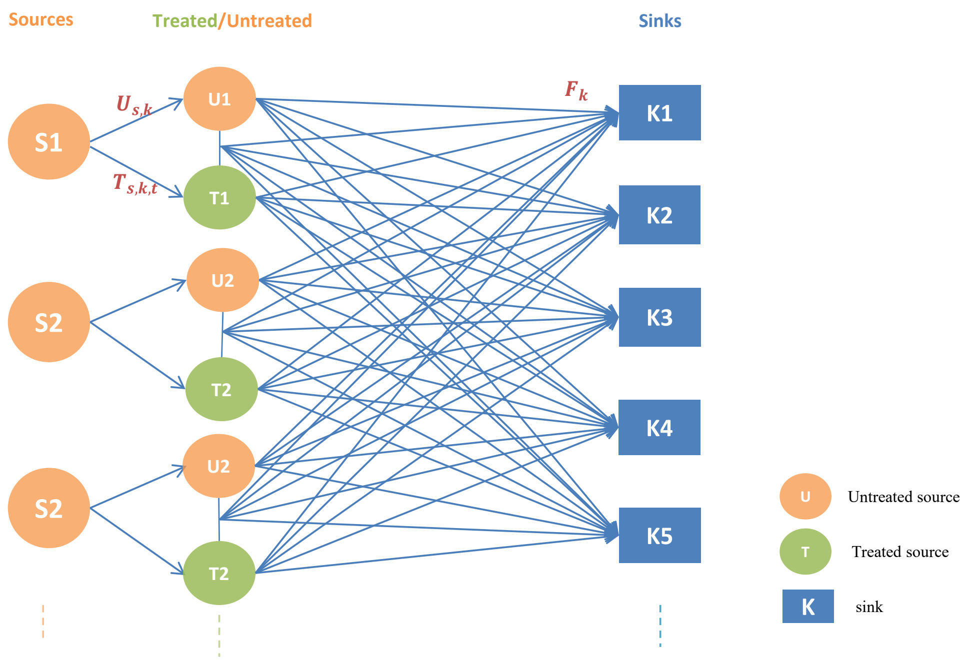

Figure 1: Network representation for sources and sinks.

3. MILP Model Formulation

The formulation of the mass balance for CCUS is presented as follows. Raw source flow can be allocated between an upper and a lower limit, shown as Eq(1). The mass balances around raw sources s are given as Eq(2) and Eq(3). The total and component balance around sinks k are given as Eq(4) and Eq(5). Any source can be connected to any sink subject to the sink minimum concentration requirement Z_k^{min} and the sink flow requirement G_k^{max} as described in Eq(7) and Eq(8). The net carbon reduction target (NCRT) is specified by the user whereas the net capture is defined as total carbon dioxide emitted subtracted from the total CO_2 allocated follows Eq(9).

$$L_s \leq R_s \leq M_s \tag{1}$$

$$R_s = \sum_{k\in K}\sum_{t\in T} \varepsilon_t T_{s,k,t} + \sum_{k\in K} U_{s,k} \qquad \forall s \in S \tag{2}$$

$$R_s * y_s = \sum_{k\in K}\sum_{t\in T} \varepsilon_t T_{s,k,t} * y_{s,t} + \sum_{k\in K} U_{s,k} * y_u \qquad \forall s \in S \tag{3}$$

$$F_k = \sum_{s\in S}\sum_{t\in T} \varepsilon_t T_{s,k,t} + \sum_{s\in S} U_{s,k} \qquad \forall k \in K \tag{4}$$

$$F_k * Z_k^{min} \leq \sum_{s\in S}\sum_{t\in T} T_{s,k,t} * \varepsilon_t * y_{s,t} + \sum_{s\in S} U_{s,k} * y_u \qquad \forall k \in K \tag{5}$$

$$y_s = y_u \qquad \forall s \in S \tag{6}$$

$$F_k \leq G_k^{max} \qquad \forall k \in K \tag{7}$$

$$L_{s,k}X_{s,k} \leq \varepsilon_t * T_{s,k,t} + U_{s,k} \leq M_{s,k}X_{s,k} \qquad \forall s \in S, \forall k \in K, \forall t \in T \tag{8}$$

$$\text{Net capture} = \sum F_k^{CO2} * (1-\eta_k) - \sum T_{s,k,t} * y_{s,t} * \gamma_t - \sum F_k^{CO2} * \varepsilon_p \qquad \forall s \in S, \forall k \in K, \forall t \in T \tag{9}$$

