Pol. J. Environ. Stud. Vol. 27, No. 6 (2018), 2573-2583
DOI: *10.15244/pjoes/80897* ONLINE PUBLICATION DATE: 2018-06-11

Original Research

Life Cycle CO_2 Emission Estimation of CCS-EOR System Using Different CO_2 Sources

Yong Jiang[1, 2], Yalin Lei[1, 2]*, Yongzhi Yang[3], Fang Wang[3]

[1]School of Humanities and Economic Management, China University of Geosciences, Beijing, P.R.China
[2]Key Laboratory of Carrying Capacity Assessment for Resources and Environment, Ministry of Land and Resources, Beijing, P.R. China
[3] Petrochina Research Institute of Petroleum Exploration & Development, Beijing, China

Received: 2 September 2017
Accepted: 29 November 2017

Abstract

Balancing sustained economic growth with energy security and environmental and climate change constraints is a common but difficult challenge. China, as the largest energy consumer in the world – 90% of which is fossil fuel-based – faces the enormous task of transforming its energy mix to low-emissions. CO_2 has been successfully injected for the purposes of both carbon capture and storage (CCS) and enhanced oil recovery (EOR). This study employs life cycle assessment to quantify the CO_2 emissions from the CCS-EOR system to analyze net CO_2 emissions. This system includes carbon capture, transportation, EOR, downstream, and consumption. Our model analyzes life cycle CO_2 emissions from plants of integrated gasification combined cycle (IGCC) with CCS, pulverized coal plants (PC) with CCS, and oxy-fuel plants with CCS while we use technologies of fractionation, refrigeration, Ryan-Holmes, and membrance in the process of EOR. Total CO_2 emissions are 114.69-121.50 Mt CO_2e, 222.95-236.19 Mt CO_2e, and 49.09-51.96 Mt CO_2e from IGCC, PC, and oxy-fuel plants, respectively, based on IGCC with 426 MW, PC with 600 MW, and oxy-fuel with 200 MW in China. Emissions from the combustion of refined petroleum fuel is the most of total emissions – from 66.21% to 71.35%, emissions from EOR are 14.27-19.32%, emissions from downstream are 8.47-9.13%, emissions from capture are 4.12-5.09%, and emissions from transportation are 0.47-1.61%. Based on these results, CCS-EOR (where CO_2 is sourced from IGCC, PC and oxy-fuel plants) provides one potential means for producing electricity and oil to meet growing energy demand and reducing CO_2 emissions to abate global warming.

Keywords: CCS-EOR, life cycle assessment, CO_2 emissions, global warming

Introduction

China is the largest carbon emitter, contributing 27.32% of the world's total in 2015, while its coal consumption is 50.01% of the world's total and oil consumption is 12.92% [1]. Carbon dioxide emissions are a major contributor to climate change and they affect human health and performance [2-4]. CO_2-EOR can both produce oil and permanently store CO_2 in the subsurface and reduce oil viscosity, making it lighter and detaching it from the rock surface [5]. Consequently, CO_2-EOR provides decreasing

*e-mail: leiyalin@cugb.edu.cn

CO_2 emissions from oil production and combustion via geological storage of CO_2. The process of capturing CO_2 from an industrial plant, liquefying it, and transporting it for use in an oil field is commonly called carbon capture, utilization, and storage (CCUS) technology. CO_2-EOR could address the twin important options for both CO_2 mitigation and oil recovery in China.

As of 2016 there were 38 large-scale and pilot projects developed, while 6 of them were under construction in the world (GCCSI, 2016). Thus CO_2-EOR has the great potential to present the twin challenges of climate change and energy security by producing oil with lower CO_2 emissions [6]. Although the potential for CO_2-EOR technology could increase oil production at mature fields using CO_2, there is a question about detailed assessment of the full life cycle CO_2 emissions of the CO_2-EOR process. The objective of this paper is to investigate life cycle CO_2 emissions from power plants to consumption.

Therefore, the study of life cycle CO_2 assessment becomes necessary. How to rationalize CO_2 emissions in the CCS-EOR system is the key for sound policy decisions for supporting CCUS.

Literature Review

Scholars have done extensive research on CO_2 emissions associated with CO_2-EOR. Several authors have summarized site-specific data from one or more particular oil reservoirs.

In the literature of CO_2 leakages from CCS, Shitashima et al. (2015) applied an in situ pH/p CO_2 sensor to the QICS experiment for detection and monitoring of leaked CO_2, and carried out several observations [7]. Hurry et al. (2016) presented field test results of a multi-gas atmospheric detection technique that uses observed trace gas ratios (CO_2, CH_4, and H_2S) to discriminate plumes of gas originating from different sources and focuses on multi-scale fugitive emissions detection and plume discrimination [8]. Zhang et al.(2015) simulated the effects of elevated soil CO_2 on CH_4 and N_2O through pot experiments and revealed that significant increases of CH_4 and N_2O emissions were induced by the simulated CO_2 leaks; the emission rates of CH_4 and N_2O were substantial [9].

In the issue of monitoring CO_2 migration in CO_2-EOR, Ren et al. (2016) used gas tracer testing to examine the inter-well connectivity [10]. Sevik et al. (2015), Guney et al. (2017), and Cetin et al. (2013) demonstrated that the migration of CO_2 has great effect on human health and plants [11-13]. Yang et al. (2017) conducted an empirical study based on remotely sensed data and field observations from an enhanced oil recovery (EOR) site in China. Geostatistical analysis and general linear model regression were performed to detect the impact of fugitive CO_2 emissions from oil buffer tanks. It estimated that the emitted CO_2 resulted in CO_2 enrichment about 25-100 m away from the buffer tanks [14].

