CHEMICAL ENGINEERING TRANSACTIONS
VOL. 76, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976001

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

Shuai Zhang, Ran Tao, Linlin Liu*, Lei Zhang, Jian Du

Institute of Chemical Process Systems Engineering, School of Chemical Engineering, Dalian University of Technology, Dalian, 116024, Liaoning, China
liulinlin@dlut.edu.cn

Carbon capture utilisation and storage (CCUS) is widely recognised as a key mitigation technology that can significantly reduce carbon dioxide (CO_2) 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) problem, 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 (CO_2), a primary anthropogenic greenhouse gas (GHG) (Leung et al., 2014). Recently, the CO_2 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 CO_2 via physical or chemical process from the flue gas; then, compress and transport the captured CO_2 via pipeline, truck, rail and ship; last, the transported CO_2 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 CO_2 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 CO_2 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 CO_2, 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 CO_2 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.

Paper Received: 14/03/2019; Revised: 22/04/2019; Accepted: 06/05/2019
Please cite this article as: Zhang S., Tao R., Liu L., Zhang L., Du J., 2019, Economic and Environmental Optimisation Framework for Carbon Capture Utilisation and Storage Supply Chain, Chemical Engineering Transactions, 76, 1-6 DOI:10.3303/CET1976001

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, CO_2 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 CO_2 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 CO_2 capture amounts from each selected source.
- CO_2 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*.

$$\text{Min } \text{TC}=\sum_{i,j,k}(\text{TAC-TAR}) \quad \forall i \in G, j \in G, k \in K \tag{1}$$

TAC is the total annual CCUS cost consisting of feed dehydration cost, CO_2 capture and compression investment cost ($CIC_{i,k}$) and operating cost ($COC_{i,k}$), CO_2 pipeline investment cost ($PAIC_{i,j}$) and operating and maintenance (O&M) cost ($POC_{i,j}$), CO_2 storage injection annual investment cost ($IAIC_j$) and O&M cost (IOC_j), as presented in Eqs.(2)-(7). *TAR* is the total revenue obtained by EOR-utilisation since oilfield sites need high purity CO_2 to improve the production of oil. The revenue is calculated by multiplying the total amount of CO_2 transported to oilfield sites by the unit price of CO_2 set by the oilfield decision-maker.

$$CIC_{i,k} = \alpha_k \times y_{i,k} + \left(\beta_k x_i^{n_k} + \gamma_k\right) \times Ft_i^{m_k} \times (m_{11k} \times FR_{i,k} + m_{12k} \times y_{i,k}) \quad \forall i \in I, k \in K \tag{2}$$

$$COC_{i,k} = \alpha_k^{'} \times y_{i,k} + \left(\beta_k^{'} x_i^{n_k^{'}} + \gamma_k^{'}\right) \times Ft_i^{m_k^{'}} \times (m_{21k} \times FR_{i,k} + m_{22k} \times y_{i,k}) \quad \forall i \in I, k \in K \tag{3}$$

$$PAIC_{i,j} = \frac{r(1+r)^{l_{life}}}{(1+r)^{l_{life}} - 1} \times \left\{\left(\beta_t \times F_{i,j} + \alpha_t \times z_{i,j}\right) \times F_T \times L_{i,j}\right\} \quad \forall i \in G, j \in G, i \neq j \tag{4}$$

$$POC_{i,j} = O\&M_{pipeline} \times \left\{\left(\beta_t \times F_{i,j} + \alpha_t \times z_{i,j}\right) \times F_T \times L_{i,j}\right\} \quad \forall i \in G, j \in G, i \neq j \tag{5}$$

$$IAIC_j = \frac{r(1+r)^{l_{life}}}{(1+r)^{l_{life}} - 1} \times \left\{\left(m_1 d_{well,j} + m_2\right) \times \left\lceil \frac{\sum_i F_{i,j}}{M_{well}} \right\rceil\right\} \quad \forall j \in (S \cup U) \tag{6}$$

$$IOC_j = O\&M_{well} \times \left\{\left(m_1 d_{well,j} + m_2\right) \times \left\lceil \frac{\sum_i F_{i,j}}{M_{well}} \right\rceil\right\} \quad \forall j \in (S \cup U) \tag{7}$$

Where $Ft_i^{m_k}$ is flue gas flowrate of node *i*, $FR_{i,k}$ is the fraction of captured from flue gas, $y_{i,k}$ is the binary denoting the selected technology, $F_{i,j}$ is the amount of CO_2 transported from node *i* to node *j*, $L_{i,j}$ is the distance from node *i* to node *j*, F_T is the terrain factor, *r* is the annual discount rate, and l_{life} 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).

$$GWP=\sum_{spc}\omega_{spc}\times LCI_{spc} \tag{8}$$

where *spc* denotes the index of GHG species, ω_{spc} is the impact factor of species *spc*, and 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).

