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Robust Decarbonization Planning of Multi-regional Energy Sector with Flexible Carbon Capture and Storage Systems

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Carbon capture and storage (CCS) plays a vital role in the global transition to a low-carbon energy society, enabling the continued use of fossil fuels until low-carbon energy sources become viable and widely accessible. However, one of the drawbacks is the energy penalty associated with the capture process, requiring compensatory power from renewables to make up for power losses. A potential solution involves bypassing the capture unit during increased electricity demands to recover the generation capacity lost due to capture. This flexible "on/off" mechanism eliminates the requirement of additional generation capacity to compromise the power loss and be economically beneficial by selling more electricity during periods of peak demand. A mixed integer linear program (MILP) model is developed to systematically plan robust CCS retrofit systems of multiple regions with fossil fuel-fired power plant fleets subject to operational adjustments for numerous periods and scenarios. The model considers energy transfer between regions due to insufficient resources to compensate for parasitic power losses in retrofitting capture technologies. The decision for retrofit includes options for flexible and non-flexible capture. Operational adjustments relate to decisions to switch off the flexible capture plants to compensate for the power losses due to capture. A case study is presented to illustrate the model. Results of the case study indicates that up to 70 % reduction in CO_2 emissions can be achieved through retrofitting of power plants with CO_2 capture option. A reduction of 24 % can still be achieved even if the available compensatory power is reduced by 70 %. In all scenarios, the maximum 30 % increase in energy production costs are all met.

1. Introduction

Currently, the world's primary energy sources are still in the majority based on fossil fuels. In 2019, 80.9 % of the world's total energy supply was met from fossil sources, namely coal, oil, and natural gas (IEA, 2021). Two effective solutions were suggested to reduce the world's dependency on fossil fuels: increasing energy efficiency to reduce energy requirements in every process and boosting the uptake of renewable energy (RE) technologies with lower carbon density. However, the world's reliance on fossil fuels makes the phase-out of fossil fuels highly challenging. RE deployment was done simultaneously with fossil energy but did not serve as a replacement (le Quéré et al., 2020). Technology such as carbon capture, utilization and storage (CCUS) is an important technology that allows simultaneous use of fossil fuel as energy source with renewable energy as compensatory power for CCUS operation. One of the options for CO_2 capture in CCUS involves flexible mechanisms.

Flexible CO_2 capture involves the adjustment of the operating capacity of CO_2 capture plant in response to the changing demand in energy (Gibbins and Crane, 2004). This approach has been discussed and illustrated in different forms such as variation in CO_2 capture rate using a bypass configuration (Cohen et al., 2011), or solvent storage system (Husebye et al., 2011). These configurations allow the partial or zero operation levels for the CO_2 capture plant, allowing additional energy output. There is a lack of knowledge about flexible mechanisms in CO_2 capture technology, especially in post-combustion capture on a larger scale (Bui et al., 2014). Assessment and demonstration of this technology have been done, including in Australia (Bui et al., 2016), Norway (Bui et al., 2020) and China (Hao et al., 2020). These studies provide information on the technical feasibility of the flexible capture through dynamic simulation partnered with pilot-scale plants.

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Several mathematical tools are proposed for optimal deployment of flexible capture technologies. A mixed integer linear programming (MILP) model has been developed for maximizing economic benefits from flexible CO_2 capture based on solvent regeneration and storage (Husebye et al., 2011). A capture plant is optimized for flexible capture accounting for variable power demand (Zaman and Lee, 2015) which later is extended to account for uncertainties (Zaman et al., 2016). Lambert et al. (2016) utilizes a multi-objective optimization approach to assess the economic feasibility of CO_2 capture at various capture rates. These mathematical approaches only focus on the improvements of the flexible approach in single plants. A model that utilizes flexible capture options in power plants has been proposed by Tapia et al. (2021) which involves retrofit decisions and operational strategies in response to varying availability of renewable energy. The integration of flexible CO_2 capture in energy systems can also drive the synergistic interaction between regions with different energy demands. To date, no study has been able to discuss a mathematical model for multi-region energy systems with flexible CO_2 capture. In this study, a robust MILP model is developed for retrofitting flexible CO_2 capture technology in a multi-regional setting. The model incorporates three main aspects of CCS planning as its novel contribution: selection of power plants with flexible and non-flexible capture options, planning of retrofit in multiple regions simultaneously, and synergistic trading of energy to meet compensatory power requirements. The advantage of flexible CO_2 capture is emphasized by incorporating robust optimization to anticipate scenarios of renewable energy shortage. The rest of the paper is organized as follows. Section 2 discusses the formal problem statement while Section 3 presents the optimization model. Section 4 illustrates the model through a case study and Section 5 presents the conclusions and prospects for future work.

