

Original Research

Life Cycle CO₂ Emission Estimation of CCS-EOR System Using Different CO₂ Sources

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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. CO₂ 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 CO₂ emissions from the CCS-EOR system to analyze net CO₂ emissions. This system includes carbon capture, transportation, EOR, downstream, and consumption. Our model analyzes life cycle CO₂ 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 membrane in the process of EOR. Total CO₂ emissions are 114.69-121.50 Mt CO₂e, 222.95-236.19 Mt CO₂e, and 49.09-51.96 Mt CO₂e 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 CO₂ 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 CO₂ emissions to abate global warming.

Keywords: CCS-EOR, life cycle assessment, CO₂ 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]. CO₂-EOR can both produce oil and permanently store CO₂ in the subsurface and reduce oil viscosity, making it lighter and detaching it from the rock surface [5]. Consequently, CO₂-EOR provides decreasing

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CO₂ emissions from oil production and combustion via geological storage of CO₂. The process of capturing CO₂ 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. CO₂-EOR could address the twin important options for both CO₂ 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 CO₂-EOR has the great potential to present the twin challenges of climate change and energy security by producing oil with lower CO₂ emissions [6]. Although the potential for CO₂-EOR technology could increase oil production at mature fields using CO₂, there is a question about detailed assessment of the full life cycle CO₂ emissions of the CO₂-EOR process. The objective of this paper is to investigate life cycle CO₂ emissions from power plants to consumption.

Therefore, the study of life cycle CO₂ assessment becomes necessary. How to rationalize CO₂ emissions in the CCS-EOR system is the key for sound policy decisions for supporting CCUS.

Literature Review

Scholars have done extensive research on CO₂ emissions associated with CO₂-EOR. Several authors have summarized site-specific data from one or more particular oil reservoirs.

In the literature of CO₂ leakages from CCS, Shitashima et al. (2015) applied an in situ pH/p CO₂ sensor to the QICS experiment for detection and monitoring of leaked CO₂, 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 (CO₂, CH₄, and H₂S) 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 CO₂ on CH₄ and N₂O through pot experiments and revealed that significant increases of CH₄ and N₂O emissions were induced by the simulated CO₂ leaks; the emission rates of CH₄ and N₂O were substantial [9].

In the issue of monitoring CO₂ migration in CO₂-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 CO₂ 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 CO₂ emissions from oil buffer tanks. It estimated that the emitted CO₂ resulted in CO₂ enrichment about 25-100 m away from the buffer tanks [14].

In the aspects of environmental LCA for estimating CO₂ emissions, Jaramillo et al. (2009) used as case studies Northeast Purdy, SACROC, Ford Geraldine, Joffre Viking, and Weyburn to analyze the net life cycle CO₂ emissions in an EOR system. This study assessed the overall life cycle emissions associated with sequestration via CO₂-flood EOR under a number of different scenarios and explored the impact of various methods for allocating CO₂ 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 CO₂-EOR based on various CO₂ sources, including conventional CO₂ sources (e.g., natural source, coal synthetic natural gas (SNG) plant) and alternative CO₂ 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 CO₂ and to non-CO₂ EOR methods [16]. All EOR techniques were compared to the base case of natural-source CO₂-EOR. Cooney et al. (2015) claimed that the relationship between EOR efficiency and GHG emissions can be varied when the CO₂ source is changed from natural source to fossil power plant, and furthermore showed detailed GHG emissions for activities of the CO₂ EOR project, namely CO₂ 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 CO₂-enhanced oil recovery (EOR) projects that was compiled for estimating oil reserves to better understand CO₂ retention, incremental oil recovery, and net CO₂ utilization for these oil fields. Cumulative CO₂ retention (in the formation), incremental oil recovery factors, and net CO₂ 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 CO₂ 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 CO₂ [21-23].

