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An Extended MILP Model for Planning CCS Retrofit in Power Plant Fleets

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Carbon capture and storage (CCS) is an important technology that can contribute to the reduction of greenhouse gas emissions. It involves the capture of CO_2 from point sources such as power plants and subsequent storage in secure geological reservoirs. However, capture incurs parasitic power loss; thus, compensatory power from clean sources such as renewables will be needed to make up for the power losses. The conventional capture process is designed for steady-state operation, but flexible capture is possible to offset the intermittency of renewable energy. Systematic planning for robust CCS systems is needed to incorporate flexible mechanisms in CO_2 capture. In this study, a mixed integer linear program (MILP) is developed to robust CCS retrofit subject to operational adjustments for multiple periods or scenarios. Retrofit decisions include options for flexible and non-flexible capture, accounting for trade-offs between the two options. Operational adjustments pertain to decisions to switch off the flexible capture plants to compensate for depressed renewable energy supply. A case study is presented to demonstrate the optimization model. From the case study, flexible mechanism can provide a more robust planning, where low availabilities of renewable energy can contribute up to 18% of the power demand.

1. Introduction

According to International Energy Agency (2021), electricity demand is expected to increase steadily due to economic and population growth in developing countries. This increased energy demand will be met with a progressively decarbonized electricity generation mix with a high proportion of renewable energy (RE). RE has been one of the main considerations for policy decisions for sustainable energy (Halder et al., 2015) due to its low carbon footprint (Rani et al., 2020). However, a constant supply of energy cannot be fully guaranteed by inherently volatile RE. For example, prolonged droughts can decrease energy supply from hydroelectric power plants. The effect of the California drought on the Folsom Dam led to electricity shortages, increased costs, and CO_2 emissions from the supply of fossil fuel-based electricity (Lund et al., 2018). Thus, the dependence on non-RE sources will still be present in the future to maintain steady energy supply. To address the problem of greenhouse gas (GHG) emissions from fossil fuel-fired power plants, carbon capture and storage (CCS) technology can be used.

CCS is one the long-term solutions for CO_2 emissions reduction (Asian Development Bank, 2013). CCS can reduce overall mitigation costs, increase flexibility, and reduce CO_2 emissions (Freund et al., 2005). The prospect of using the CO_2 has also led to the extended carbon capture, utilization, and storage (CCUS) concept (Tapia et al., 2018). CCS has three major components: capture, transport, and storage. Among these components, CO_2 capture has the highest energy penalty from the power plants (De Coninck and Benson, 2014). Options for CO_2 capture includes pre-combustion, post-combustion, and oxyfuel combustion (Rackley, 2010). The captured CO_2 will then be transported and stored to different reservoirs such as unminable coal seams, depleted oil and gas reservoirs, and saline aquifers (Niu et al., 2014). CCS can be retrofitted to existing power plants and combustion plants in industries that are highly dependent on fossil fuels; alternatively, capture systems can also be integrated into the design of new plants. However, CCS comes at the expense of increased required power or efficiency penalty ranging from 10 to 15% due to the additional processes CCS entails:

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the separation of air, the reheating of solvents, and the compressing of CO_2 (Thorbjörnsson et al., 2015). The development of new CO_2 capture design allows reverting the power generation capacity to its baseline state whenever needed; a mechanism called flexible CO_2 capture (Cohen et al., 2012). Flexible mechanisms in CCS can supply the expected electricity to the power grid by switching the capture system off when the renewable energy supply is depressed (Goto et al., 2013). These mechanisms allow to respond to the changes with energy demand during long seasons of drought (Huber et al., 2014). Retrofitting flexible and non-flexible options for CO_2 capture requires systematic planning due to higher costs and lower steady-state efficiency of flexible capture systems.

Process Integration (PI) techniques for CCS have been proposed to aid in decision-making and planning (Tapia et al., 2018). The optimal decision for retrofitting non-flexible capture can be done using Pinch Analysis (PA) (Tan et al., 2009) or Mathematical Programming (MP) (Tan et al., 2010) methods. Techno-economic assessment of flexible CO_2 capture was performed by Craig et al. (2017) considering emissions limits. The economic implications of retrofitting flexible CO_2 capture were studied by Oates et al. (2014). Optimization of flexible CCS has been done previously as mentioned, but the focus has been on short-term RE fluctuations due to changes in wind speed or insolation. No models have been developed for planning flexible CO_2 capture retrofits to account for long-term variations in RE supply.