In the aspects of environmental LCA for estimating CO_2 emissions, Jaramillo et al. (2009) used as case studies Northeast Purdy, SACROC, Ford Geraldine, Joffre Viking, and Weyburn to analyze the net life cycle CO_2 emissions in an EOR system. This study assessed the overall life cycle emissions associated with sequestration via CO_2-flood EOR under a number of different scenarios and explored the impact of various methods for allocating CO_2 system emissions and the benefits of sequestration [15]. Hussain et al. (2013) and Cooney et al. (2015) used hypothetical reservoir models to evaluate GHG emissions for CO_2-EOR based on various CO_2 sources, including conventional CO_2 sources (e.g., natural source, coal synthetic natural gas (SNG) plant) and alternative CO_2 sources (e.g., coal IGCC, switch grass IGCC, natural gas combined cycle (NGCC), and biogas NGCC). And they also carried out sensitivity analysis for the range of EOR parameters [16-17]. Hussain et al. (2013) used a process lifecycle inventory (LCI) to compare the lifecycle greenhouse gas (GHG) emissions of enhanced oil recovery (EOR) operations using different sources for CO_2 and to non-CO_2 EOR methods[16]. All EOR techniques were compared to the base case of natural-source CO_2-EOR. Cooney et al. (2015) claimed that the relationship between EOR efficiency and GHG emissions can be varied when the CO_2 source is changed from natural source to fossil power plant, and furthermore showed detailed GHG emissions for activities of the CO_2 EOR project, namely CO_2 emissions related to land use, construction, well operation, 3-phase separation, oil storage, and gas processing. Azzolina et al. (2015) analyzed a database of 31 existing CO_2-enhanced oil recovery (EOR) projects that was compiled for estimating oil reserves to better understand CO_2 retention, incremental oil recovery, and net CO_2 utilization for these oil fields. Cumulative CO_2 retention (in the formation), incremental oil recovery factors, and net CO_2 utilization factors were calculated for each of the sites [18]. Laurenzi et al. (2016) conducted a life cycle assessment of Bakken crude using data from operations throughout the supply chain, including drilling and completion, refining, and use of refined products, and assessed the life cycle freshwater consumptions of Bakken-derived gasoline and diesel to be 1.14 and 1.22 barrel/barrel, respectively, 13% of which is associated with hydraulic fracturing [19]. Lacy et al. (2015) used a novel "well-to-well" approach that included the operations from natural gas production at oil field to CO_2 injection for EOR operations at depleted oil fields [20]. Sevik et al. (2015 and 2017) and Cetin et al. (2016) identified the water stress tolerance for some plants used in landscaping works and found that plants could be effectively used to reduce the concentrations of CO_2 [21-23].

In previous studies, efforts on environmental evaluation of CO_2-EOR had obtained more realistic results. However, these studies did not consider fully the feature related to CO_2 supply for CO_2-EOR operation and, the life cycle analysis was not fully integrated. Therefore, they cannot easily be used to assess the net CO_2 emissions to explore a variety of sites and scenarios for CO_2-EOR. This paper presents a CO_2-EOR system where the CO_2 is sourced from power plants, utilized in the oil injection, and stored in the oil reservoir. This study employs life cycle assessment to quantify the CO_2 emissions from the CCS-EOR system, including carbon capture, transportation, EOR, downstream, combustion, and CO_2 sequestration loss.

Material and Methods

LCA Framework and Data Acquisition

The system boundaries include emissions associated with 5 parts of the life cycle: carbon source, pipeline CO_2 transportation, CO_2-EOR, downstream segments, combustion, and carbon sequestration loss (Fig. 1). There are two CO_2 sources for CO_2-EOR: power plants and industry. There are 3 main technologies in the capture process of power plants: post-combustion technology, pre-combustion technology, and oxy-fuel technology. This paper uses the main carbon sources for CO_2-EOR. In the emissions of CO_2-EOR, we include indirect emissions associated with consumption of electricity and direct emissions from the consumption of oil, coal, etc. After CO_2-EOR, there are emissions from crude oil pipe transportation, petroleum refining, fuel transportation, and fuel combustion.

CO_2 Emissions from the Life Cycle CO_2-EOR System

$$C_{LCA} = \sum_i C_{cap.} + \sum_j C_{tran.} + \sum_k C_{EOR} + \sum_l C_{downstream} + \sum_m C_{combustion} \quad (1)$$

C_{LCA} is life cycle CO_2 emissions from the CO_2-EOR system. $C_{cap.}$, $C_{tran.}$, C_{EOR}, $C_{downstream}$, and $C_{combustion}$ present carbon emissions from carbon capture, transportation from the carbon source to EOR fields, the life cycle of the EOR process, the downstream part, and combustion of refined petroleum fuel, respectively.

Carbon Emissions from Different Power Generators

Power plant emissions are derived from the higher heating value (HHV) and the carbon (C) content of the coal and the net conversion efficiency of the plant [24].

$$E = \frac{c}{q} \times \frac{C_{CO_2}}{C_m} \times \frac{1}{E_{net}} \quad (2)$$

…where E is the power plant CO_2 emission factor (kg CO_2/kWh), c is carbon content in the coal/gas (kg C/kg fuel), q is energy content of the coal/gas (kWh/kg fuel), C_m is molecular weight of carbon (kg/mol carbon), C_{CO2} is molecular weight of carbon dioxide (kg/mol CO_2), and E_{net} is net conversion efficiency of the plant (fraction).

There is uncertainty of carbon emissions from the power plant and scholars estimate carbon emissions from different sources based on calculations by IPCC (2005), Rubin et al. (2007), Singh et al. (2011), and Iribarren et al. (2013) [25-28] (Table 1).

Iribarren (2013) and Azzolina (2016) have calculated CO_2 produced from Supercritical BAT with CCS, IGCC with CCS and oxy-fuel capture, and they are 1.32 kg/kwh, 1.02 kg/kwh, and 1.02 kg/kwh, respectively [24, 28].

