Economic and Environmental Optimisation Framework for Carbon Capture Utilisation and Storage Supply Chain

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Carbon capture utilisation and storage (CCUS) is widely recognised as a key mitigation technology that can significantly reduce carbon dioxide (CO₂) emission. This study develops an optimisation framework focused on the economic and environmental aspects of Northeast China CCUS supply chain. The overall network is economically optimised over a 20 years’ time horizon to provide the geographic location and scale of capture and sequestration sites as well as the most convenient transport routes. The resulting problem is a multi-objective mixed integer linear programming (MILP) model, whose objectives include minimising its total annual cost and minimising life cycle greenhouse gas (GHG) emission. The economic and environmental performances are optimised by ε-constraint method. To demonstrate the application of the proposed model, a realistic case study from Northeast China involving 16 sources and 3 sinks is illustrated. The results provide valuable insights to adopt more sustainable strategic alternatives in the design of CCUS supply chain.

1. Introduction

Fossil fuels combustion has been recognised as the main contributor for the rising emission of carbon dioxide (CO₂), a primary anthropogenic greenhouse gas (GHG) (Leung et al., 2014). Recently, the CO₂ emission in the atmosphere is expected to increase at an average rate of 0.6% from 2015 to 2040 (UNFCC, 2018). Given that the fossil fuels are still expected to constitute the backbone of current energy mix in the foreseeable future (Nataly and Xiu, 2014), it appears that carbon capture utilisation and storage (CCUS) should play a key role in decarbonizing the energy-intensive industry. In general, CCUS chain comprises three main steps: first, capture CO₂ via physical or chemical process from the flue gas; then, compress and transport the captured CO₂ via pipeline, truck, rail and ship; last, the transported CO₂ is injected into various geological formations including saline aquifers, inaccessible coal deposits and depleted oil or gas reservoirs, provided that these sinks are suitable for storage based on geological surveys of geochemical, seismic risk or other physical consideration (Holloway, 2007). Thus, CCUS is able to mitigate climate impacts by preventing CO₂ from entering into atmosphere.

Recently, extensive studies have been developed to aid in planning the commercial deployment of CCUS. Hasan et al. (2016) proposed a multi-scale framework for the optimal supply chain design for CO₂ capture, utilisation, and sequestration, which required decision making at material, process and supply chain levels simultaneously. d’Amore and Bezzo (2017) introduced a mixed integer linear programming (MILP) model for the economic optimisation of a European CCS supply chain. The network was optimised to decide where to capture and store CO₂, how much to capture as well as the transportation routes. Analytic hierarchy process data envelopment analysis was developed to select oil and gas reservoirs (Tapia et al., 2017). A two-stage stochastic MILP model was proposed to achieve the optimal retrofit planning of power plants with capture technology and CO₂ source-sink matching with considering uncertainties in sink physical constraints and investment limit (Zhang et al., 2018). Xing et al. (2018) introduced four business models based on the different stakeholders involved in CCUS projects by Monte-Carlo simulation. Their results provided insights on the selection of appropriate business model for the early-stage of CCUS projects in China.
However, many of the previously existed studies have focused their efforts on reducing the total cost for the deployment of CCUS supply chain, whilst neglecting the environmental impacts on the system. It is important to ensure that climate change is not mitigated at the expense of other environmental issues. Therefore, this study proposes a MILP model to optimise the strategic CCUS deployment in Northeast China. This model is optimised by making simultaneous selection of emission sources, capture facilitates, CO₂ pipeline, intermediate transportation sites, utilisation and storage sites. The life cycle environmental impacts of CCUS supply chain are analysed. At last, to better capture the performance of a CCUS supply chain from a sustainable perspective, simultaneous optimisation of economics and life cycle GHG emission is launched as a multi-objective optimisation problem.

2. Problem statement

The goal of this work is to reveal the economic and environmental potentials of carbon capture, utilisation and storage supply chain for GHG mitigation. The formal problem statement addressed in this paper is as follows:

Given:
- The target amount of CO₂ reduction.
- The capital cost data for each type of capture technology, transportation mode and injection well.
- The operation cost data for each type of capture technology, transportation mode and injection well.
- Transportation availability and distance data between available arcs.