2. Problem Statement

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

- An energy system consists of K regions with I power plant sources available for retrofit with J options for CO_2 capture.
- Each kth region is characterized by a maximum amount of available renewable energy resource, RM_k (MW), with a CO_2 footprint of ER_k (t CO_2/MWh) per unit of power generated. The region k can transmit to region l or receive electricity from region l. It is also assumed that there are no losses in electricity distribution between regions.
- Each ith power plant source generates a fixed electricity capacity of $P_{i,k}$ (MW) and emits $E_{i,k}$ (t CO_2/MWh) of CO_2 per unit of power generated.
- Each jth CO_2 capture technology removes a portion of CO_2 emission based on the retrofitted technology selected, described by its removal ratio RR_j. Each technology has parasitic loss which lowers the plant power output and relative cost increase, described by L_j and A_j, respectively. A binary parameter, τ_j, is assigned to indicate the suitability of tech j for flexible mechanism.
- The system is assumed to have sufficient capacity to utilize or store all captured CO_2. The fate of CO_2 captured in the system may include conversion to high-value products with long life or geological storage.
- Each mth scenario constitutes natural conditions characterized by renewable energy availability, $\Phi_{k,m}$ estimated at the beginning of the time horizon. A weight, W_m is assigned as an emission cost for each scenario, considering the relative probability of one scenario to the other.
- The aim of this study is to minimize the total carbon footprint considering all scenarios. The planning of the multi-region CCS retrofit includes the decision of which capture technology option should be retrofitted to each power plant, whether the mode of capture is flexible or not, whether the option is to turn off the flexible capture mode during shortage scenarios, the amount of compensatory power to be invested at the beginning of the time horizon, and power distribution between the regions. 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 with an objective of minimizing the total weighted carbon emissions for all scenarios m with weight W_m and total carbon emission, F_m (t CO_2/h)) in Eq(1):

$$\min \sum_m W_m \cdot F_m \tag{1}$$

subject to:

$$\begin{aligned}&\left[\sum_i P_{i,k} - \sum_i P_{i,k} \sum_j x_{i,j,k} - \sum_i P_{i,k} \sum_j \left(y_{i,j,k} - z_{i,j,k,m}\right)\right] + \left[\sum_i P_{i,k} \sum_j x_{i,j,k}\left(1 - L_j\right) + \right.\\ &\left.\sum_i P_{i,k} \sum_j \left(y_{i,j,k} - z_{i,j,k,m}\right)\left(1 - L_j\right)\right] + \left[\Phi_{k,m} \cdot r_k\right] + \left[\sum_l v_{l,k,m} - \sum_l v_{k,l,m}\right] = \sum_i P_{i,k}\end{aligned} \qquad \forall(k,m) \tag{2}$$