$$\text{Net capture} \geqslant \text{NCRT} \tag{10}$$

$$T_{s,k,t} \gg 0 \qquad \forall s \in S, \forall k \in K, \forall t \in T \tag{11}$$

$$U_{s,k} \gg 0 \qquad \forall s \in S, \forall k \in K \tag{12}$$

$$y_{s,t} \gg 0 \qquad \forall s \in S, \forall t \in T \tag{13}$$

The optimization function is to minimize the total annual cost of the CMN in Eq(14). It is considered as treatment and separation cost, compression cost, transportation cost, CO_2 tax, and the cost of processing carbon dioxide in a given sink, shown as Eqs(15-21). For treatment and separation cost, compression cost, and the cost of processing carbon dioxide in a given sink refer to the published model by Al-Mohannadi and Linke (2016). For CO_2 transportation the authors only considered pipelines. The CO_2 tax revenue as the amount of CO_2 captured (F_k) multiplied by the tax (C^{tax}) in Eq(21).

$$\min_k Z = \min_k \sum\nolimits_s \sum\nolimits_k \sum\nolimits_t (C_{s,k}^{Treatment} + C_{s,k}^{Compression} + C_{s,k}^{Transportation} + C_{s,k}^{Sinks} + C_{s,k}^{Taxes}) \tag{14}$$

$$C_{s,k}^{Treatment} = \sum_{s\in S}\sum_{t\in T}\sum_{k\in K} T_{s,k,t} * C^T \tag{15}$$

$$C_{s,k}^{Compression} = C_{s,k}^{compressor} + C_{s,k}^{pump} \tag{16}$$

$$C_{s,k}^{compressor} = \sum_{s\in S}\sum_{k\in K}\begin{Bmatrix} 158{,}902\left([P^{comp}\left(T_{s,k,t} * \varepsilon_t + U_{s,k}\right)]/224\right)^{0.84} \\ * \text{CRF} + P^{comp}\left(T_{s,k,t} * \varepsilon_t + U_{s,k}\right) * \text{Elec} * 8{,}000 \end{Bmatrix} + 31{,}800 * \left(T_{s,k,t} * \varepsilon_t + U_{s,k}\right) \tag{17}$$

$$\begin{aligned} C_{s,k}^{pump} = \sum_{s\in S}\sum\nolimits_{k\in K} \{ 1.11 * 10^6 \left(\frac{P^{pump}\left(T_{s,k,t} * \varepsilon_t + U_{s,k}\right)}{1{,}000} + 0.07 * 10^6\right) * \text{CRF} + 0.8 \\ * P^{pump}\left(T_{s,k,t} * \varepsilon_t + U_{s,k}\right) * \text{Elec} * 8{,}000 + 22{,}200 * \left(T_{s,k,t} * \varepsilon_t + U_{s,k}\right)\} \end{aligned} \tag{18}$$

$$C_{s,k}^{\text{Transportation}} = \left(\text{CRF} + \text{OM}_{\text{piping}}\right) * \left\{C_{\text{base,piping}}\left(\frac{T_{s,k,t} * \ \varepsilon_{\ t} + U_{s,k}}{M_{\text{base}}}\right)^{\alpha}\right\} * \{H_{\text{pipe,s,k}} * 10^{3}(H_{\text{pipe,s,k}}/H_{\text{base}})^{\beta}\} \quad (19)$$

$$C_{s,k}^{\text{Sinks}} = \sum_{k} F_k * C_k^{\text{sink}} \quad (20)$$

$$C_{s,k}^{\text{Taxes}} = \sum_{k} F_k * C^{\text{tax}} \quad (21)$$

4. Case Study

The CCUS supply chain network model was implemented in a city of Shandong Province, China, considering two power plants as point sources (Power Plant 1, Power Plant 2), three CO_2 utilization points (greenhouse, methanol production, urea production) and a storage point (EOR). For each point source, the known flue gas mass flow and its composition, pressure, and cost of treating the separated CO_2 are shown in Table 1. Among the two point sources, Power Plant 1 has a larger emission. For each carbon sink, the known CO_2 demand and its composition, pressure and sink cost, sink efficiency are shown in Table 2 (Al-Mohannadi and Linke, 2016). All plants are assumed to operate 8,000 h/y. The cost of electricity is 0.02 USD/kWh (Al-Mohannadi and Linke, 2016) and a capital recovery factor (CRF) of 0.15 is used to annualize capital costs. The distance between source and sink is shown in Table 3. In this case study, the MINLP is implemented in the commercial software GAMS (Brooke et al., 2011) using a laptop with Intel(R) Core™ i7-6700U CPU at 2.60GHz.