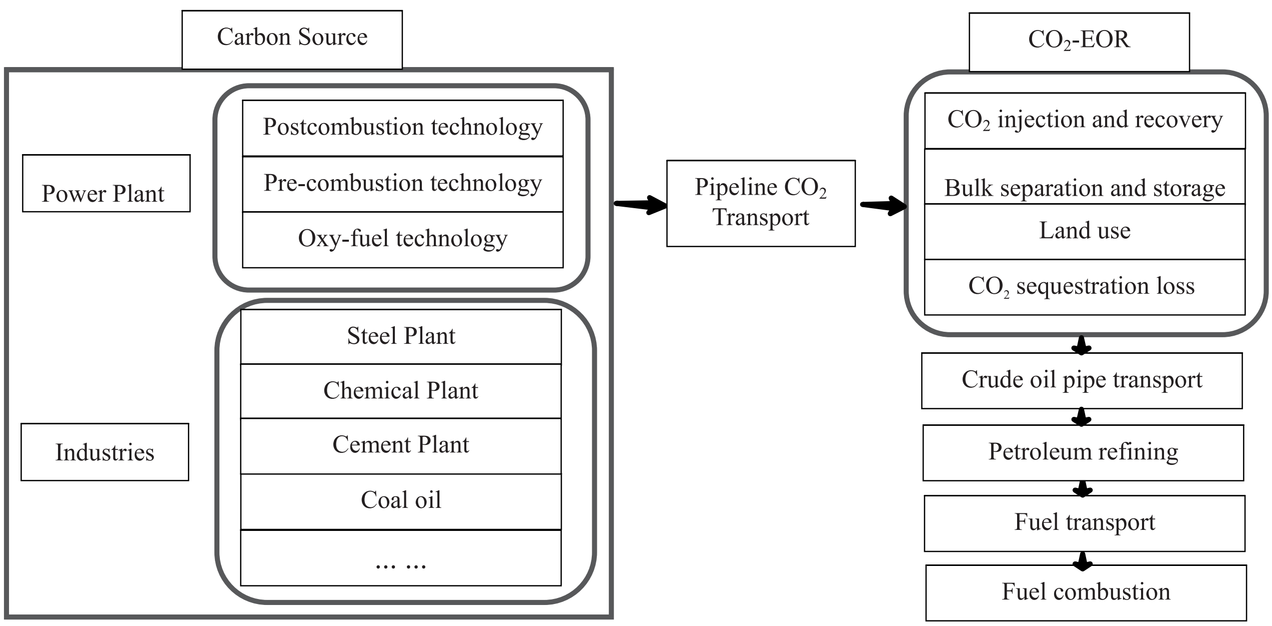

Fig. 1. System boundaries for life cycle CO_2 emissions from the CO_2-EOR system.

Table 1. Performance parameters for different power generation systems.

Parameter		Coal					
		World average	Post combustion technology		Pre-combustion		Oxy-fuel capture
			Supercritical BAT	Supercritical BAT with CCS	IGCC	IGCC with CCS	
CO_2 capture	%	-	-	90	-	90	90
Net efficiency	%	35	43.4	33.2	44.1	37.6	34.6
Energy penalty	%	-	-	10.2	-	6.5	8.8
Power plant capital cost	$/kW	1,286	1,286	2,096	1,326	1,825	1,857
Emissions							
CO_2	g/kWh	946.6	763.4	100.1	722.8	85.7	95.5
SO_2	mg/kWh	673.5	543.2	26.8	287.5	341	679.4
NO_X	mg/kWh	637.6	514.2	641.1	328.6	389.8	322.1
NH_3	mg/kWh	7.2	5.8	39	1.6	1.9	2
Particulates	mg/kWh	108.5	87.5	57.3	86.1	51.1	109.4
Solvent	mg/kWh	-	-	3.2	-	0.007	-
Parameter		Natural gas					
		World average	Post-combustion technology		Pre-combustion		Oxy-fuel capture
			NGCC	NGCC with CCS	Partial oxidation	Partial oxidation with CCS	
CO_2 capture	%	-	-	90		85	96
Net efficiency	%	42	58.1	50.1	56	48.1	46.8
Energy penalty	%			8		7.9	11.3
Power plant capital cost	$/kW	568	568	998	447	978	1,034
Emissions							
CO_2	g/kWh	479.6	346.7	40.5	359.7	62.8	17.4
SO_2	mg/kWh	4.3	3.1	0.0005	3.2	3.7	3.9
NO^X	mg/kWh	428.2	309.6	343.9	321.2	374	194.1
NH_3	mg/kWh	-	-	12.7	-	-	-
Particulates	mg/kWh	4.3	3.1	1.8	3.2	1.9	3.9
Solvent	mg/kWh	-	-	3.2	-	0.007	-

Sources: IPCC (2005), Rubin et al. (2007), Singh (2011), Iribarren (2013)

CO_2 Pipeline Transport

We use data from McCoy (2008), who showed that 6.5 kWh of electricity is needed per ton of CO_2 transported [29]:

$$C_{tran.} = m_{tran.} \times q_{ele.} \times f_{ele.} \tag{3}$$

… where $C_{tran.}$ is carbon emission in the transportation part(t), and $m_{tran.}$, q_{ele}, and $f_{ele.}$ present purchased CO_2 from the carbon source to the EOR field (t), electricity demand in CO_2 transportation (6.5kwh/t), and electricity CO_2 emission factor (kg CO_2e/Mwh), respectively.

CO_2 emissions from pipelines are assumed to be 75 kg CO_2/km-yr, while emissions from pipeline servicing are assumed to be 3.7 kg CO_2/service-yr (Lamb et al., 2015). This paper assumes 10-20 services per year. The 95% upper confidence limits derived by Lamb et al. (2015) are used for the high estimate in our model (282 kg CO_2/km-yr and 5.5 kg CO_2/service-year) [30].

CO_2 Capture, CO_2 Injection, CO_2 Retention, and CO_2 Recycling

Azzolina et al. (2015) published results for CO_2 retention, which is a metric that expresses the fraction of total injected CO_2 at a CO_2-EOR facility that is not recycled but remains in the subsurface [18]. Approximately 50% of the total injected CO_2 is produced together with the oil, separated, and recycled/reinjected, but nearly all (over 95%) of the purchased CO_2 delivered to the oil field is stored in the subsurface and remains securely trapped within the deep geological formation (Melzer, 2012; Azzolina et al., 2015). Here, we assume that half of the total injected CO_2 is recycled [4, 18].

$$U_{injected,gross} = U_{captured} + \frac{1}{2}U_{captured} + (\frac{1}{2})^2 U_{captured} + \ldots + (\frac{1}{2})^n U_{captured} \quad (4)$$

$$U_{injected,gross} = \frac{1-(\frac{1}{2})^{n+1}}{1-\frac{1}{2}} U_{captured} = \left[1-(\frac{1}{2})^{n+1}\right] 2U_{captured} \quad (5)$$

When n is approaching infinity, $U_{injected,\ gross}$ is twice $U_{captured}$. That is to say, the CO_2 injected to the EOR field is twice the amount of CO_2 captured from the power plants when we omit the loss of CO_2 in the process of transportation.

