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Planning of carbon capture storage deployment using process graph approach

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A B S T R A C T

Carbon capture and storage (CCS) is an emerging technology to mitigate carbon dioxide (CO_2) emissions from industrial sources such as power plants. However, retrofitting a power plant for carbon capture causes an increase in unit power cost due to parasitic power losses as well as capital outlays for additional process equipment. Mathematical optimisation and pinch analysis techniques have been used to systematically plan for the retrofit of power plants. In this work, the planning of power plants retrofit along with CO_2 source-sink matching is analysed using *process graph* (P-graph) optimisation technique. CO_2 sources are assumed to be characterised by fixed flowrates and operating lives; while CO_2 sinks are characterised by storage capacity limits and earliest time of availability. Illustrative case studies are solved to demonstrate the approach.

1. Introduction

Global carbon dioxide (CO_2) emissions are now regarded as a major issue to society. Climate change is considered as a critical problem, with the current atmospheric CO_2 concentration now in excess of safe limits [1]. In addition, human activities continue to add a steady stream of greenhouse gases to the atmosphere. Power generation from fossil fuels (coal, oil and natural gas) contributes to a significant portion of these CO_2 emissions. Fossil fuels currently supply more than 85% of the energy used worldwide due to their low cost, availability, reliability, and energy density [2,3]. In order to reduce the climatic impacts, efficiency improvement on current technologies, fuels substitution and utilisation of low-carbon energy for cleaner electricity generation have been implemented [4,5]. However, fossil fuels will probably remain as a major contributor to the world's power generation mix in the future, due to the limitations of many low-carbon alternatives [6,7]. In particular, fossil fuels continue to dominate the energy markets, especially in developing countries characterised by growing economies and rising energy demands. In addition, most renewable energy options are often subject to significant geographic limitations. Although nuclear power is a mature, low-carbon alternative to fossil fuels, it has recently raised worldwide concerns on environmental and safety issues after several major accidents, e.g. the 2011 Fukushima disaster in Japan. These factors contribute to the requirement for the deployment of *carbon capture and storage* (CCS) technology in order to mitigate climate change by reducing industrial CO_2 emissions.

As its name suggests, CCS first entails *carbon capture* (i.e., isolation of CO_2 from combustion flue gas) and then *carbon storage* (i.e., disposal of the CO_2 in an appropriate geological storage reservoir). Current capture technologies include oxy-fuel combustion (OFC), chemical looping combustion, pre-combustion using integrated gasification combined cycles (IGCC), or post-combustion capture via flue gas scrubbing (FGS) [8–11]. Typically, 80–90% of CO_2 from power plant exhaust gases can be captured using these technologies and subsequently, compressed for secure storage in

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various geological formations, such as depleted oil or gas reservoirs, inaccessible coal deposits, saline aquifers and other geological structures of sufficient integrity.

Note however that, retrofitting power plant with CCS has some major issues, one of which is the energy consumption of additional process equipment to isolate and compress CO_2. When plants are retrofitted for capture, the power output of the retrofitted plant is 15–20% lower than original output due to parasitic energy demands (i.e. the additional energy demands for CO_2 capture) [9]. In addition, capital cost for plants with CCS will be 25–50% higher than that of baseline plants due to the additional process equipment, such as air separation units for OFC and absorption columns for FGS [9]. Subsequently, these equipment cause a drop in plant thermal efficiency of 5–10%, resulting in an increase in the cost of electricity generated [12]. To compensate for the power loss, additional electricity also needs to be generated from new plants in order to maintain the grid-wide power output prior to CCS deployment, which ultimately contributes to incremental costs. Alternatively, electricity may need to be imported from nearby regions (if these have surplus supply); such measures may, of course, potentially compromise energy security or independence of a country. Failure to compensate for the energy penalties incurred by CCS will result in power shortages. All of these complex considerations result in the need for proper planning of CCS deployment in power generation sector. Market allocation optimisation model has been used to analyse economic aspect of CCS systems [13]. Life cycle assessment has also been used to study the trade-offs between different environmental impacts after implementation of CCS systems [14]. However, there are still significant uncertainties with respect to economics of CCS systems and technical uncertainties in CO_2 life cycle [15], mainly are grid power problems and CO_2 source-sink matching.