In previous studies, efforts on environmental evaluation of CO₂-EOR had obtained more realistic results. However, these studies did not consider fully the feature related to CO₂ supply for CO₂-EOR operation and, the life cycle analysis was not fully integrated. Therefore, they cannot easily be used to assess the net CO₂ emissions to explore a variety of sites and scenarios

for CO₂-EOR. This paper presents a CO₂-EOR system where the CO₂ 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 CO₂ emissions from the CCS-EOR system, including carbon capture, transportation, EOR, downstream, combustion, and CO₂ 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 CO₂ transportation, CO₂-EOR, downstream segments, combustion, and carbon sequestration loss (Fig. 1). There are two CO₂ sources for CO₂-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 CO₂-EOR. In the emissions of CO₂-EOR, we include indirect emissions associated with consumption of electricity and direct emissions from the consumption of oil, coal, etc. After CO₂-EOR, there are emissions from crude oil pipe transportation, petroleum refining, fuel transportation, and fuel combustion.

CO₂ Emissions from the Life Cycle CO₂-EOR System

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

C_{LCA} is life cycle CO₂ emissions from the CO₂-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].

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

...where E is the power plant CO₂ emission factor (kg CO₂/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 CO₂), 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 CO₂ 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].

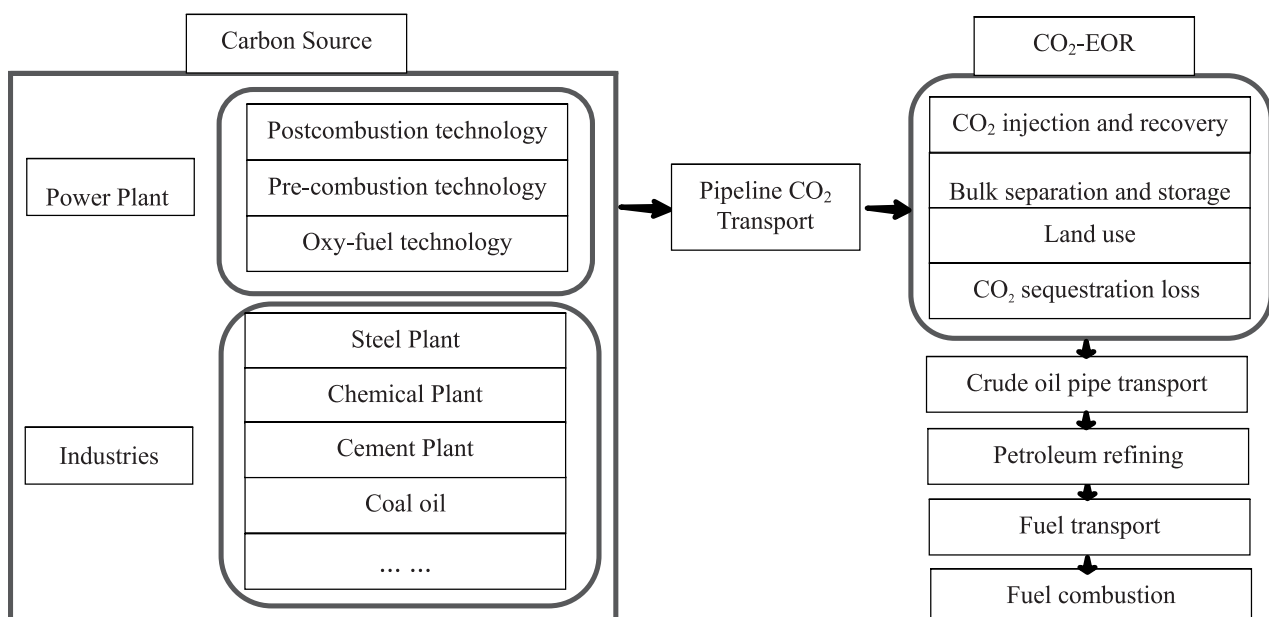


Fig. 1. System boundaries for life cycle CO₂ emissions from the CO₂-EOR system.

Table 1. Performance parameters for different power generation systems.