Table 1: Carbon dioxide source streams.

Sources	CO_2 composition(wt%)	Flow CO_2 (t/y)	P(mPa)	Treatment cost(＄/t)
Power Plant 1	10	130,6000	8.43	26
Power Plant 2	10	254,0184	10.95	32

Table 2: Carbon dioxide sinks.

sink	CO_2 composition(wt%)	CO_2 demand (t/y)	P(mPa)	Sink cost(＄/t)	η_k
Greenhouses	94	40,3315	0.101	-5	0.5
Methanol	99.9	36,8650	8.08	-21	0.098
Urea	99.9	37,3395	14.14	-15	0.39
EOR	94	59,8355	15.198	-30	0

Table 3: Distances between sources and sinks $H_{base,s,k}$ (km).

Source/Sink	Greenhouse	Methanol	Urea	EOR
Power Plant 1	32.7	1.07	2.86	1.91
Power Plant 2	33.3	4.67	3.45	1.31

This study considers the CO_2 emission reduction revenue and uses US$ 15/tCO_2 as the CO_2 tax to obtain the distribution of the CCUS network when the emission reduction targets are 20 %, 40 %, 50 % and 60 %. Optimization problems were solved for the four net carbon reduction targets to understand the changes in flows and types of connections as footprint reduction goals increase. The resulting CMN is shown in Figure 2.
Figure 3 shows cost breakdowns for optimal carbon networks at five CO_2 net reduction targets in terms of treatment, compression, piping, CO_2 taxes and the cost of processing CO_2 in given sinks. The breakdown shows how specific carbon reduction costs vary as specific reduction targets are incrementally increased.

5. Conclusions

In this work, a MINLP model for carbon management network of regional CCUS system is proposed here for planning regional CCUS networks. In general, the optimal structure of a CCUS system is strongly influenced by the amount of flue gas emissions and the cost of the transport mode, the transport distance, the capacity of the sink, the cost of the associated technology, and the CO_2 tax. For the given case study, the lowest cost CMN under different emission reduction targets was derived, and the results show that the CMN and costs vary with CO_2 reduction targets. When the carbon emission reduction target is 60%, the emission reduction is the largest, which is 2.3 Gt of CO_2 per year. At this time, the total cost is US$ 39,555,910/y, of which the largest cost is the transportation cost. However, the CCUS system involves multiple actors operating across different sectors, so future work needs to involve a government push to ensure that CCUS becomes a practical option for later large-scale commercial deployment. Furthermore, multi-objective optimization models can be developed that consider both the economic and intrinsic safety aspects of the technology.