EOR Procedure

To determine the net CO_2 emissions of the CO_2-EOR system, this analysis assumes a set of 4 core functional activities: CO_2 injection and crude recovery, bulk separation and storage, and gas processing and land use.

$$C_{EOR} = \sum_n C_{inj-rec} + \sum_o C_{bulksep.} + \sum_p C_{pro.} + C_{lanuse} + C_{loss} \quad (6)$$

C_{EOR} is CO_2 emissions from the CO_2-EOR system. $C_{inj-rec}$, $C_{bulksep.}$, $C_{pro.}$, $C_{landuse}$, and C_{loss} present CO_2 emissions from CO_2 injection and crude recovery, bulk separation and storage, gas processing, land use, and carbon sequestration loss, respectively.

1) CO_2 injection and crude recovery

CO_2 injection and crude recovery includes the distribution of CO_2 to the injection wells and all technical measures to maintain necessary pressure and temperature. The injected CO_2 stream is a combination of makeup CO_2 from a pipeline and recycled CO_2 from a gas processing plant. The calculation of the electricity requirements includes a compression load to increase the pressure of the recycled gas and a pumping load to increase the pressure of the entire supercritical CO_2 injection stream (recycle plus makeup) to the injection pressure. Artificial fluid lifting is often required for EOR wells to yield production levels that are economical. Pumps are utilized to lift the reservoir products to the surface in cases where the produced fluid is too deep or viscous to reach the surface based on reservoir pressure alone. CO_2 emissions from injection and crude recovery include CO_2 emissions from EOR construction and well operation.

$$C_{inj-rec} = \sum_q C_{cons.} + \sum_r C_{wellop.} \quad (7)$$

$C_{inj-rec}$ is CO_2 emissions from CO_2 injection and recovery. $C_{cons.}$ and $C_{wellop.}$ present CO_2 emissions from EOR construction and well operation. $C_{cons.}$ include CO_2 emissions from the EOR injection well workover, water dispocal well construction, water disposal well closure, injection well closure, and EOR gas process facility construction; $C_{wellop.}$ includes CO_2 from formation leakage, crude oil artificial lift pump electricity, CO_2 injection compressor emissions, CO_2 injection compressor electricity, and brine injection pump electricity.

2) Bulk separation and storage

The production wells at an EOR site produce a mix of crude oil, brine water, and gas. These 3 products must be separated to produce marketable crude and brine water that can be re-injected into the formation, and gas that can be sent to CO_2 removal and hydrocarbon processing.

$$C_{bulksep.} = C_{ogwsep.} + C_{crudesec.} + C_{brinesto.} \quad (8)$$

$C_{bulksep.}$ is CO_2 emissions from bulk separation and storage. $C_{ogwsep.}$, $C_{crudesec.}$, and $C_{brinesto.}$ present CO_2 emissions from oil, gas, and water separation that includes venting and flaring, natural gas upstream and natural gas combustion, crude sector (which includes venting and flaring), brine water storage (which includes venting and flaring), and brine disposal pump electricity.

3) Gas separation

Gas separation comprises activities to separate hydrocarbons from CO_2 and to adjust the composition of hydrocarbon streams so that CO_2 can be sold or used as plant fuel. We use Cooney's model to account 3 different gas processing technologies: 1) refrigeration and fractionation, 2) Ryan-Holmes, and 3) membrane.

$$C_{gaspro.} = C_{upstr.} + C_{comb.} + C_{ele.-pro} \quad (9)$$

$C_{gaspro.}$ is CO_2 emissions from gas processing. $C_{uostr.}$, $C_{comb.}$, and $C_{ele-pro}$ present CO_2 emissions from gas and diesel upstream, gas and diesel combustion, and electricity upstream.

4) Land use

CO_2 emissions have an effect on some plant species directly and then they affect land use [31-33]. Direct land use change is determined by tracking the change from an existing land use type (native vegetation or agricultural lands) to a new land use that supports production required for the supply chain, and Cooney estimated about 6 kg CO_2e/bbl crude from the EOR system (Cooney 2015).

Table 2. CO_2 emissions from EOR procedure (Kg CO_2e/barrel crude).

Parameter			Fractiona-tion/refrig-eration	Ryan-Holmes	Mem-brane	Fractiona-tion/refrig-eration	Ryan-Holmes	Membrane
			Current crude recovery			Advanced crude recovery		
			2 bbl/tonne CO_2			4.35 bbl/tonne CO_2		
CO_2 injection and recovery	Construc-tion	EOR injection well workover	1.3	1.2	1.2	1.4	1.3	1.3
		Water disposal well const.	1.1	1.0	1.0	1.2	1.1	1.1
		Water disposal well closure	0.0	0.0	0.0	0.0	0.0	0.0
		injection well closure	0.0	0.0	0.0	0.0	0.0	0.0
		EOR gas process facility const.	2.9	2.5	2.5	3.0	2.8	2.8
	Well operations	Formation leakage	2.3	2.0	2.0	1.1	1.1	1.0
		Crude oil artifical lift pump elec.	9.3	8.3	8.1	9.8	9.3	9.1
		CO_2 injection compressor emis-sions	0.2	0.2	0.2	0.1	0.1	0.1
		CO2 injection compressor elec.	49.4	43.9	42.9	23.9	22.6	22.3
		Brine injection pump elec.	1.6	1.5	1.4	0.8	0.7	0.7
Bulk seperation and storage	Oil, gas and water separation	Venting and flaring	3.2	2.9	2.8	3.4	3.2	3.2
		Natural gas upstream	0.3	0.3	0.3	0.3	0.3	0.3
		Natural gas combustion	1.1	1.0	0.9	1.1	1.1	1.1
	Crude sector	Venting and flaring	0.5	0.4	0.4	0.5	0.5	0.5
	Brine water storage	Venting and flaring	0.1	0.1	0.1	0.0	0.0	0.0
		Brine disposal pump elec.	1.0	0.9	0.8	0.5	0.4	0.4
Gas processing	upstream	Gas/diesel upstream	0.0	0.2	0.0	0.0	0.1	0.0
	combustion	Gas/diesel combustion	0.0	8.5	0.0	0.0	4.4	0.0
	electricity	Electricity upstream	10.1	41.2	15.9	4.9	21.2	8.3
Land use	Land use	Direct land use	6.7	6.0	5.8	7.1	6.7	6.6
Total			91.1	122.1	86.3	59.1	76.9	58.8