Determine:
- Sources to be selected and CO₂ capture amounts from each selected source.
- CO₂ capture technology and material for each selected source.
- Intermediate sites to be selected from potential sites (capture sites, geological storage sites and utilisation sites) to provide the opportunity to build a more economic and practical pipeline network.
- Transportation logistics.

3. Model formulation

A MILP optimisation model based on the novel superstructure from authors’ previous work (Zhang et al., 2018) for the strategic design and planning of CCUS supply chain is proposed. The model is formulated with new constraints and two objective functions to address two concerned aspects of the CCUS supply chain network: economic evaluation and environmental impact. The economic objective is to minimise the annualized net cost of the CCUS supply chain TC, which is the difference between total annual cost TAC and annual revenue TAR.

\[
\text{Min } TC = \sum_{i,j,k} (TAC - TAR) \quad \forall i \in G, j \in G, k \in K
\]  

\( TAC \) is the total annual CCUS cost consisting of feed dehydration cost, CO₂ capture and compression investment cost (\( CIC_{i,k} \)) and operating cost (\( COC_{i,k} \)). CO₂ pipeline investment cost (\( PAIC_{i,j} \)) and operating and maintenance (O&M) cost (\( POC_{i,j} \)). CO₂ storage injection annual investment cost (\( IAIC_{i,j} \)) and O&M cost (\( IOC_{i,j} \)), as presented in Eqs.(2)-(7). \( TAR \) is the total revenue obtained by EOR-utilisation since oilfield sites need high purity CO₂ to improve the production of oil. The revenue is calculated by multiplying the total amount of CO₂ transported to oilfield sites by the unit price of CO₂ set by the oilfield decision-maker.

\[
CIC_{i,k} = \alpha_k \times y_{i,k} + \left( \beta_k \times y_{i,k} + \gamma_k \right) \times F_{i,k}^{in} \times (m_{i,k} \times FR_{i,k} + m_{2,k} \times y_{i,k}) \quad \forall i \in I, k \in K
\]

\[
COC_{i,k} = \alpha_k \times y_{i,k} + \left( \beta_k \times y_{i,k} + \gamma_k \right) \times F_{i,k}^{in} \times (m_{2,k} \times FR_{i,k} + m_{2,k} \times y_{i,k}) \quad \forall i \in I, k \in K
\]

\[
PAIC_{i,j} = \frac{r}{(1+r)^{\omega}} \left[ \left( \beta_i \times F_{i,j} + \alpha_i \times z_{i,j} \right) \times F_{j} \times L_{i,j} \right] \quad \forall i \in G, j \in G, i \neq j
\]

\[
POC_{i,j} = O \& M_{\text{pipeline}} \times \left[ \left( \beta_i \times F_{i,j} + \alpha_i \times z_{i,j} \right) \times F_{j} \times L_{i,j} \right] \quad \forall i \in G, j \in G, i \neq j
\]

\[
IAIC_{i,j} = \frac{r}{(1+r)^{\omega}} \left[ \left( \beta_i \times F_{i,j} + \alpha_i \times z_{i,j} \right) \times \frac{\sum F_{i,j}}{M_{\text{well}}} \right] \quad \forall j \in (S \cup U)
\]

\[
IOC_{i,j} = O \& M_{\text{well}} \times \left[ \left( \beta_i \times F_{i,j} + \alpha_i \times z_{i,j} \right) \times \frac{\sum r_{i,j}}{M_{\text{well}}} \right] \quad \forall j \in (S \cup U)
\]
Where $P_i^n$ is flue gas flowrate of node $i$, $FR_{ik}$ is the fraction of captured from flue gas, $y_{ik}$ is the binary denoting the selected technology, $F_{ij}$ is the amount of CO$_2$ transported from node $i$ to node $j$, $L_{ij}$ is the distance from node $i$ to node $j$, $F_t$ is the terrain factor, $r$ is the annual discount rate, and $T_{ne}$ is the planning horizon.

