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# An inexact optimization model for planning regional carbon capture, transportation and storage systems under uncertainty

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ABSTRACT

$CO_2$ capture and storage (CCS) is widely recognized as a climate-change mitigation technology that can significantly sequestrate human-induced $CO_2$ emission. However, there are two main issues that affect the development and deployment of CCS in a region/country: one is the shortage of planning tool for supporting effective decision making regarding timing, sitting and scaling of CCS capture, transport and storage facilities as well as dynamic sink-source matching between capture and storage. The other is uncertainty in technical, economic, political and other dimensions of CCS as the technology is still in early stage of commercialization. Therefore, the objective of this study is to develop an inexact CCS optimization model (ICCSM) for supporting regional carbon capture, transportation and storage planning under interval-format uncertainty with a least-cost strategy. It could address issues related to optimal sink-source matching in a region with multiple capture and storage options. The developed model was then applied to a case study of long term regional CCS planning under uncertainty. To demonstrate its applicability and capability, further scenario analysis indicated that high concentration $CO_2$ from coal-to-chemical/liquids/gas for EOR storage would be early opportunity for CCS in China. In addition, carbon price would be an effective policy instrument for encouraging deployment of CCS. Without sufficient carbon price, it could be difficult for moving CCS from demonstration stage to deployment stage in a short term.



## 1. Introduction

Climate change has wide impacts on humans and the environment (Metz et al., 2005; UNFCC, 1997). The public concern about climate change has resulted in the United Nations Framework Convention on Climate Change (UNFCCC) (Pires et al., 2011; Han and Lee, 2011a). Carbon dioxide capture and storage (CCS), which consists of three technological components – capture, transportation and storage, is an essential element in a portfolio of climate change mitigation technologies that can significantly sequestrate human-induced $CO_2$ emission (Middleton et al., 2012). Thus, CCS technologies have attracted great interests of researchers worldwide as it is believed that the technologies can significantly contribute to stabilization of concentrations of $CO_2$ in the atmospheric (Hoffert et al., 1998; Hoffer et al., 2002; McCoy and Rubin, 2008).

In the last decade, the understanding of CCS technologies has increased greatly, which is reflected by the IPCC Special Report on Carbon Dioxide Capture and Storage (Metz et al., 2005). However, there are two main issues that affect the development and deployment of CCS in a region/country: one is the shortage of planning tool for supporting effective decision making regarding the timing, sitting and scaling of CCS capture, transport, and storage facilities as well as dynamic sink-source matching between $CO_2$ capture and storage. The other is significant uncertainty in technical, economic, political and financial factors and other dimensions of CCS.

Aiming at the gaps of CCS planning tool, a number of modeling works were undertaken toward the development of CCS planning tool from either a component or a full-chain perspective. For example, McCoy and Rubin developed an engineering-economic model of pipeline $CO_2$ transport with application to CCS for planning $CO_2$ transportation over a range of distances for different regions in United States (McCoy and Rubin, 2008). Rubin et al. proposed a generalized modeling tool to estimate and compare the emissions,

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efficiency, resource requirements and current costs of power plants with CCS on a systematic basis (Rubin et al., 2007). Broek et al. applied an energy bottom-up model to carry out a quantitative scenario study for planning electricity and cogeneration sector with CCS technologies (BroekMachteld van den et al., 2008). Middleton and Bielicki introduced a scalable infrastructure model for CCS which could help determine where and how much $CO_2$ to capture and store, and where to build and connect pipelines of different sizes in order to minimize the costs of sequestering a given amount of $CO_2$ (Middleton and Bielicki, 2009). Hildebrand and Herzog developed a model through approximating relevant technical and economic aspects of partial capture for pulverized coal-fired power plants and integrated gasification combined cycle (IGCC) plants to plan the step in implementing CCS in a near-term horizon (Hildebrand and Herzog, 2009). Koo et al. introduced a modeling approach based on a modified energy flow optimization model which allowed a robust optimization of sustainable energy planning over a period of years with minimizing total costs in planning capacities of power plants and CCS to be added, stripped and retrofitted (Koo et al., 2011). Laude and Ricci reported a discount cash flow method to study the economic feasibility of capturing $CO_2$ emission from a small sugar beet plant and storing the emission in a deep saline aquifer (Lau and Ricci, 2011). Han et al. planned an energy infrastructure with the installation of CCS and renewable energy systems simultaneously in the context of mathematical programming with the objective to minimize total system cost (Han et al., 2012).