In this study, this research gap is addressed by developing a robust optimization model to provide adjustments in flexible CO_2 capture during long-term power shortage. Robust optimization requires assigning design variables to be fixed for all scenarios and operational variables to be adjusted in different scenarios. This approach has been applied to water network (Kumawat and Chaturvedi, 2020) and biofuel supply chain (Yue and You, 2016). The availability of flexible CCS allows the user to decide on a particular CO_2 capture type during planning and adjust the flexible capture options at different scenarios. This feature enables satisfaction of energy demands during low energy supply and minimize the need for rotational electricity cuts.

2. Problem Statement

The formal problem statement addressed in this paper is discussed as follows:

- The power plant consists of *n* power plant sources capable of being retrofitted with *m* options for CO_2 capture.
- Each power plant source *i* generates a constant electricity supply of P_i and emits $\underline{E_i}$ of CO_2 per unit of power generated.
- Each CO_2 capture option *j* removes a portion of CO_2 emission depending on the mode it is retrofitted. The amount of CO_2 captured from a given power plant is represented as α_{ij} when retrofitted capture mode is non-flexible and β_{ij} when it is flexible. Depending on the nature of the technology, each option may or may not have a flexible option.
- Each scenario, k, is characterized by the availability of renewable energy, Φ_k estimated at the beginning of the planning horizon. One default scenario includes planning under 100% availability or Φ_k=1. A weight, W_k is also given as an emission cost for each scenario. These weights are assigned to consider the relative importance of one scenario with respect to the other. The decision whether to switch-off a particular capture plant will depend on these parameters.
- Planning CCS retrofit involves the decision of which technological option should be adapted to each power plant, whether the mode of capture is flexible or not, and whether the flexible capture mode should be turned off during shortage scenarios. It is assumed that when the flexible capture is switched off, the electricity supplied by a power plant returns to its baseline state.

3. Optimization Model

The MILP model is formulated as follows:

$$\min \sum_k W_k C_k \tag{1}$$

subject to:

$$C_k = \sum_i [P_i E_i - \sum_j (\alpha_{ij} x_{ij} + \beta_{ij}(y_{ij} - z_{ijk}))] + (\phi_k)(E^R)(r) \qquad \forall k \tag{2}$$

$$\sum_i [P_i - \sum_j (A_{ij} x_{ij} + B_{ij}(y_{ij} - z_{ijk}))] + (\phi_k)(r) = D \qquad \forall k \tag{3}$$

$$\sum_j (x_{ij} + y_{ij}) \leq 1 \qquad \forall i \tag{4}$$

$$\sum_i y_{ij} \leq F_j \qquad \forall j \qquad (5)$$

$$y_{ij} \geq z_{ijk} \qquad \forall i, j, k \qquad (6)$$

$$x_{ij}, \in \{0,1\} \qquad \forall i, j \qquad (7)$$

$$y_{ij} \in \{0,1\} \qquad \forall i, j \qquad (8)$$

$$z_{ijk} \in \{0,1\} \qquad \forall i, j, k \qquad (9)$$

$$r \geq 0 \qquad (10)$$

The objective function (Eq(1)) minimizes the total weighted CO_2 emissions from all scenarios, allowing also the minimization of individual CO_2 per scenario. Eq(2) expresses the total CO_2 emission (C_k) for each scenario considered in the model. The first term in the equation denotes the total CO_2 emissions generated by each power plant in their baseline states. It is reduced depending on capture option selected, as well as the capture system operating state (i.e., on or off). The last term gives the CO_2 footprint of the renewable energy. Eq(3) ensures that the power demand is satisfied for all scenarios. The amount of power generated by each power plant also depends on the capture option selected, its flexibility, and the operating state for the latter. The binary variable, x_{ij}, determines the retrofitting of a non-flexible capture option (i.e., x_{ij}=1 if retrofitted with non-flexible capture, 0, otherwise). Then, y_{ij} is a binary variable that determines the retrofitting of a flexible capture option while z_{ijk} is a binary variable that determines whether the flexible option is switched off (z_{ijk}=0) or on (z_{ijk}=1) at a given scenario *k.* Eq(4) allows the selection of either a flexible or non-flexible option while Eq(5) restricts capture retrofit to technologies capable of flexible capture. This constraint is possible by setting F_j to zero if flexible option is not available. Eq(6) denotes that switching on and off is possible only when flexible capture is retrofitted. Eqs(7) to (10) set x_{ij}, y_{ij} and z_{ijk} as binary variables while the compensatory RE supply, *r*, is set as a non-negative variable. The model is implemented in AIMMS 4.77.3 in a PC with 16.0 Gb RAM and 3.59 GHz processor.