5) CO_2 sequestration loss

For consistency with DOE NETL (2010, 2013) and Cooney et al. (2015), we assume a 0.5% leakage rate of stored CO_2 from the reservoir over a 100-year period, with a range of 0% to 1%. Table 2 summarizes CO_2 emissions from the EOR procedure [17, 34-35].

Crude oil Recovery Ratio

The efficiency of the EOR process is defined as barrels of produced crude per ton of CO_2 sequestered (i.e., ton of CO_2 purchased as makeup) [11]. Table 3 provides a comparison of values utilized in the literature for EOR crude recovery ratio. Cooney et al. (2015) estimate a "low" (2 bbl/t CO_2) and "advanced" (4.35 bbl/t CO_2) crude oil recovery ratio; the low estimate is closer to Chinese operational data using a crude oil recovery ratio of 2 bbl/t CO_2 based on the CO_2-EOR project in China.

Downstream Fuel Modeling

Downstream fuel modeling includes crude oil transport from the CO_2-EOR field to the refinery, crude oil refining, fuel transport and distribution from the refinery to point of sale, and combustion of refined petroleum fuel.

$$C_{downstream} = C_{COT-EOR} + C_{ref.} + C_{F-D} \tag{10}$$

$C_{downstream}$ is the entire carbon emissions from downstream. $C_{COT-EOR}$ is carbon emissions in the crude oil transportation from the CO_2-EOR field to the refinery .$C_{ref.}$ is the emissions from crude oil refining. C_{F-D} is emissions in fuel transportation and distribution from the refinery to point of sale. Table 4 shows CO_2 emissions from the downstream part.

Table 3. Comparison of EOR crude recovery ratios from literature [17, 34, 36].

Region/Situation	Total CO_2 purchased	Crude oil production	Crude recovery ratio	Data source
	×10³tonne/day	×10³bbl/day	bbl/tonne CO_2	
Permian	93.894	19.6	2.09	Murrell et al.,2013
Rockies	20.344	45	2.21	Murrell et al.,2013
Gulf Coast	49.555	36	0.73	Murrell et al.,2013
Mid-Continent	7.824	21	2.68	Murrell et al.,2013
Zhongyuan oil field	43.4	44.8	1.03	SINOPEC, 2015
Yaoyangtai oil field	83.0	9.8	0.12	SINOPEC, 2015
Shengli oil field	76.6	126.0	1.64	SINOPEC, 2015
Caoshe oil field	170.0	483.0	2.84	SINOPEC, 2015
EOR best practices	-	-	4.35	DOE NETL, 2010
Case A	-	-	4.60	Hussain et al.,2013
Current crude recovery	-	-	2.00	Cooney et al.,2015
Advanced crude recovery	-	-	4.35	Cooney et al.,2015

Table 4. CO_2 emissions from downstream part.

Process	Emission factor Kg CO_2e/bbl	Data source
Crude oil transport from the CO_2-EOR field to the refinery	4.0	Azzolina et al.,2016
Crude oil refining	46.0	Azzolina et al.,2016
Fuel transport and distribution from the refinery to point of sale	5.0	Azzolina et al.,2016

Combustion of Refined Petroleum Fuel

CO_2 from combustion of refined petroleum fuel is carbon content in the combustion of refined petroleum fuel. We use the emission factor of 430 Kg CO_2e/bbl based on studies of Azzolina et al. (2016) and EPA (2015) [24, 37].

Results and Discussion

CO_2 Emission Summary of CO_2-EOR System

We evaluate the overall CO_2 emissions for the CO_2-EOR projects in the life cycle perspective. Net CO_2 emissions include the life cycle of the electricity generated at the power plants where CO_2 is captured, transport of CO_2 from the power plants to the oil field, oil extraction, transport of the crude oil produced in the field, crude oil refining, and combustion of the refined petroleum products. The net emissions from the systems are positive, meaning that CO_2 emissions are larger than the CO_2 injected and stored in the reservoir (Jaramillo 2009).

We use total power output of 426 MW annual in IGCC, 600 MW in PC, and 200 in oxy-fuel plants based on the ADB assessment (2015) [38]. Crude oil recovery is 2 bbl/ton. We assume that the CO_2 captured from the power plants are all sold to oil companies for EOR. Our model assumes an operational period of 25 years, and the basic data is in Table 5 based on ADB. Therefore, the oil field yields 95 Mbbl, 185 Mbbl, and 40 Mbbl.

Table 6 indicates that CO_2 emissions are associated with carbon capture, transportation, EOR, downstream, and combustion. CO_2 transportation has the smallest contribution to CO_2 emissions, representing only 0.47-1.16%. Similarly, CO_2 capture only had a small impact on CO_2 emissions, representing 4.12-5.09% of CO_2 emissions of the base case value for CO_2-EOR cases. Oil field operation emissions were a more significant contribution to CO_2-EOR, representing 15.18%, 15.21%, and 14.93% of fractionation, refrigeration in IGCC, PC, and oxy-fuel plants, respectively; and 19.29%, 19.32%, and 18.99% of Ryan-Holmes in IGCC, PC, and oxy-fuel plants, respectively; 14.50%, 14.53%, and 14.27% of membrane in IGCC, PC, and oxy-fuel plants, respectively. In all cases, CO_2 emissions associated with consumption of the final refined crude oil products were large, representing more than 65% of the net emissions. However, these emissions did not impact the comparative analysis of different cases presented there since CO_2 emissions associated with combustion were the largest for all cases.