$$\begin{aligned}&\left[\sum\nolimits_{(i,k)} P_{i,k}E_{i,k} - \sum\nolimits_{(i,k)} P_{i,k}E_{i,k}\sum\nolimits_j x_{i,j,k} - \sum\nolimits_{(i,k)} P_{i,k}E_{i,k}\sum\nolimits_j\left(y_{i,j,k} - z_{i,j,k,m}\right)\right] + \\ &\left[\sum\nolimits_{(i,k)} P_{i,k}E_{i,k}\sum\nolimits_j x_{i,j,k}\left(1 - RR_j\right) + \sum\nolimits_{(k,i)} P_{i,k}E_{i,k}\sum\nolimits_j(y_{i,j,k} - z_{i,j,k,m})\left(1 - RR_j\right)\right] + \\ &\left[\sum\nolimits_k \Phi_{k,m} \cdot r_k \cdot ER_k\right] = F_m \end{aligned} \qquad \forall m \tag{3}$$

$$\begin{aligned}&\left[\sum\nolimits_i P_{i,k} - \sum\nolimits_i P_{i,k}\sum\nolimits_j x_{i,j,k} - \sum\nolimits_i P_{i,k}\sum\nolimits_j y_{i,j,k}\right] + \left[\sum\nolimits_i P_{i,k}\sum\nolimits_j A_j(x_{i,j,k} + y_{i,j,k})\left(1 - L_j\right)\right] + \left[B \cdot r_k\right] \le \\ &C \cdot \sum\nolimits_i P_{i,k}\end{aligned} \qquad \forall(k,m) \tag{4}$$

$$r_k \le RM_k \qquad \forall k \tag{5}$$

$$v_{k,l,m} \le M \cdot u_{k,l,m} \qquad \forall(k,l,m) \tag{6}$$

$$u_{k,l,m} + u_{l,k,m} \le 1 \qquad \forall(k,l,m) \tag{7}$$

$$\sum\nolimits_l u_{k,l,m} \ge \epsilon - M \cdot \left(1 - \delta_{k,m}\right) \qquad \forall(k,m) \tag{8}$$

$$\sum\nolimits_l u_{k,l,m} \le M \cdot \delta_{k,m} \qquad \forall(k,m) \tag{9}$$

$$-M \cdot \left(1 - \delta_{k,m}\right) \le \sum\nolimits_l u_{l,k,m} \le M \cdot \left(1 - \delta_{k,m}\right) \qquad \forall(k,m) \tag{10}$$

$$\sum\nolimits_j(x_{i,j,k} + y_{i,j,k}) \le 1 \qquad \forall(i,k) \tag{11}$$

$$x_{i,j,k} \le T_{i,j,k}, \qquad y_{i,j,k} \le T_{i,j,k} \qquad \forall(i,j,k) \tag{12}$$

$$x_{i,j,k} \le \tau_j \qquad \forall(i,j,k) \tag{13}$$

$$y_{i,j,k} + \tau_j \le 1 \qquad \forall(i,j,k) \tag{14}$$

$$y_{i,j,k} \ge z_{i,j,k,m} \qquad \forall(i,j,k,m) \tag{15}$$

$$u_{k,l,m} \in \{0,1\} \qquad \forall(k,l,m) \tag{16}$$

$$x_{i,j,k} \in \{0,1\}, \qquad y_{i,j,k} \in \{0,1\} \qquad \forall(i,j,k) \tag{17}$$