4. Case Study

The case study shown in Table 1 is adapted from Tan et al. (2010). It consists of ten power plants with three options for CO_2 capture, namely, pre-combustion capture, post-combustion capture and oxyfuel combustion capture. The information about these options is shown in Table 2. Only post-combustion capture is capable of flexible operation. The flexible mechanism of post-combustion capture gives the same capture ratio as that of the non-flexible option; however, it entails larger power losses due to the presence of additional energy requirements in the capture system (Kang et al., 2012). Option such as oxy-fuel combustion has higher capture rate than post-combustion capture. Two scenarios are considered for the case study: baseline and power shortage scenarios. Here, the total power demand is 3,100 MW for both scenarios, however, the shortage scenarios assume that the available capacity of RE is reduced to 60% of the installed capacity. The capacity of RE at full availability is to be determined by the model as compensatory power loss for retrofitting the capture technologies. This scenario assumes hydroelectric plants whose capacity may drop during a prolonged drought. It is also assumed that the weights for both scenarios are equal. The emission factor of the renewable energy is given as 0.0001 Mt/MW-y.

Table 1: Power plant data for the case study

Power Plant	Type of Fuel	Installed Capacity (MW)	Emission factor (Mt CO_2/MW-y)
1	Coal	200	0.008
2	Coal	250	0.008
3	Coal	150	0.008
4	Coal	600	0.008
5	Coal	500	0.008
6	Natural Gas	250	0.004
7	Natural Gas	300	0.004
8	Natural Gas	400	0.004
9	Oil	200	0.0056
10	Oil	250	0.0056

Table 2: Parameters for the capture options in the case study

	Post-combustion Capture	Pre-combustion	Oxyfuel Combustion
Flexible?	Yes	No	No
CO_2 Capture Ratio (Non-Flexible)	0.90	0.85	0.95
CO_2 Capture Ratio (Flexible)	0.90	-	-
Power Loss Ratio (Non-Flexible)	0.20	0.23	0.25
Power Loss Ratio (Flexible)	0.22	-	-

The optimal solution for the case study is illustrated in Table 3 showing the technologies retrofitted to each power plant and their states in both scenarios. The required capacity for renewable energy is equal to 660 MW due to a decrease of 21.3% of the generation capacity of all power plants retrofitted with CO_2 capture technologies. Under the baseline state, renewable energy is supplied at 100% of its capacity and it is reduced to 396 MW at the shortage scenario. The CO_2 reduction is 90% in the baseline scenario and 66% in the shortage scenario compared to an emission of 19.92 Mt/y before retrofitting. In this case, the flexible capture is switched off during the shortage scenario to generate more energy to satisfy the energy demand. In this case, a 23% increase in CO_2 emissions is observed to satisfy the additional 264 MW of power. The optimal decision generated by the model allows the determination of which capture option can be made non-flexible to minimize the CO_2 emissions in all scenarios to develop a robust energy system.

Table 3: Optimal solution for the case study (RE = Renewable energy)

Power Plant	Retrofitted Technology	Scenario where capture is switched-off	Power generated, MW (Baseline)	Power generated, MW (Shortage)	CO_2 emissions, Mt/y (Baseline)	CO_2 emissions, Mt/y (Shortage)
1	Oxyfuel combustion	n/a	150	150	0.080	0.080
2	Non-flexible post-combustion	n/a	200	200	0.200	0.200
3	Non-flexible post-combustion	n/a	120	120	0.120	0.120
4	Non-flexible post-combustion	n/a	480	480	0.480	0.480
5	Non-flexible post-combustion	n/a	400	400	0.400	0.400
6	Flexible post-combustion	Shortage	195	250	0.100	1.000
7	Flexible post-combustion	Shortage	234	300	0.120	1.200
8	Flexible post-combustion	Shortage	312	400	0.160	1.600
9	Pre-combustion	n/a	154	154	0.168	0.168
10	Flexible post-combustion	Shortage	195	250	0.140	1.400
RE	-	-	660	396	0.066	0.0396
Total	-	-	3,100	3,100	2,.034	6.714

Sensitivity analysis was performed by varying the RE supply from 80% to 20%. Figure 1 shows the selected capture options and their operating states. The normal scenario states are omitted. At higher RE availability, options for non-flexible capture such as oxyfuel combustion are selected. Coal-fired power plants adopt a non-flexible option most of the time, while oil- and natural gas-fired power plants adopt a flexible option in a wide range of RE supply scenarios. Minimization of CO_2 emissions set by the model allows the generation of less CO_2 emissions under shortage scenarios, where power plants with lower CO_2 emission at baseline state are retrofitted with flexible capture options. This insight allows planning of energy systems to decide on which power plants should be retrofitted with a flexible CO_2 capture option to adapt to a wide range of possible RE supply variations.