To estimate the environmental impact of CCUS supply chain network, the Life Cycle Assessment (LCA) method is applied. In this work, global warming potential (GWP) with respect to a 100-year time span is chosen as the environmental objective, which aggregates the environmental impacts of all GHG into a single indicator in terms of CO$_2$-equivalent, as presented in Eq(8).

$$\text{GWP} = \sum_{spc} \omega_{spc} \times \text{LCI}_{spc} \tag{8}$$

where $spc$ denotes the index of GHG species, $\omega_{spc}$ is the impact factor of species $spc$, and $\text{LCI}_{spc}$ is the life cycle inventory of species $spc$.

Environmental objective is to minimise GWP in carbon capture, pipeline transportation, utilisation and carbon injection, as shown in Eq(9).

$$\text{Min } \text{GWP}_{\text{total}} = \text{GWP}_{\text{capture}} + \text{GWP}_{\text{pipeline}} + \text{GWP}_{\text{injection}}$$

$$= \left( \sum_{a} \sum_{s} b_{as} \times \text{ep}_{\text{capture}} \right) + \left( \sum_{j} \sum_{i} f_{ij} \times L_{pipe,ij} \times \text{ep}_{\text{pipeline}} \right) + \left( k_k \times \text{ep}_{\text{EOR}} + (k_{k2} + k_{k3}) \times \text{ep}_{\text{SACT}} \right) \tag{9}$$

Eq(10) ensures that one capture technology at most and the corresponding material is selected for each chosen source $i$. Eq(11) and Eq(12) guarantee that the transported CO$_2$ leaving each node is not allowed to split into multiple other nodes. Eq(13) is the mass balance, stipulating that all CO$_2$ captured at or flowing into a node must be equal to that injected or transported out of the node. To guarantee the quantity of captured CO$_2$ at node $i$ does not exceed the total emission produced at node $i$, Eq(14) is introduced. Analogously, to ensure the quantity of CO$_2$ sent to a storage node $i$ does not exceed its capacity, Eq(15) is developed. Eq(16) denotes that an annual CO$_2$ emission reduction target $(T_{ne})$ must be fulfilled respecting to government legislations.

$$\sum_{s} y_{ik} \leq 1 \quad \forall i \in l \tag{10}$$

$$\sum_{j} z_{ij} \leq 1 \quad \forall i \in G, i \neq j \tag{11}$$

$$F_{ij} \leq F_{\text{max}} \times z_{ij} \tag{12}$$

$$\sum_{j \in G} F_{ij} + c_i = \sum_{j \in S} F_{ij} + u_i \quad \forall i \in G, i \neq j \tag{13}$$

$$c_i \leq E_i \times FR_{ik} \quad \forall i \in l \tag{14}$$

$$u_i \leq \frac{S_{i,\text{max}}}{l_{ij}} \quad \forall \ i \in (S \cup U) \tag{15}$$

$$\sum_{i} c_i \geq T_{\text{min}} \tag{16}$$

Where $z_{ij}$ is the binary variable to denote where to transport CO$_2$, $c_i$ is the captured CO$_2$ at node $i$, $u_i$ is the stored CO$_2$ at node $i$, $E_i$ is the CO$_2$ emission flowrate at node $i$, and $S_{i,\text{max}}$ is the storage capacity of node $i$.

4. Case study

This section presents a case study for the application of the proposed model in Northeast region of China. The concerned region is located in the Northeast China including Heilongjiang province, Jilin province, Liaoning Province and five league Cities in eastern Inner Mongolia. In this work, 17 sources are collected as the stationary emission sources, 13 technology-material combinations are given for capture & compression, and 3 geological reservoirs are given as alternatives for CO$_2$ sequestration. Based on the geological information of emission sources and storage sinks, the region is meshed into 9×15 (135) equal-sized grids to get the intersection nodes, which are proposed as the potential intermediate sites in addition to the sources and sinks. The intermediate sites provide extra opportunities to funnel CO$_2$ captured at different sources into a trunk pipeline. In summary, 155 (17×3+135) intermediate sites are determined for transit shipment. Tables 1-3 are the detailed information of the source data, sink data and capture technology-material combinations. This model is applied to analyse
life cycle environmental impacts of CCUS supply chain and then reveal the tradeoff between economic objective and environmental objective.