Table 5. Summary of carbon capture and storage reference plant technical parameters in China.

		IGCC		PC		Oxy-fuel	
		No CCS	w/CCS	No CCS	w/CCS	No CCS	w/CCS
Total power output	MW	430	426	600	600	200	200
Net power output	MW	375	326	570	389	186	89
HHV	%	43.9	35.9	41.0	28.0	-	-
CO_2 Produced	Mt/yr	2.1	2.1	4.1	4.1	0.9	0.9
CO_2 emission	Mt/yr	2.1	0.2	4.1	0.4	0.9	0.1
CO_2 capture	Mt/yr	-	1.9	-	3.7	-	0.8

The results of this study reveal that the life cycle CO_2-EOR achieves a significant reduction of CO_2 emissions but has various trade-offs depending on the capture technologies. The implementation of CCS reduces the CO_2 emissions by 38.49-41.49% in the full chain of CO_2-EOR.

As can be seen in Fig. 2, emissions associated with capture, transportation, EOR, and downstream were different for all cases. CO_2 emissions with Ryan-Holmes technology from IGCC, PC, and oxy-fuel plants took the smaller in the process of capture, transportation, and downstream than CO_2 emissions with fractionation, refrigeration, and membrance. CO_2 emissions with membrane technology from IGCC, PC, and oxy-fuel plants took the smaller in the process of EOR than CO_2 emissions with fractionation, refrigeration, and Ryan-Holmes. CO_2 emissions with Ryan-Holmes technology from IGCC, PC, and oxy-fuel plants took the smaller in the process of combustion than CO_2 emissions with fractionation, refrigeration, and membrane.

Cost Benefits of CO_2-EOR

Oil companies require a large and stable volume of CO_2 at an affordable cost for the CO_2-EOR operation to be sustainable [39-41]. Operators of power plants and industrial plants that emit millions of tons of CO_2 each year hesitate to invest in facilities for CO_2 capture and transport to oil fields without an established market or price for CO_2 in China. CO_2 permit price is uncertain in the carbon emissions trading market in China. Because of this uncertainty, CO_2-EOR activities are languishing at pilot scale and are typically "capture-only" plants. China has developed its pilot carbon emission trading markets

Table 6. Life cycle summary of CO_2 emissions for CO_2-EOR.

Parameter	Unit	IGCC	IGCC	IGCC	PC	PC	PC	Oxy-fuel	Oxy-fuel	Oxy-fuel
CO_2 emissions from capture	Mt CO_2e	5.00	5.00	5.00	10.00	10.00	10.00	2.50	2.50	2.50
CO_2 capture	Mt	47.50	47.50	47.50	92.50	92.50	92.50	20.00	20.00	20.00
Transportation	Mt CO_2e	0.91	0.91	0.91	1.10	1.10	1.10	0.79	0.79	0.79
Crude recovery ratio	2bbl/ton									
Technologies		F/R	RH	Membrane	F/R	RH	Membrane	F/R	RH	Membrane
EOR	Mt CO_2e	17.55	23.44	16.63	34.17	45.64	32.39	7.39	9.87	7.00
Downstream	Mt CO_2e	10.45	10.45	10.45	20.35	20.35	20.35	4.40	4.40	4.40
Combustion	Mt CO_2e	81.70	81.70	81.70	159.10	159.10	159.10	34.40	34.40	34.40
Total	Mt CO_2e	115.61	121.50	114.69	224.72	236.19	222.95	49.48	51.96	49.09
Capture	%	4.33%	4.12%	4.36%	4.45%	4.23%	4.49%	5.05%	4.81%	5.09%
Transportation	%	0.79%	0.75%	0.79%	0.49%	0.47%	0.49%	1.60%	1.52%	1.61%
EOR	%	15.18%	19.29%	14.50%	15.21%	19.32%	14.53%	14.93%	18.99%	14.27%
Downstream	%	9.04%	8.60%	9.11%	9.06%	8.62%	9.13%	8.89%	8.47%	8.96%
Combustion	%	70.67%	67.25%	71.23%	70.80%	67.36%	71.36%	69.52%	66.21%	70.07%

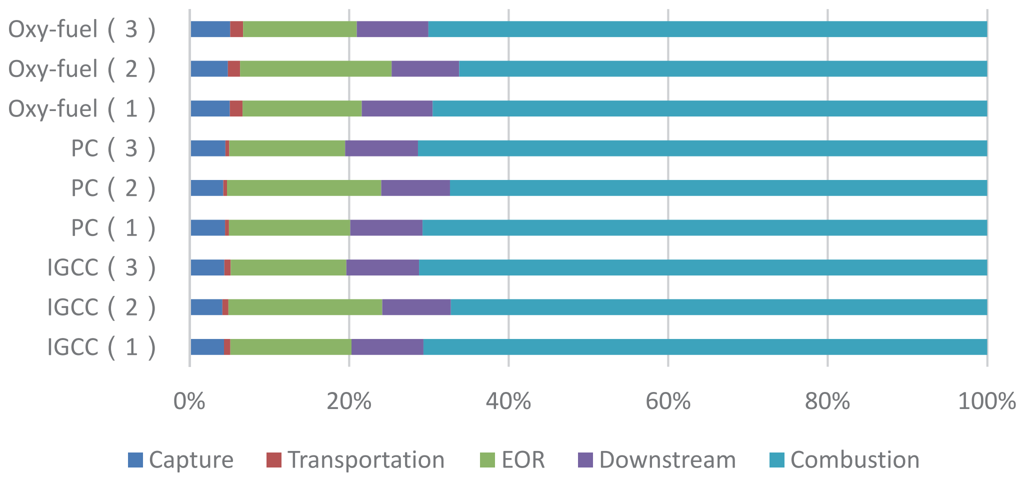

Fig. 2. Life cycle emissions from different sources.

in 7 regions for more than 3 years. The permit price is around \$5/ton while the cost of CO_2 is very high at more than \$100/ton. It is great gap between permit price and cost of CO_2, and power plants have no incentive to invest in CO_2-EOR projects. In this analysis, it was assumed that the total CO_2 emissions are twice those of CO_2 capture, while oil companies should pay for CO_2 behaves. If the cost price of CO_2 is \$100/ton and the oil price is \$50/barrel, the oil company could not get their profits and they should pay the additional investment cost and additional operational costs for CO_2-EOR projects while both power plants and oil companies do not take responsibility for CO_2 emissions in the full CO_2-EOR chain. The oil companies do not necessarily have to pay for the CO_2 captured by the electricity producer.