Parameter		Coal						Oxy-fuel capture
		World average	Post combustion technology		Pre-combustion			
			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						Oxy-fuel capture
		World average	Post-combustion technology		Pre-combustion			
			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)

CO₂ Pipeline Transport

We use data from McCoy (2008), who showed that 6.5 kWh of electricity is needed per ton of CO₂ transported [29]:

$$C_{tran.} = m_{tran.} \times q_{ele.} \times f_{ele.} \quad (3)$$

... where $C_{tran.}$ is carbon emission in the transportation part(t), and $m_{tran.}$, $q_{ele.}$, and $f_{ele.}$ present purchased CO₂ from the carbon source to the EOR field (t), electricity demand in CO₂ transportation (6.5kwh/t), and electricity CO₂ emission factor (kg CO₂e/Mwh), respectively.

CO₂ emissions from pipelines are assumed to be 75 kg CO₂/km-yr, while emissions from pipeline servicing are assumed to be 3.7 kg CO₂/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 CO₂/km-yr and 5.5 kg CO₂/service-year) [30].

CO₂ Capture, CO₂ Injection, CO₂ Retention, and CO₂ Recycling

Azzolina et al. (2015) published results for CO₂ retention, which is a metric that expresses the fraction

of total injected CO₂ at a CO₂-EOR facility that is not recycled but remains in the subsurface [18]. Approximately 50% of the total injected CO₂ is produced together with the oil, separated, and recycled/reinjected, but nearly all (over 95%) of the purchased CO₂ 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 CO₂ is recycled [4, 18].

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

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

When n is approaching infinity, $U_{injected, gross}$ is twice $U_{captured}$. That is to say, the CO₂ injected to the EOR field is twice the amount of CO₂ captured from the power plants when we omit the loss of CO₂ in the process of transportation.

EOR Procedure

To determine the net CO₂ emissions of the CO₂-EOR system, this analysis assumes a set of 4 core functional activities: CO₂ 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 CO₂ emissions from the CO₂-EOR system. $C_{inj-rec}$, $C_{bulksep.}$, $C_{pro.}$, C_{lanuse} , and C_{loss} present CO₂ emissions from CO₂ injection and crude recovery, bulk separation and storage, gas processing, land use, and carbon sequestration loss, respectively.

1) CO₂ injection and crude recovery

CO₂ injection and crude recovery includes the distribution of CO₂ to the injection wells and all technical measures to maintain necessary pressure and temperature. The injected CO₂ stream is a combination of makeup CO₂ from a pipeline and recycled CO₂ 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 CO₂ 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. CO₂ emissions from injection and crude recovery include CO₂ emissions from EOR construction and well operation.

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

$C_{inj-rec}$ is CO₂ emissions from CO₂ injection and recovery. $C_{cons.}$ and $C_{wellop.}$ present CO₂ emissions from EOR construction and well operation. $C_{cons.}$ include CO₂ emissions from the EOR injection well workover, water disposal well construction, water disposal well closure, injection well closure, and EOR gas process facility construction; $C_{wellop.}$ includes CO₂ from formation leakage, crude oil artificial lift pump electricity, CO₂ injection compressor emissions, CO₂ 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 CO₂ removal and hydrocarbon processing.

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

$C_{bulksep.}$ is CO₂ emissions from bulk separation and storage. $C_{ogwsep.}$, $C_{crudsec.}$, and $C_{brinesto.}$ present CO₂ 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 CO₂ and to adjust the composition of hydrocarbon streams so that CO₂ 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 CO₂ emissions from gas processing. $C_{uostr.}$, $C_{comb.}$, and $C_{ele-pro}$ present CO₂ emissions from gas and diesel upstream, gas and diesel combustion, and electricity upstream.

4) Land use

CO₂ 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 CO₂e/bbl crude from the EOR system (Cooney 2015).

Table 2. CO₂ emissions from EOR procedure (Kg CO₂e/barrel crude).