$$\begin{aligned}&\text{Min }\ \mathrm{GWP}_{\text{total}}=GWP_{capture}+GWP_{pipeline}+GWP_{injection}\\&=\left(\sum_s\sum_k b_{s,k}\times ep_{capture}\right)+\left(\sum_i\sum_j f_{i,j}\times L_{pipe,i,j}\times ep_{pipeline}\right)+\left\{kk_{SINK1}\times ep_{EOR}+(kk_{SINK2}+kk_{SINK3})\times ep_{salt}\right\}\end{aligned} \tag{9}$$

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_{min}) must be fulfilled respecting to government legislations.

$$\sum_{k\in K} y_{i,k}\le 1\quad \forall i\in I \tag{10}$$

$$\sum_{j\in G} z_{i,j}\le 1\quad \forall i\in G, i\ne j \tag{11}$$

$$F_{i,j}\le F^{\max}\times z_{i,j} \tag{12}$$

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

$$c_i\le E_i\times FR_{ik}\quad \forall\ i\in I \tag{14}$$

$$u_i\le\frac{S_i^{\max}}{l_{life}}\quad \forall\ i\in(S\cup U) \tag{15}$$

$$\sum_{i\in I} c_i\ge T_{\min} \tag{16}$$

Where $z_{i,j}$ 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 $S_i^{\max}$ 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

Source	CO_2 Concentration	Emission, Mt/y	Source	CO_2 Concentration	Emission, Mt/y
S1	17%	19.05	S10	11%	5.90
S2	18%	14.77	S11	17%	5.86
S3	4%	10.40	S12	15%	5.58
S4	14%	9.20	S13	13%	5.52
S5	13%	7.27	S14	11%	5.43
S6	21%	6.99	S15	14%	5.20
S7	13%	6.53	S16	22%	5.10
S8	18%	6.16	S17	15%	5.00
S9	15%	6.10	Total	N/A	130.06

Table 2: Sink data for case study

Sink	Type	Capacity, Mt
SINK1	Oilfield	400.00
SINK2	Saline Aquifer	6,000.00
SINK3	Saline Aquifer	1,000.00

Table 3: Capture technology-material data for case study

Capture Technology	Material	CO_2 Concentration
Absorption	MEA	0.01-0.70
	PZ	0.01-0.70
Membrane	FSC PVAm	0.30-0.70
	POE-1	0.30-0.70
	POE-2	0.30-0.70
PSA	AHT	0.05-0.70
	MVY	0.05-0.70
	WEI	0.05-0.70
VSA	13X	0.10-0.70
	AHT	0.10-0.70
	MVY	0.10-0.70
	WEI	0.10-0.70

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 CO_2 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 CO_2-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 CO_2 capture, transport from the emission source to the storage sink, oil extraction, crude oil refining, CO_2 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 CO_2-eqivalent/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 CO_2 equivalent/y, however the system still reduces about 50 % of the total CO_2 emission, due to its remarkable contribution in CO_2 storage.

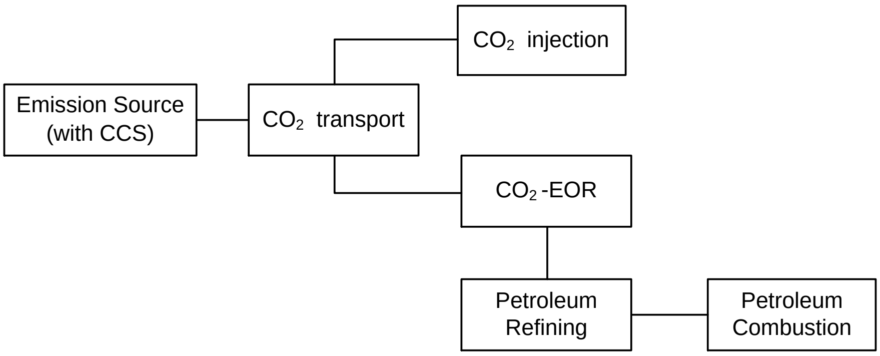

Figure 1: Boundary of CCUS supply chain network

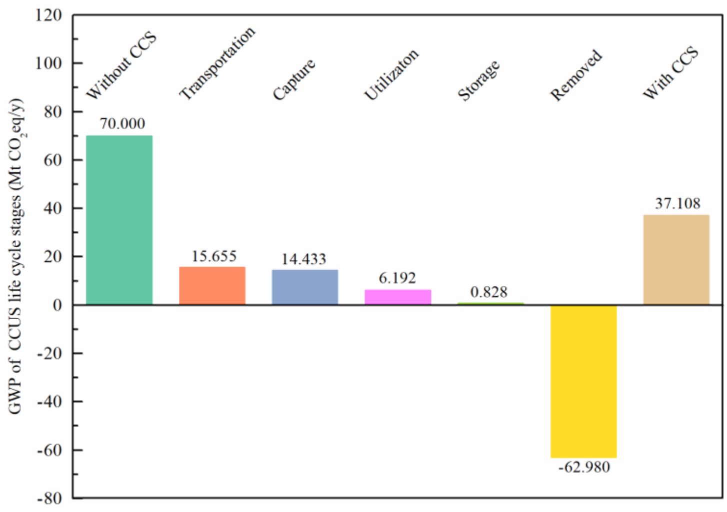

Figure 2: Contribution to global warming potential of different life cycle stages of CCUS supply chain

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 to 1.74 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.