Conclusions

This study performs a life cycle CO_2 assessment of the CO_2-EOR system with consideration of CO_2 supply from different CO_2 sources, CO_2 transportation, oil injection, downstream of CO_2-EOR, and consumption. Different sources are carried out to illustrate the detailed procedure for the estimation of CO_2-EOR performance and CO_2 evaluation. This study compared the life cycle CO_2 emissions of fractionation, refrigeration, Ryan-Holmes, and membrance technologies on the basis case of IGCC, PC, and oxy-fuel plants. CO_2 emissions from consumption were the largest, while CO_2 emissions from transportation were the smallest. This study found that flaring and venting emissions can exceed all other emissions, especially when consumption takes about two thirds of total CO_2 emissions. Meanwhile, there are uncertainties of life cycle emissions presented in this study. It adopts 2 bbl/ton of crude recovery ratio. When the crude recovery ratio is increasing or fluctuating, the parameters of every step in life cycle CO_2 emissions are changing.

There are uncertainties on the technologies of CO_2 capture and CO_2 recycling in the oil fields. The results indicate that different technologies make a slight differences in CO_2 emissions and technologies of CO_2 capture is more important than one in recycling in oil fields.

CO_2 permit price and the price of CO_2 behavior and oil price are essential for power plants and oil companies when they make a decision to invest in CO_2-EOR projects. Only at oil prices higher than \$50/barrel and CO_2 selling price lower than \$100/ton will an oil company be willing to invest in CO_2-EOR to pay for the CO_2 and use oil revenues to share the investment in CO_2 capture, especially when power plants could get the subsidies for retrofitting their plants and they take the free tax in carbon tax or take an allowance in carbon tax. Further research is warranted to validate the results of this study, including field tests with various CO_2 sources and different technologies considered.

Acknowledgements

The authors gratefully acknowledge the support provided by the National Natural Science Foundation of China under grant No. 71173200, the National Science and Technology Major Project under grant No. 2016ZX05016005-003, and the Development and Research Center of China Geological Survey under grant No. 12120114056601.

References

1. BP. Statistical Review of World Energy June 2015. Workbook (XLSX), London, **2015**.
2. HASZELDINE R.S. Carbon Capture and Storage: How Green Can Black Be? Science, **325** (5958), 1647, **2009**.
3. CETIN M., SEVIK H. Measuring the Impact of Selected Plants on Indoor CO_2 Concentrations. Polish Journal of Environmental Studies, **25** (3), 973, **2016**.
4. CETIN M., SEVIK H., SAAT A. Indoor Air Quality: the Samples of Safranbolu Bulak Mencilis Cave. Fresenius Environmental Bulletin, **26** (10). 5965, **2017**.