Parameter			Fractionation/refrigeration	Ryan-Holmes	Membrane	Fractionation/refrigeration	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	Construction	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 artificial lift pump elec.	9.3	8.3	8.1	9.8	9.3	9.1
		CO ₂ injection compressor emissions	0.2	0.2	0.2	0.1	0.1	0.1
		CO ₂ 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 separation 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	0.1	0.1	0.1	0.0	0.0	0.0
Gas processing	upstream	Gas/diesel upstream	0.0	0.2	0.0	0.0	0.1	0.0
		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) CO₂ sequestration loss

For consistency with DOE NETL (2010, 2013) and Cooney et al. (2015), we assume a 0.5% leakage rate of stored CO₂ from the reservoir over a 100-year period, with a range of 0% to 1%. Table 2 summarizes CO₂ 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 CO₂ sequestered (i.e., ton of CO₂ 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 CO₂) and “advanced” (4.35 bbl/t CO₂) crude oil recovery ratio; the low estimate is closer to Chinese operational data using a crude oil recovery ratio of 2 bbl/t CO₂ based on the CO₂-EOR project in China.

Downstream Fuel Modeling

Downstream fuel modeling includes crude oil transport from the CO₂-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.

$$C_{\text{downstream}} = C_{\text{COT-EOR}} + C_{\text{ref.}} + C_{\text{F-D}} \quad (10)$$

$C_{\text{downstream}}$ is the entire carbon emissions from downstream. $C_{\text{COT-EOR}}$ is carbon emissions in the crude oil transportation from the CO₂-EOR field to the refinery. $C_{\text{ref.}}$ is the emissions from crude oil refining. $C_{\text{F-D}}$ is emissions in fuel transportation and distribution from the refinery to point of sale. Table 4 shows CO₂ 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
	×10 ³ tonne/day	×10 ³ bbl/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. CO₂ emissions from downstream part.

Process	Emission factor Kg CO ₂ e/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

CO₂ from combustion of refined petroleum fuel is carbon content in the combustion of refined petroleum fuel. We use the emission factor of 430 Kg CO₂e/bbl based on studies of Azzolina et al. (2016) and EPA (2015) [24, 37].

Results and Discussion

CO₂ Emission Summary of CO₂-EOR System

We evaluate the overall CO₂ emissions for the CO₂-EOR projects in the life cycle perspective. Net CO₂ emissions include the life cycle of the electricity generated at the power plants where CO₂ is captured, transport of CO₂ 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 CO₂ emissions are larger than the CO₂ 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 CO₂ 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 CO₂ emissions are associated with carbon capture, transportation, EOR, downstream, and combustion. CO₂ transportation has the smallest contribution to CO₂ emissions, representing only 0.47-1.16%. Similarly, CO₂ capture only had a small impact on CO₂ emissions, representing 4.12-5.09% of CO₂ emissions of the base case value for CO₂-EOR cases. Oil field operation emissions were a more significant contribution to CO₂-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, CO₂ 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 CO₂ 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 CO₂-EOR achieves a significant reduction of CO₂ emissions but has various trade-offs depending on the capture technologies. The implementation of CCS reduces the CO₂ emissions by 38.49-41.49% in the full chain of CO₂-EOR.

As can be seen in Fig. 2, emissions associated with capture, transportation, EOR, and downstream were different for all cases. CO₂ emissions with Ryan-Holmes technology from IGCC, PC, and oxy-fuel plants took the smaller in the process of capture, transportation, and downstream than CO₂ emissions with fractionation, refrigeration, and membrane. CO₂ emissions with membrane technology from IGCC, PC, and oxy-fuel plants took the smaller in the process of EOR than CO₂ emissions with fractionation, refrigeration, and Ryan-Holmes. CO₂ emissions with Ryan-Holmes technology

from IGCC, PC, and oxy-fuel plants took the smaller in the process of combustion than CO₂ emissions with fractionation, refrigeration, and membrane.

Cost Benefits of CO₂-EOR

Oil companies require a large and stable volume of CO₂ at an affordable cost for the CO₂-EOR operation to be sustainable [39-41]. Operators of power plants and industrial plants that emit millions of tons of CO₂ each year hesitate to invest in facilities for CO₂ capture and transport to oil fields without an established market or price for CO₂ in China. CO₂ permit price is uncertain in the carbon emissions trading market in China. Because of this uncertainty, CO₂-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 CO₂ emissions for CO₂-EOR.