Pinch analysis was first introduced to address CCS planning problem, particularly for carbon capture planning [16–18]. In the seminal work of Tan et al. [16], which was an extension based on carbon emission pinch analysis [19], useful insights and performance targets (e.g. minimum extent of retrofit) to facilitate the CCS retrofit planning stage are obtained using the graphical tool known as the *CCS planning composite curve*. However, there are several limitations in this approach. First, it only handles highly aggregated energy sources and demands, in which planning can only be made at the sectorial level. Besides, various design constraints and economic considerations for detailed planning cannot be included. Shenoy and Shenoy [17] employed *table algorithm* and *nearest neighbour algorithm* to design the carbon emission networks, and followed by total cost optimisation using mixed integer linear programming (MILP) formulation. A significant advantage of this methodology is that network can be designed separately, without requiring the cost data. Therefore, many alternative networks can be obtained by just varying order of satisfaction in table algorithm. The drawback of this methodology is the optimum network can only be obtained after going through few distinct stages of analysis. A recent work of Sahu et al. [18] improves the previous work of Tan et al. [16], where compensatory power was assumed to be generated only from carbon-neutral sources. The group makes use of algebraic technique to handle cases where compensatory power is generated from both carbon-neutral and non-carbon-neutral sources.

In order to overcome the limitation of pinch analysis techniques, several works based on *mathematical optimisation* techniques have been developed for the planning of CCS deployment. These include those based on superstructure model [20–22] and automated targeting technique [23,24]. Mathematical optimisation technique is preferable, when detailed planning scenarios are encountered. Such models also provide an opportunity to integrate more complex, case-specific goal functions especially to handle the deployment of CCS retrofit with concern for cost-effectiveness [25].

On the other hand, different techniques have also been developed for carbon storage planning problem, in order to match multiple CO_2 sources and sinks (storage sites). Graphical techniques based on pinch analysis were developed to cater for capacity [26] and injectivity constraints [27]. Diamante et al. [28] improved their previous work [27] by considering time availability of sources and sinks, simultaneously with injectivity limits. However, geographical distances and pipeline costs between various sources and sinks are neglected due to inherent simplifications and lower expandability of pinch approaches.

Different mathematical optimisation models have also been presented for the carbon storage problem. A discrete-time MILP model was developed for optimal source-sink matching with temporal, injection rate and storage capacity constraints [25]. This constraint is tackled by dividing a finite planning horizon into discrete time intervals. However, this model is only suitable for mid-term planning of CCS option for plants located in close geographical proximity to sinks. For an increase in precision, shorter time intervals are required in the model, which results in the increase in model variables with the associated penalties in computational effort. A related continuous-time MILP model for CO_2 source-sink matching in CCS systems also developed [29]. This model accounts for CO_2 emission penalties result from generating electricity to compensate for grid-wide CCS power losses [16,17,20,21]. The main assumption of Tan et al. [29] is by omitting injection rate, since physical characteristic of CO_2 sinks capacity is more significant. Later, Lee and Chen [30] proposed an improved MILP model for similar problems. Lee et al. [31] has recently presented a unified multi-period MILP model to consider CCS retrofit planning and CO_2 source-sink matching simultaneously.

As mentioned, different approaches for planning CCS deployment have been proposed, each with their own unique advantages and disadvantages. In this work, we propose a novel alternative approach to CCS system planning based on *process network synthesis* (PNS), which is based on *process graph* (P-graph). P-graph methodology is a powerful approach which utilises graph theory to perform an efficient search of the solution space of a given problem domain. P-graph framework was first introduced by Friedler et al. [32] for synthesis of process system. This approach resorts to the well-established mathematics of graph theory and it is heavily based on a unique class of graphs as well as combinatorial techniques [32]. It focuses on structures of the whole system and rigorously examines all possible structures from mathematical perspective, while allowing for a more efficient search of the solution space than is possible from MILP approaches. A wide range of successful application has then been reported, which include molecular design [33], reaction pathway synthesis [34,35], synthesis of separation network [36–39], heat exchanger network synthesis [40], process synthesis [41–43], and energy supply chain [44,45]. However, no attempt has been reported for the use of P-graph for CCS planning problem, which is the main aim of this work.

This paper proposes a P-graph approach for the systematic planning of CCS deployment in the power generation sector. The rest of the work is organised as below. First, a formal problem statement is given. A brief explanation on methodology used in this paper is next discussed. A literature case study on carbon capture is adapted as base case and solved using P-graph approach. Furthermore, different parameters are used to illustrate the potential future scenarios in CCS planning; and sensitivity analysis is carried out by generating Pareto optimal curve. Extensions are then developed from this base case to determine appropriate source-sink matching for carbon capture planning based on temporal