Table 1: Source data for case study

<table>
<thead>
<tr>
<th>Source</th>
<th>CO₂ Concentration</th>
<th>Emission, Mt/y</th>
<th>Source</th>
<th>CO₂ Concentration</th>
<th>Emission, Mt/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>17%</td>
<td>19.05</td>
<td>S10</td>
<td>11%</td>
<td>5.90</td>
</tr>
<tr>
<td>S2</td>
<td>18%</td>
<td>14.77</td>
<td>S11</td>
<td>17%</td>
<td>5.86</td>
</tr>
<tr>
<td>S3</td>
<td>4%</td>
<td>10.40</td>
<td>S12</td>
<td>15%</td>
<td>5.58</td>
</tr>
<tr>
<td>S4</td>
<td>14%</td>
<td>9.20</td>
<td>S13</td>
<td>13%</td>
<td>5.52</td>
</tr>
<tr>
<td>S5</td>
<td>13%</td>
<td>7.27</td>
<td>S14</td>
<td>11%</td>
<td>5.43</td>
</tr>
<tr>
<td>S6</td>
<td>21%</td>
<td>6.99</td>
<td>S15</td>
<td>14%</td>
<td>5.20</td>
</tr>
<tr>
<td>S7</td>
<td>13%</td>
<td>6.53</td>
<td>S16</td>
<td>22%</td>
<td>5.10</td>
</tr>
<tr>
<td>S8</td>
<td>18%</td>
<td>6.16</td>
<td>S17</td>
<td>15%</td>
<td>5.00</td>
</tr>
<tr>
<td>S9</td>
<td>15%</td>
<td>6.10</td>
<td>Total</td>
<td>N/A</td>
<td>130.06</td>
</tr>
</tbody>
</table>

Table 2: Sink data for case study

<table>
<thead>
<tr>
<th>Sink</th>
<th>Type</th>
<th>Capacity, Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINK1</td>
<td>Oilfield</td>
<td>400.00</td>
</tr>
<tr>
<td>SINK2</td>
<td>Saline Aquifer</td>
<td>6,000.00</td>
</tr>
<tr>
<td>SINK3</td>
<td>Saline Aquifer</td>
<td>1,000.00</td>
</tr>
</tbody>
</table>

Table 3: Capture technology-material data for case study

<table>
<thead>
<tr>
<th>Capture Technology</th>
<th>Material</th>
<th>CO₂ Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption</td>
<td>MEA</td>
<td>0.01-0.70</td>
</tr>
<tr>
<td></td>
<td>PZ</td>
<td>0.01-0.70</td>
</tr>
<tr>
<td>Membrane</td>
<td>FSC PVAm</td>
<td>0.30-0.70</td>
</tr>
<tr>
<td></td>
<td>POE-1</td>
<td>0.30-0.70</td>
</tr>
<tr>
<td></td>
<td>POE-2</td>
<td>0.30-0.70</td>
</tr>
<tr>
<td>PSA</td>
<td>AHT</td>
<td>0.05-0.70</td>
</tr>
<tr>
<td></td>
<td>MVY</td>
<td>0.05-0.70</td>
</tr>
<tr>
<td></td>
<td>WEI</td>
<td>0.05-0.70</td>
</tr>
<tr>
<td>VSA</td>
<td>13X</td>
<td>0.10-0.70</td>
</tr>
<tr>
<td></td>
<td>AHT</td>
<td>0.10-0.70</td>
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<tr>
<td></td>
<td>MVY</td>
<td>0.10-0.70</td>
</tr>
<tr>
<td></td>
<td>WEI</td>
<td>0.10-0.70</td>
</tr>
</tbody>
</table>