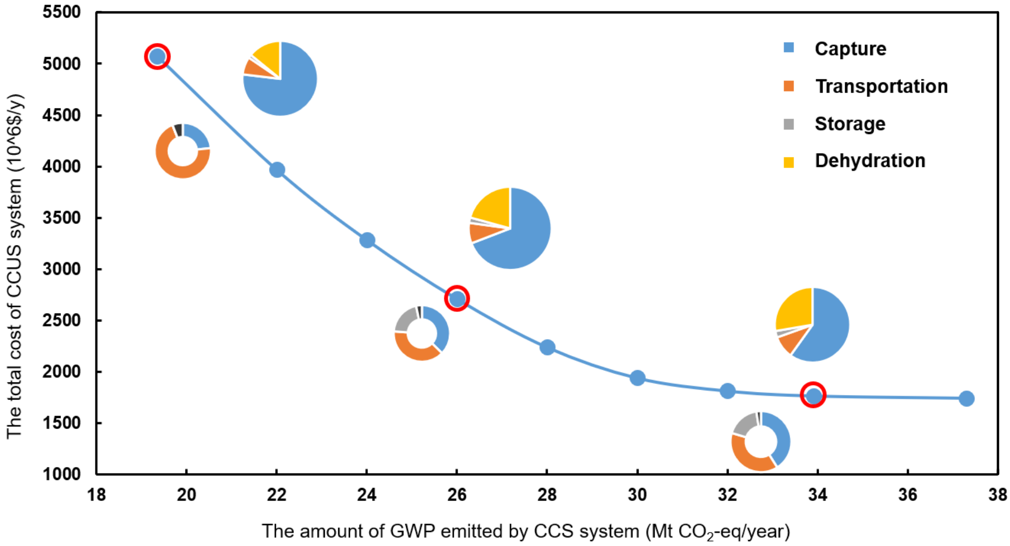

Figure 3：Pareto curve of the case study with breakdowns of the cost and emission

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 CO_2 emitted from power plants and other energy-insensitive industrial sources. The life cycle of the emission within capture plant for CO_2 capture, transport of the CO_2 from the emission source to the storage sink, oil extraction, crude oil refining, emission associated of electricity for CO_2 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.

Acknowledgments

The authors gratefully acknowledge the financial support from "Natural Science Foundation of China" (No. 21878034, 21776035) and the Fundamental Research Funds for Central Universities of China (DUT18LAB11).

References

d'Amore F., Bezzo F., 2017, Economic optimisation of European supply chains for CO_2 capture, transport and sequestration, International Journal of Greenhouse Gas Control, 65, 99–116.

Hasan M.M.F., First E.L., Boukouvala F., Floudas C.A., 2015, A multi-scale framework for CO_2 capture, utilization, and sequestration: CCUS and CCU, Computers and Chemical Engineering, 81, 2–21.

Holloway S., 2007, Carbon dioxide capture and geological storage, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365, 1095–1107.

Leung D.Y.C., Caramanna G., Maroto-Valer M.M., 2014, An overview of current status of carbon dioxide capture and storage technologies, Renewable and Sustainable Energy Review, 39, 426–443.

Nataly E.H.R., Xiu J.T., 2014, Energy related CO_2 emissions and the progress on CCS projects: A review, Renewable and Sustainable Energy Review, 31, 368–385.

Tapia J.F.D., Promentilla M.A.B., Tseng M.L., Tan R.R., 2017, Screening of carbon dioxide utilization options using hybrid Analytic Hierarchy Process-Data Envelopment Analysis method, Journal of Cleaner Production, 165, 1361–1370.

UNFCCC, 2016, Historic Paris Agreement on climate change: 195 nations set path to keep temperature rise well below 2 ℃, United Nations Framework Convention on Climate Change <newsroom.unfccc.int/unfccc-newsroom/finale-cop21> accessed 15 December 2018.

Yao X., Zhong P., Zhang X., Zhu L., 2018, Business model design for the carbon capture utilization and storage (CCUS) project in China, Energy Policy, 121, 519–533.

Zhang S., Liu L.L., Zhang L., Meng Q.W., Du J., 2018, Optimal planning for regional carbon capture and storage systems under uncertainty, Chemical Engineering Transactions, 70, 1207–1212.