$$z_{i,j,k,m} \in \{0,1\} \qquad \forall(i,j,k,m) \tag{18}$$

$$\delta_{k,m} \in \{0,1\} \qquad \forall(k,m) \tag{19}$$

$$r_k \ge 0 \qquad \forall(k) \tag{20}$$

$$v_{k,l,m} \ge 0 \qquad \forall(k,l) \tag{21}$$

The power demand constraint is given by Eq(2). The first, second, and third term gives the total capacity from baseline power plants, retrofitted plants considering both non-flexible and flexible options, and new compensatory RE plants, respectively. The power capacity to be invested by the decision-maker to compensate for losses due to capture is given by r_k (MW). The fourth term considers the power transmission between regions. The subscripts k,l for the transmission term denotes the link between the transmitter and the receiver. In this case, $v_{l,k,m}$ is the power transmitted from region l to k; the summation term is positive since power is received by k. The term $v_{k,l,m}$ gives the power transmitted from region k to l. The summation of $v_{k,l,m}$ is negative as power is directed out of region k. The binary variable, $x_{i,j,k}$, decides the retrofitting of a non-flexible capture option while The binary variable, $y_{i,j,k}$, is for the flexible capture option (i.e., 1 if retrofitted and 0 otherwise). The binary decision $z_{i,j,k,m}$ is a binary variable that determines whether the flexible option is switched on ($z_{i,j,k,m}$ = 0) or off ($z_{i,j,k,m}$ = 1). The first, second, third, and fourth term of Eq(3) gives the total CO_2 emissions for a given. Eq(4) is the regional cost constraint, where the overall relative cost increase, with coefficient C, must be greater than or equal to the costs from all the power sources. Cost coefficient B is for compensatory plants.

Eq(5) expresses the capacity invested in new compensatory plants must be less than the maximum described per region. On Eq(6), a big-M constraint is used to quantify the availability of a power transmission link from region *k* to *l*: The binary variable, $u_{k,l,m}$, denotes availability (i.e., $u_{k,l,m}$ = 1 if there is a power transfer from *k* to *l*). The power transfer between regions is one-way (Eq(7)). The condition by Eq(8) to Eq(10) is two-fold: where if an output link exists for region *k*, then the region cannot receive any power from other regions; else, if there is no output link for region *k*, the region can accept power from other regions. $\delta_{k,m}$ is a binary decision variable that determines the existence of the link and ϵ is a small constant that forces the creation of the output link if available. Eq(11) limits the choice of CCS technology for each plant to a maximum of one. Eq(12) define the allowable ($T_{i,j,k}$ = 1) and forbidden ($T_{i,j,k}$ = 0) between the capture option and power plant. Eq(13) and Eq(14) restrict the availability of a flexible capture option for a technology. From Eq(15), switching on and off is only feasible when flexible capture technology has been retrofitted. Eq(16) to Eq(19) treats $u_{k,l,m}$, $x_{i,j,k}$, $y_{i,j,k}$, $z_{i,j,k,m}$, and $\delta_{k,m}$ as binary variables. Eq(20) and Eq(21) treat r_k and $v_{k,l,m}$ as non-negative variables. The model is implemented in LINGO 21.0 on a PC with 16.0 GB RAM and a 3.30 GHz processor.

4. Case Study

This case study is an adapted case from Tan et al. (2010) and modified in which the power plants are separated by region. The power plants use different fuel sources and emit varying CO_2 flow rates. The case study at baseline is illustrated in Figure 1A where it is assumed with the same timelines as that of Tan et al. (2010). The demand of the first region is 3,100 MW, the second region is 2,750 MW, and the third region is 2,850 MW. The rated capacities of each power plant are hypothetical. For all regions, the emission factors of coal, oil, natural gas, and renewable energy plants are 1, 0.7, 0.5, and 0.1 t CO_2/MWh, respectively. The emission factors follow the study of Tan et al. (2010), describing these values as realistic. The maximum number of renewable plants to be invested in is 40 % of the total power capacity of the region. It is assumed that each unit of power generated by new compensatory plants costs 30 % more than the baseline cost, corresponding to a cost coefficient for compensatory plants (*B*) of 1.30. The cost constraint was set for the overall power capacity cost not to increase by more than 30 %, corresponding to an overall cost coefficient for (*C*) of 1.30. The illustrative case study considers three scenarios which are based on the probability of drought recurrence by the World Meteorological Organization (Svoboda et al., 2012). Each scenario will have different weights and varying levels of renewable energy (RE) availability. The normal operation scenario has a weight of 60 % and RE availability of 100 %, the moderate drought scenario has a weight of 30 % and RE availability of 80 %, and the severe drought scenario has a weight of 10 % and RE availability of 30 %. Three carbon capture options are available for retrofit: pre-combustion (PC), post-combustion (PCC), and oxyfuel combustion capture (OFC). Table 1 recapitulates the properties of these options, which are adapted from Tapia et al. (2021) for the parasitic power loss and Thorbjörnsson et al. (2014) for the capture ratio. The capture options with flexible mechanism were assumed to have a 5 % increase in relative cost from the non-flexible capture option.