Regarding the uncertainties associated with $CO_2$ capture, transport, and storage activities, there were a few studies reported in the past years. For instance, McCoy and Rubin applied a probabilistic model to quantify the impact of uncertainty and variability on $CO_2$ transport cost (McCoy and Rubin, 2008). Hansson and Bryngelsson interviewed experts involved with CCS research and/or development and analyzed experts' framing of CCS with focus on the function and potential of CCS and uncertainties (Hansson and Bryngelsson, 2009). Han and Lee developed a model which could outline all possible architectures of future CCS, to optimize the design of the infrastructure required to treat $CO_2$ on the east coast of Korea in 2020 (Han and Lee, 2011b). Markusson et al. developed a socio-technical assessment framework to identify key uncertainties of future CCS development and deployment linkages between different uncertainties, as well as qualitative and quantitative indicators for assessing these uncertainties (Markusson et al., 2012). Cristobal et al. proposed a two-stage stochastic mixed-integer linear programming approach for the optimal investment timing and operation of a $CO_2$ capture system under uncertainty in the $CO_2$ allowance price (Cristobal et al., 2013).

However, most of previous planning studies tackled CCS within a full-chain or an energy system framework, thus they could hardly get insights into the complex interactions among capture, transportation and storage activities in a regional scale. This shortcoming would lead to underestimation of cost-mitigation approach through optimizing a variety of capture, transportation and storage activities in a regional level jurisdiction. In addition, the previous studies could only handle the uncertainty existing in CCS systems in the form of probabilistic distribution. In fact, CCS is still in the early stage of commercialization, most of the CCS information could only be quantified as an interval without known probabilistic distribution. Lack of the analysis of such uncertainties would affect the decisions on deployment of CCS in a region.

Therefore, the objective of this study is to develop an inexact CCS optimization model (ICCSM) for planning regional CCS systems under uncertainty. The objective entails: (1) the development of a regional CCS system planning model to address interactions among $CO_2$ emission capture, transportation, and storage; (2) the integration of interval-parameter and mixed-integer programming techniques into the developed regional CCS optimization model to deal with uncertainty presented as inexact parameters; (3) application of the developed model to a hypothetical case within China's context to demonstrate its capability in providing decision bases for planning of carbon capture, transportation and storage in a region under uncertainty.

## 2. Development of inexact CCS optimization model (ICCSM)

In a typical regional-scale carbon capture and storage (CCS) system, there are four main modules to be considered. They are (I) $CO_2$ emission sources, (II) $CO_2$ capture module which involves capture and compression technologies used for capturing $CO_2$ emission with high purity, (III) $CO_2$ transportation module which is determined by the distance and the amounts of $CO_2$ emission, and (IV) $CO_2$ storage module which consists of multiple storage options. These four modules, on one hand, are interacted along a full-chain (capture, transportation and storage) CCS technical route; on the other hand, each module contains multiple options which competing among each other based on timing, siting, scaling and many other technical and economic factors. Hence, the decision problems facing decision makers in a region would be how to identify CCS technical route for mitigating $CO_2$ emission and how to determine the timing, siting and scale of a selected capture, transportation and storage technology in a region based on the least-cost strategy. Such problems can be addressed through a regional CCS optimization model which can be formulated as minimizing system cost with capacity expansion planning schemes handled by an integer programming. In addition, optimizing a regional CCS planning system are associated with a variety of uncertainty of $CO_2$ capture, transportation and storage parameters and various impact factors. While most of the parameters and factors could be quantified as interval values; to address such an interval-format uncertainty, an inexact regional CCS model can be formulated in terms of an objective function and a large number of constraints.

### 2.1. Objective function

In the ICCSM, the decision variables are used to describe key discrete points of a CCS system. They can be classified into two types: continuous and integer. The continuous variables are related to amounts of $CO_2$ capture, transport and storage; the integer ones stand for the expansions of $CO_2$ capture, transport and storage facilities. Each facility may have multiple options representing different expansion scales. The objective function of ICCSM is to minimize the total system cost subjects to a set of constraints. These constraints reflect the interactions among various economic, environmental and technical factors. The total system cost is a function of a linear combination of costs associated with various technology options along with $CO_2$ flows from emission to storage end. Accordingly, the objective function of the ICCSM can be categorized into the following equation:

$$Min\ \ f^{\pm} = f_1^{\pm} + f_2^{\pm} + f_3^{\pm} + f_4^{\pm} - f_5^{\pm} - f_6^{\pm} \tag{2.1a}$$

where $f^{\pm}$ = net system cost ($10^3$ \$).

$f_1^{\pm} - f_6^{\pm}$ can be formulated as the following equations:

$$\begin{aligned} f_1^{\pm} = & \sum_{t=1}\sum_{g=1}\sum_{h=1}\sum_{i=1}\sum_{k=1} YCE^{\pm}_{t,g,h,i,k} \times CCE_{t,g,h,i,k} \times ICE^{\pm}_{t,g,h,i,k} \\ & + \sum_{t=1}\sum_{g=1}\sum_{h=1}\sum_{i=1} XCC^{\pm}_{t,g,h,i} \times VCC^{\pm}_{t,g,h,i} \\ & + \sum_{t=1}\sum_{g=1}\sum_{h=1}\sum_{i=1}\left(\sum_{k=1} YCE^{\pm}_{t,g,h,i,k} \times CCE_{t,g,h,i,k}\right) \times FCC^{\pm}_{t,g,h,i} \end{aligned} \tag{2.1b}$$