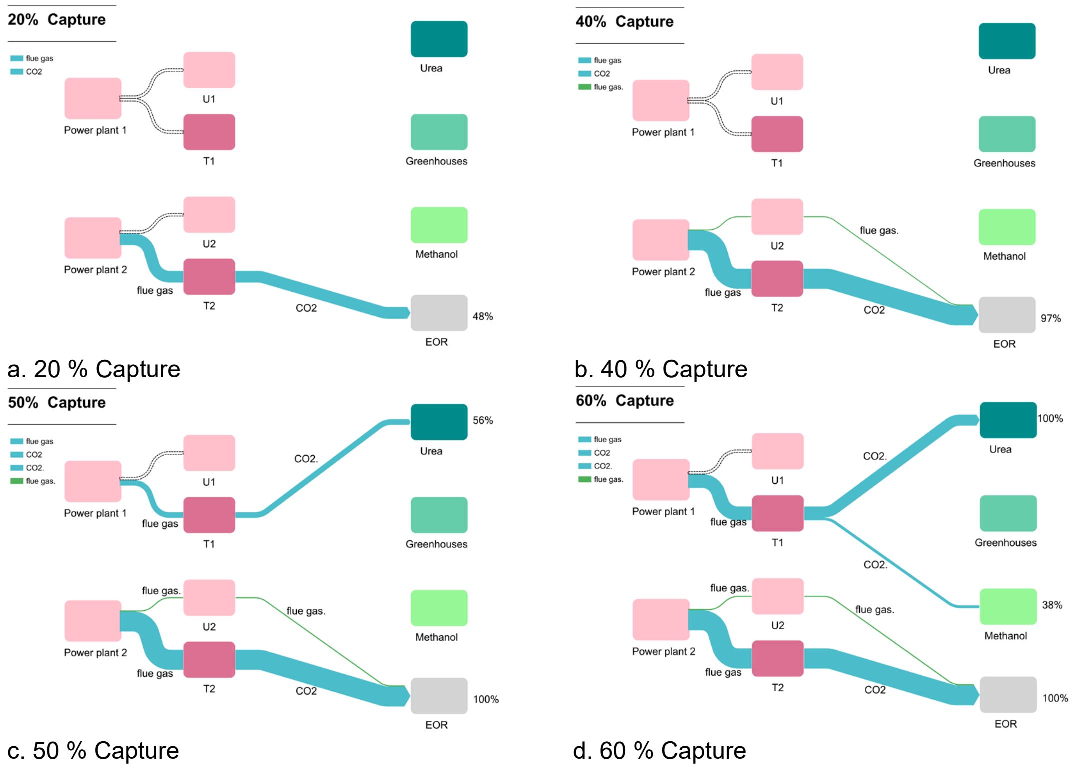

Figure 2: Carbon emissions integration network under different carbon emission reduction targets.

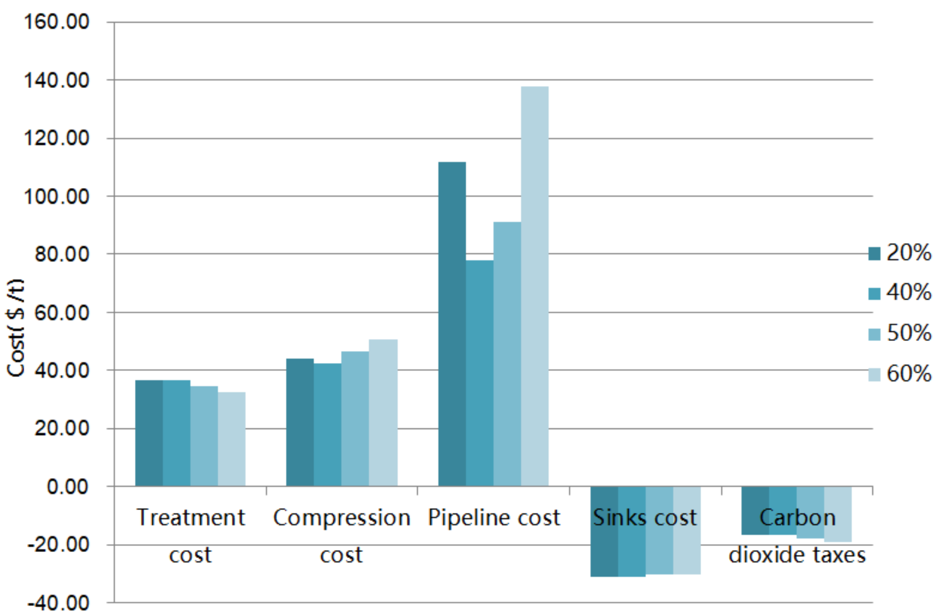

Figure 3: Costs for carbon emissions management network.

Nomenclature

Parameters

$C_{base,piping}$ – base cost for CO_2 pipeline capital cost calculation
C^T– treatment cost
Elec – electricity cost
F_K – CO_2 flow into the sink
$H_{base,s,k}$ – base length for CO_2 pipeline calculation in km
$H_{pipe,s,k}$ – length of the pipeline from s to k
L_S –minimum flow available from the raw source
M_{base} – CO_2 base flow for pipeline capital cost calculation in tons CO_2/d
M_S – maximum flow available from the raw source
OM_{piping} – operation and maintenance cost rate/y of TOC for pipelines
P^{comp} – compression power parameters
P^{pump} – pumping power parameters
R_S– raw source flow
α – CO_2 flow rate scaling factor
β – distance scaling factor
γ_t– amount of carbon dioxide emitted from the treatment unit energy use
η_k – sinks efficiency
ε_t – carbon removal efficiency
ε_p – power use carbon footprint

Variables

$T_{s,k,t}$ – treated source
$U_{s,k}$ – untreated source

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