Table 1: Parameters for the capture options.

Parameter	PCC, Flex.	PCC, Non-Flex.	PC, Flex.	PC, Non-Flex.	OFC
CO_2 capture ratio	0.90	0.90	0.85	0.85	0.95
Power loss ratio	0.23	0.21	0.20	0.18	0.25
Cost Coefficient	1.50	1.45	1.45	1.40	1.50
τ_j	0	1	0	1	1

The optimal solution is shown in Figures 1B to 1D, illustrating the technologies and their states retrofitted to each plant, available capacities from all plants, RE, and transmission in all scenarios. The optimal result for the base case system for all scenarios requires 33.33 % of all plants to require the PCC with a flexible mechanism, 16.67 % to require PC with a flexible mechanism, 16.67 % for PC, 6.67 % for OFC, and 26.67 % to remain unmodified. PCC was not chosen by the model, in any case, to meet the power demand per scenario and cost constraint. Natural gas-fired power plants were not prioritized with the decision to retrofit due to their low emission factor compared to coal- and oil-fired power plants. The retrofitted capture options are the same for all scenarios. The difference in optima between scenarios is two-fold: the decision to turn on or turn off a capture option with a flexible option, and transfer of energy between regions. In all cases, the cost of energy production is met at a maximum increase of only 30 %. It is met through both optimal selection of capture options and energy trading between regions in different scenarios.

The regional RE capacity is 524.77 MW, 489.88 MW, and 479.35 MW for regions 1, 2, and 3, respectively. The required RE capacity considers retrofitted technologies, shortage scenarios, and power transmission. The effect of drought reduces the generative capacity of compensatory RE plants. To compensate for the loss in capacity and meet the power demand, plants retrofitted with flexible mechanism CC should turn off, especially for RE sources affected by drought, like hydroelectricity. The implementation of CCS aids the coalition of countries and businesses to achieve net-zero emissions. However, commitments by the 195 signatories of the Paris Agreement currently fall short of achieving net zero by 2050. For the global temperature rise to be under 1.5 °C, emissions need to be reduced by 45 %, which is not met (Schleussner et al., 2022). This model provides insights to policymakers at the state and municipality levels to contribute to the global initiative. The CO_2 reduction is 70.41 % in normal operation, 62.08 % in moderate drought, and 23.73 % in severe drought, compared to a 6,290 t CO_2/h net emission at baseline. Two common scenarios are on par with the 45 % requirement of the Paris Agreement. In the worst-case scenario, three regions can still achieve more than a 20 % reduction in CO_2 emissions.