Parameter	Unit	IGCC	IGCC	IGCC	PC	PC	PC	Oxy-fuel	Oxy-fuel	Oxy-fuel
CO ₂ emissions from capture	Mt CO ₂ e	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 ₂ e	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 ₂ e	17.55	23.44	16.63	34.17	45.64	32.39	7.39	9.87	7.00
Downstream	Mt CO ₂ e	10.45	10.45	10.45	20.35	20.35	20.35	4.40	4.40	4.40
Combustion	Mt CO ₂ e	81.70	81.70	81.70	159.10	159.10	159.10	34.40	34.40	34.40
Total	Mt CO ₂ e	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%

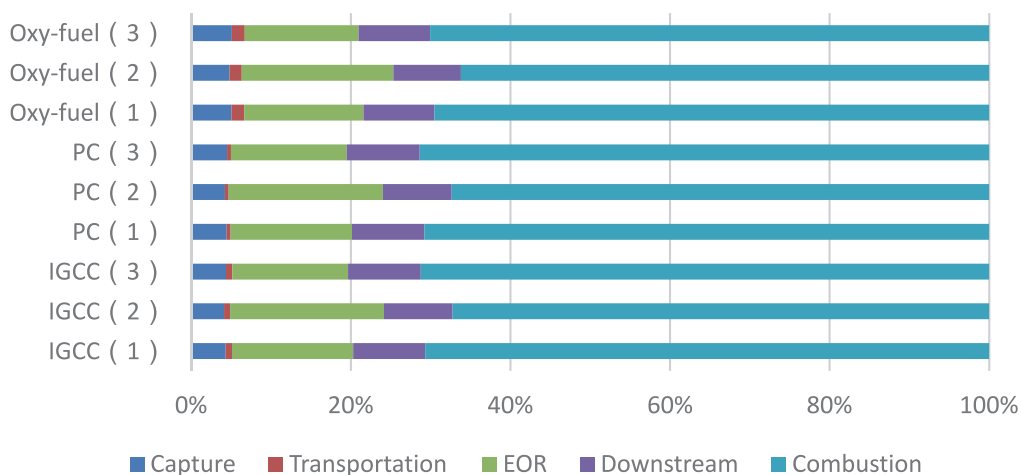


Fig. 2. Life cycle emissions from different sources.

in 7 regions for more than 3 years. The permit price is around \$5/ton while the cost of CO₂ is very high at more than \$100/ton. It is great gap between permit price and cost of CO₂, and power plants have no incentive to invest in CO₂-EOR projects. In this analysis, it was assumed that the total CO₂ emissions are twice those of CO₂ capture, while oil companies should pay for CO₂ behaves. If the cost price of CO₂ 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 CO₂-EOR projects while both power plants and oil companies do not take responsibility for CO₂ emissions in the full CO₂-EOR chain. The oil companies do not necessarily have to pay for the CO₂ captured by the electricity producer.

Conclusions

This study performs a life cycle CO₂ assessment of the CO₂-EOR system with consideration of CO₂ supply from different CO₂ sources, CO₂ transportation, oil injection, downstream of CO₂-EOR, and consumption. Different sources are carried out to illustrate the detailed procedure for the estimation of CO₂-EOR performance and CO₂ evaluation. This study compared the life cycle CO₂ emissions of fractionation, refrigeration, Ryan-Holmes, and membrane technologies on the basis case of IGCC, PC, and oxy-fuel plants. CO₂ emissions from consumption were the largest, while CO₂ 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 CO₂ 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 CO₂ emissions are changing.

There are uncertainties on the technologies of CO₂ capture and CO₂ recycling in the oil fields. The results

indicate that different technologies make a slight differences in CO₂ emissions and technologies of CO₂ capture is more important than one in recycling in oil fields.

CO₂ permit price and the price of CO₂ behavior and oil price are essential for power plants and oil companies when they make a decision to invest in CO₂-EOR projects. Only at oil prices higher than \$50/barrel and CO₂ selling price lower than \$100/ton will an oil company be willing to invest in CO₂-EOR to pay for the CO₂ and use oil revenues to share the investment in CO₂ 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 CO₂ sources and different technologies considered.

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