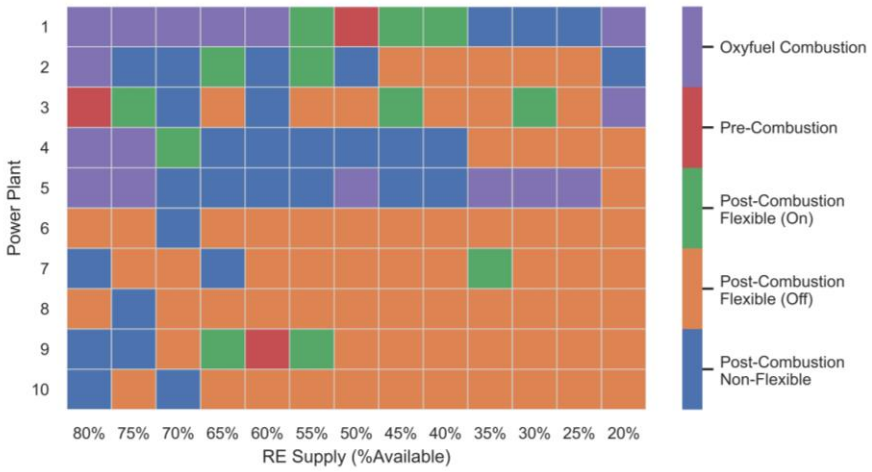

Figure 1: Capture options retrofitted at different levels of renewable energy supply

The CO_2 emissions at different availability levels are shown in Figure 2. An increasing trend in the CO_2 emissions is observed for RE shortage scenarios. However, the CO_2 emissions are maintained below 4 Mt/y at the normal scenario due to the retrofitting of flexible CO_2 capture in most power plants. These are switched off to generate more emergency power during periods of depressed RE supply. The results show that flexible CO_2 capture provides a more robust option for energy planning, addressing the fluctuations in RE supply. In comparison with the results given by Tan et al. (2011), flexible capture system is retrofitted to power plants, especially a low RE availabilities. Long-term RE supply cuts were not considered in the previous study, thus the model present a more robust approach for CCS retrofitting.

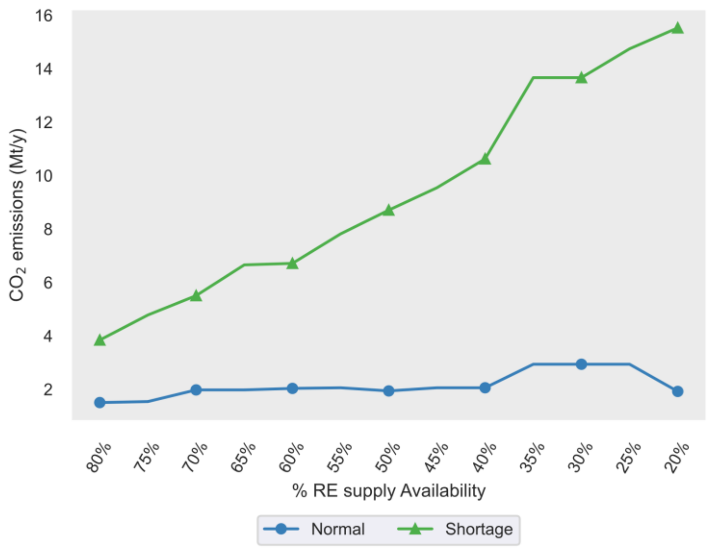

Figure 2: CO_2 emissions (Mt/y) of the energy system in the case study at baseline and shortage scenarios at varying renewable energy availability

5. Conclusion and Future Work

A MILP model was developed for robust planning of flexible CO_2 capture subject to potential renewable energy shortage. The model decides which retrofit option for CO_2 capture is applied to each power plant in the system and determines how much renewable energy is needed to compensate for parasitic energy losses. For any given energy scenario, the system decides which flexible option is turned off to provide additional emergency power output. This feature ensures satisfaction of the energy demand for all scenarios. Based on the case study performed, switching-off the capture system can provide an additional 4% to 18% of the power demand for 80% to 20% availability of renewable energy. More efficient non-flexible option is still adapted in the energy system as illustrated in the case study. As the risk of renewable energy shortage increases, more flexible capture units are adapted by the system. However, the CO_2 emissions are still maintained at a low level during normal scenario (i.e., when renewable energy is fully available) and adjusts only shortage scenario. Future work includes extending the model to incorporate matching CO_2 sources with geological sinks, adjustment to renewable energy systems, and considering techno-economic uncertainties in planning.

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