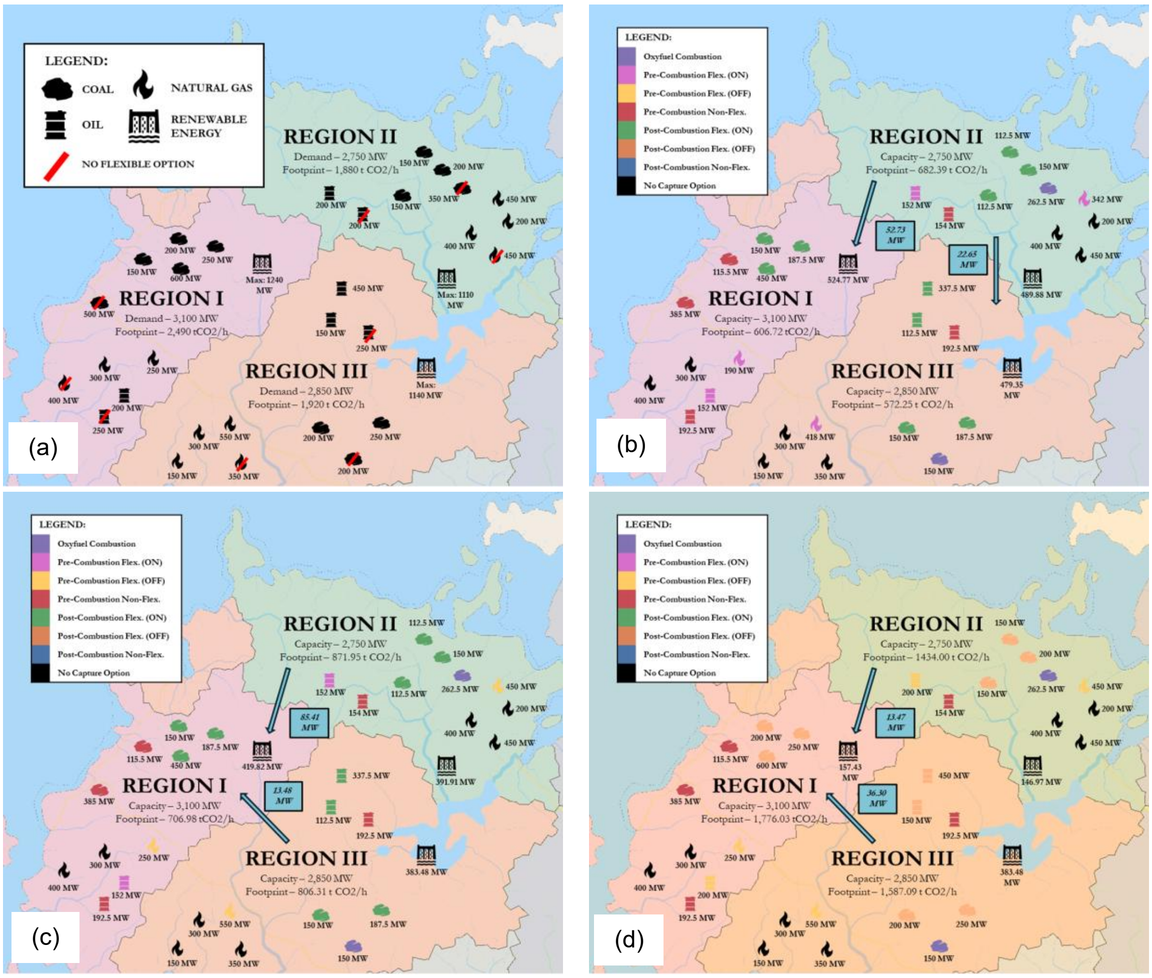

Figure 1: Illustration of the case study at the (a) baseline case, (b) normal operation, (c) moderate drought, and (d) severe drought scenarios.

Policymakers can improve the terms in which CCS can operate and provide related incentives. Compared to Tapia et al. (2021), where the non-flexible PC option is frequently employed, the current model introduces electricity flows between regions to accommodate more flexible options. Moreover, the addition of flexible retrofit suitability, and bounds to costs and baseline RE offers a more robust approach to planning multi-region energy systems with carbon capture. Compared to Tan et al. (2010), which did not account for long-term RE reductions, this model offers a more robust strategy for retrofitting power plants with flexible CO_2 capture options. The proposed model in this study provides valuable insight for large-scale energy systems planning and operation.

5. Conclusion and Future Work

This study presents a flexible CCS retrofit model that optimizes plant operations across multiple regions, accounting for cost, RE variability, and inter-regional power transfers. The model demonstrates that flexible capture options can significantly reduce CO_2 emissions, even under conditions which affect power security like drought. Sensitivity analyses further confirm the robustness of the model, showing that emissions targets can still be met within reasonable cost increases. Overall, the findings offer valuable guidance for policymakers balancing sustainability goals with economic and operational constraints. The model can be extended to address broader challenges in large-scale CCS deployment by incorporating CO_2 source-sink matching, diverse storage and utilization pathways, plant-specific configuration compatibility, and solution generation through P-graph-based optimization.

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