4.1 Life cycle analysis for CCUS supply chain

The goal of this section is to estimate the GHG emission associated with the stages of CCUS supply chain. LCA is a systematic analytical method for environmental assessment, which follows the sequential steps of (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation and reporting. Instead of calculating the absolute value of the life cycle GHG emission, the relative differences in GHG emission between CCUS system and the reference system without CCUS is the emphasis. This difference is defined as the amount of net GHG emission in this work. The total amount of CO₂ produced from the research region is the same for both systems. The GHG emission of upstream stages (material conditioning) do not influence the calculation of net GHG emission. Assuming that the oil produced in CO₂-EOR substitutes the same amount of oil in conventional system. The boundaries (as shown in Figure 1) of our analysis the emission associated with: life cycle of the emission within the capture plant for CO₂ capture, transport from the emission source to the storage sink, oil extraction, crude oil refining, CO₂ storage, and combustion of refined petroleum products.

Figure 2 shows the contribution to global warming potential of different life cycle stages of CCUS supply chain. As can be observed from Figure 2, the reference system accounts for 70 Mt CO₂-equivalent/y. For CCUS supply chain, the capture and transportation stages are the major contributors in the life cycle of CCUS, contributing for 42 % and 38 %. From the comparisons between the reference system and the CCUS supply chain, it can be found that although the life cycle stages of CCUS supply chain will discharge 37.108 Mt CO₂ equivalent/y, however the system still reduces about 50 % of the total CO₂ emission, due to its remarkable contribution in CO₂ storage.
4.2 Multi-objective optimisation for CCUS supply chain

The goal of this section is to demonstrate that integrating LCA with economic models can result in more sustainable supply chain strategies. To simultaneously optimise the economic and environmental performances of the CCUS supply chain, a multi-objective optimisation model is developed and solved, with the life cycle analysis methodology and multi-objective optimisation techniques integrated. The ε-constraint approach is implemented in GAMS/CPLEX software to generate the Pareto front. Within the approach, one of the objective functions is optimised while incorporating another objective function as additional constraint to the optimisation model. The general procedure includes three steps. First, the minimum annual cost is obtained by regarding the environmental objective as parameter. This entails performing the single objective optimisation which in turn yields the largest environmental impact. The second step is to minimise the environmental objective, which is also obtained by optimizing the single objective problem, and in turn yields the largest annual cost. The last step is to set the parameter ε to the discrete values between upper and lower bounds and optimizing the single objective problem. Then, the approximation to the Pareto curve is obtained, showing the relationship between the economic and environmental objectives. Figure 3 is the obtained approximation to the Pareto curve, with abscissa representing the quality of GHG releasing into atmosphere, and ordinate indicating the annualized total cost. Pie charts represent cost breakdowns. Doughnut charts represent emission breakdowns. It can be found that as the annualized total cost decreases from $5.07 \times 10^{12}$ USD, the amount of GHG increases from 19.35 to 37.66 Mt CO$_2$-equivalent/y. Points on the right tend to pursue a more cost-effective supply chain, while points on the left tend to minimise the GHG. This tendency shows that the selections of capture technology-material combinations greatly impact the GHG abatement result since some cost-effective technologies (e.g., absorption) has higher GWP values. These results will provide insights for the decision-maker on sustainable supply chain strategies.
5. Conclusions

This paper has analysed the life cycle environmental impacts of North Eastern China CCUS supply chain for the capture, storage and/or utilisation of CO₂ emitted from power plants and other energy-insensitive industrial sources. The life cycle of the emission within capture plant for CO₂ capture, transport of the CO₂ from the emission source to the storage sink, oil extraction, crude oil refining, emission associated of electricity for CO₂ storage, and combustion of the refined petroleum products. It can be found that the capture and transportation stages are significant contributors to the GWP, so that the development of more environmentally sustainable sorbents is one of the challenges for CCUS. To reveal the trade-off between the economic objective and environmental objective, a multi-objective model is formulated, and the obtained Pareto curve can provide more sustainable supply chain strategies according to the decision-maker’s preference.

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References