5. MELZER, L.S.. Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery. Midland Texas: Melzer Consulting. National Enhanced Oil Recovery Initiative Resource, **2012**.
6. GCCSI (Global CCS Institute). The global status of CCS: 2016 summary report. Global CCS Institute. Canberra, Australia, **2016**.
7. SHITASHIMA K., MAEDA Y., SAKAMOTO A. Detection and monitoring of leaked CO_2 through sediment,water column and atmosphere in a sub-seabed CCS experiment. International Journal of Greenhouse Gas Control, **38**, 135, **2015**.
8. HURRY J., RISK D., LAVOIE M., BROOKS B.G., PHILLIPS C.L., GOCKEDE M. Atmospheric monitoring and detection of fugitive emissions for Enhanced Oil Recovery. International Journal of Greenhouse Gas Control, **45**, 1, **2016**.
9. ZHANG X.Y., MA X., WU Y., LI Y. Enhancement of farmland greenhouse gas emissions from leakage of stored CO_2: Simulation of leaked CO_2 from CCS. Science of the Total Environment, **518-519**, 78, **2015**.
10. REN B., REN S.R., ZHANG L., CHEN G.L., ZHANG H. Monitoring on CO_2 migration in a tight oil reservoir during CCS-EOR in Jilin Oilfield China. Energy, **98**, 108, **2016**.
11. SEVIK H., CETIN M. Effects of Some Hormone Applications on Germinationand Morphological Characters of Endangered Plant Species Lilium Artvinense I. Onion Scales. Bulgarian Chemical Communications, **48** (2), 256, **2016**.
12. GUNEY K., CETIN M., GUNEY K.B., MELEKOGLU A. The Effects of Some Hormones Applications on Lilium martagon L. Germination and Morpholgical Characters. Polish Journal of Environmental Studies. **26** (6), 1, **2017**.
13. CETIN M. Chapter 27: Landscape Engineering, Protecting Soil, and Runoff Storm Water, InTech-Open Science-Open Minds, Online July 1st, 2013. Book:Advances in Landscape Architecture-Environmental Sciences, ISBN 978-953-51-1167-2, 697-722, **2013**.
14. YANG Y.J., LI Y., ZHANG S.L., CHEN F., HOU H.P., MA J., Monitoring the impact of fugitive CO2 emissions on wheat growth in CCS-EOR areas using satellite and field data, Journal of Cleaner Production, **2017**, doi: 10.1016/j.jclepro.2017.03.058
15. JARAMILLO P., MICHAELGRIFFIN W., MCCOY S.T. Life Cycle Inventory of CO_2 in an Enhanced Oil Recovery System. Environ. Sci. Technol. **43**, 8027, **2009**.
16. HUSSAIN D., DZOMBAK D.A., JARAMILLO P., LOWRY G.V. Comparative lifecycle inventory (LCI) of greenhouse gas (GHG) emissions of enhanced oil recovery (EOR) methods using different CO_2 sources. International Journal of Greenhouse Gas Control, **16**, 129, **2013**.
17. COONEY G., LITTLEFIELD J., MARRIOTT J., SKONE T.J. Evaluating the climatebenefits of CO2-enhanced oil recovery using life cycle analysis. Environ. Sci.Technol. **49** (12), 7491, **2015**.
18. AZZOLINA N.A., NAKLES D.V., GORECKI C.D., PECK W.D., AYASH S.C., MELZER L.S., CHATTERJEE S. CO_2 storage associated with CO_2 enhanced oil recovery: A statistical analysis of historical operations. International Journal of Greenhouse Gas Control, **37**, 384, **2015**.
19. LAURENZI I.J., BERGERSON J.A., MOTAZEDI K. Life cycle greenhouse gas emissions and freshwater consumption associated with Bakken tight oil. Proceedings of the National Academy of Science of the United States of America, **48**, 113, E7672-E7680, **2016**.
20. LACY R., MOLINA M., VACA M., SERRALDE C., HERNANDEZ G., RIOS G., GUZMAN E., HERNANDEZ R., PEREZ R. Life-cycle GHG assessment of carbon capture, use and geologicalstorage (CCUS) for linked primary energy and electricity production. International Journal of Greenhouse Gas Control, **42**, 165, **2015**.
21. SEVIK H., CETIN M., KAPUCU O., ARICAK B., CANTURK U. Effects of lıght on morphologıc and stomatal characterıstıcs of Turkısh Fir needles (Abies nordmanniana subsp. bornmulleriana mattf.), Fresenius Environmental Bulletin, **26** (11), 6579, **2017**.
22. SEVIK H., CETIN M. Effects of Water Stress on Seed Germination for Select Landscape Plants. Polish Journal of Environmental Studies, **24** (2), 689, **2015**.
23. CETIN M. Changes in the amount of chlorophyll in some plants of landscape studies. Kastamonu University Journal of Forestry Faculty. **16** (1), 239, **2016**.
24. AZZOLINA N.A., PECK W.D., HAMLING J.A., GORECKI C.D., AYASH S.C., DOLL T.E., NAKLES D.V., MELZER LS. How green is my oil? A detailed look at greenhouse gas accounting for CO_2-enhanced oil recovery (CO_2-EOR) sites. International Journal of Greenhouse Gas Control, **51**, 369, **2016**.
25. IPCC [Intergovernmental Panel on Climate Change]. In: Metz, B., Davidson, O., de Coninck, H.C., Loos, M., Meyer, L.A. (Eds.), IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, New York, NY, **2005**.
26. RUBIN E.S., RAO A.B., CHEN C. Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy Policy **35** (9), 4444, **2007**.
27. SINGH B., STROMMAN A.H., HERTWICH E.G. Comparative life cycle environmental assessment of CCS technologies. International Journal of Greenhouse Gas Control, **5**, 911, **2011**.
28. IRIBARREN D., PETRAKOPOULOU F., DUFOUR J. Environmental and thermodynamic evaluation of CO_2 capture, transport and storage with and without enhanced resource recovery. Energy, **50**,477, **2013**.
29. MCCOY S.T. The Economics of CO_2 Transport by Pipeline and Storage inSaline Aquifers and Oil Reservoirs. (Doctoral Dissertation). Carnegie MellonUniversity, Pittsburgh, PA, **2008**.
30. LAMB B.K., EDBURG S.L., FERRARA T.W., HOWARD T., HARRISON M.R., KOLB C.E., TOWNSEND-SMALL A., DYCK W., POSSOLO A., WHETSTONE JR. Directmeasurements show decreasing methane emissions from natural gas localdistribution systems in the United States. Environ. Sci. Technol, **49** (8), 5161, **2015**.
31. CETIN M. Change in Amount of Chlorophyll in Some Interior Ornamental Plants. Kastamonu University Journal of Engineering and Sciences **3** (1), 11, **2017**.
32. YIGIT N., SEVIK H., CETIN M., KAYA N. Chapter 3: Determination of the effect of drought stress on the seed germination in some plant species, Water Stress in Plants, Intech Open, Eds: Ismail Md. Mofizur Rahman, Zinnat Ara Begum, Hiroshi Hasegawa, ISBN:978-953-51-2621-8, **126**, 43, **2016**.
33. GUNEY K., CETIN M., SEVIK H., GUNEY K.B. Chapter 4: Effects of Some Hormone Applications on Germination and Morphological Characters of Endangered Plant Species Lilium artvinense L. Seeds, New Challenges in Seed Biology - Basic and Translational Research Driving Seed

Technology ,InTech, Eds:Araújo Susana, Balestrazzi Alma, ISBN:978-953-51-2659-1, pp: 97-112 (210 p), **2016**.
34. DOE NETL (U.S. Department of Energy National Energy Technology Laboratory). An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO_2-Enhanced Oil Recovery in the Permian Basin. National Energy Technology Laboratory, DOE/NETL-2010/1433, **2010**.
35. DOE NETL. Gate-to-Gate Life Cycle Inventory and Model of CO_2-Enhanced Oil Recovery. National Energy Technology Laboratory, DOE/NETL-2013/1599, **2013**.
36. MURRELL G, DIPIETRO P. In North American CO_2 supply and developments. In:19th Annual CO_2 Flooding Conference, Midland, TX, **2013**.
37. EPA (U.S. Environmental Protection Agency). Greenhouse Gas Equivalencies Calculator, **2015**.
38. ADB (Asian Development Bank). Roadmap for carbon capture and storage demonstration and deployment in the People's Republic of China. China. **2015**
39. HORNAFIUS K.Y., HORNAFIUS S.J. Carbon negative oil: A pathway for CO_2 emission reduction goals. International Journal of Greenhouse Gas Control, **37**, 492, **2015**.
40. KWAK D.H., KIM J.K. Techno-economic evaluation of CO_2 enhanced oil recovery (EOR) withthe optimization of CO_2 supply. International Journal of Greenhouse Gas Control, **58**, 169, **2017**.
41. BROWN S., MAHEREFTEH H., MARTYNOV S., SUNDARA V., DOWELL N.M. A multi-source flow model for CCS pipeline transportation networks. International Journal of Greenhouse Gas Control, **43**, 108, **2015**.