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### Article On the economics of CO2 contracts in the enhanced oil recovery industry

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ENVIRONMENT AND NATURAL RESOURCE ECONOMICS 3 OPEN ACCESS

# On the economics of CO<sub>2</sub> contracts in the enhanced oil recovery industry

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#### ABSTRACT

While Carbon Dioxide based Enhanced Oil Recovery (CO<sub>2</sub> -EOR) is often regarded as one of the most economically viable methods of carbon capture, utilization and storage (CCUS), little is known about the existing CO<sub>2</sub> supply contracts in the CO<sub>2</sub> -EOR industry. By studying a sample of 103 CO<sub>2</sub> sales contracts in the U.S. in the 1980s and 1990s, this paper aims to find out what drives the key terms in these contracts. In particular, a special price adjustment clause is included to peg the CO<sub>2</sub> price to the oil price. Our analyses suggest that the probability that the pegging term is used is positively associated with the contract length. Besides, initial oil prices, volatile historical oil prices, and the net CO<sub>2</sub> utilization also positively impacts the adoption of the price-pegging adjustment mechanism.

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#### 1. Introduction

Engineering and economics studies of carbon sequestration through Carbon Dioxide based Enhanced Oil Recovery (CO<sub>2</sub> -EOR) have primarily focused on the co-optimization of oil production and CO<sub>2</sub> sequestration by choosing the optimal CO<sub>2</sub> fraction of the injection stream and other management decisions.<sup>1</sup> These studies are important in determining the optimal micro-level operational and management decisions, given exogenous market conditions such as the prices of oil and CO<sub>2</sub>. This article investigates the vertical relation between the CO<sub>2</sub> seller and the buyer by examining a sample of 103 CO<sub>2</sub> sales contracts. We focus on the contract structure and price adjustments, and provide empirical evidence on the determination of CO<sub>2</sub> prices.

In our sample of 103 contracts, more than half have duration terms longer than five years, and about three quarters have price adjustment clauses included. Unlike price adjustment clauses found in numerous other industries and markets (Arnold,

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<sup>&</sup>lt;sup>1</sup>See, for example, studies by Asghari and Al-Dliwe (2004); Jessen, Kovscek, and Orr (2005); Kovscek and Cakici (2005); Babadagli (2006); Forooghi, Hamouda, and Eilertsen (2009); Pamukçu and Gumrah (2009); Ghomian, Sepehrnoori, and Pope (2010); Jahangiri and Zhang (2011, 2012); Sobers, Blunt, and LaForce (2013); Ettehadtavakkol, Lake, and Bryant (2014); Song, Li, Wei, Lai, and Bai (2014) using sophisticated reservoir models but ad hoc economics, and studies by Leach et al. (2011); Van 't Veld, Mason, and Leach (2013); Wang et al. (2018) for more rigorous economic analysis of the issue.

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Harmon, Rose, & Whitley, 2013; Goldberg & Erickson, 1987; Joskow, 1988; Skolnik, 2011), where the contract price is adjusted based on changes in the supplier's input costs, the contracted  $CO_2$  price is pegged to the price of the buyer's output, oil. Specifically, a sample contract clause that specifies the delivered  $CO_2$  price states "Delivered Price: The price to be paid by Buyer for all volumes purchased shall be calculated monthly, and shall be a percentage of the average of West Texas Intermediate Crude (the average of the first posting of the Month as posted by ExxonMobil, Chevron, and Conoco Phillips) for such Month." Note that the sample contract leaves the percentage unspecified.

This article provides an empirical analysis of the contract structure and price adjustments of the  $CO_2$  sales contracts. Our analyses show that longer contract duration increases the probability of price-pegging being used. The pegging coefficients also show that higher initial oil prices, more volatile historical oil prices, and smaller net  $CO_2$  utilization are associated with high pegging coefficients. In addition, contracts signed at the early stages of  $CO_2$  -EOR projects tend to have lower pegging coefficients.

This article contributes to the literature in several ways. First, it relates to studies on the economics of CO<sub>2</sub> -EOR and its potential in CCUS through careful examinations of actual CO<sub>2</sub> purchasing contracts. Studies based on extensive interviews with companies, government agencies, and NGOs show that CO<sub>2</sub> -EOR is a technologically and commercially viable approach for CCUS (Bloomberg, 2012; Taylor, 2012). However, one important factor that has long been overlooked is the vertical relation within the CO<sub>2</sub> -EOR industry, which has important implications since it largely determines how the profits from enhanced production are distributed. Leach, Mason, and van 't Veld (2011) and Wang, Van 't Veld, Marcy, Huzurbazar, and Alvarado (2018) show that  $CO_2$  sequestration does not respond much to the sequestration subsidy, which provides us a valuable lesson on how to use policies to promote  $CO_2$  utilization effectively. We find that the  $CO_2$  -EOR industry is highly concentrated on the supply side. The market power of the dominant player likely comes from its control of large natural CO<sub>2</sub> deposits and pipeline networks. Therefore, promoting CO<sub>2</sub> -EOR by expanding CO<sub>2</sub> supply or building required infrastructure as suggested by Wang et al. (2018) could be a viable option.

Second, this paper contributes to the literature that examines price adjustment in long-term contracts. Researchers have discovered that the  $CO_2$  -EOR industry often includes a unique price adjustment clause in their CO<sub>2</sub> purchasing contracts that pegs the CO<sub>2</sub> price to the oil price (Cook, 2013; Martin & Taber, 1992). Theoretical studies by Agarwal (2014), Van 't Veld and Phillips (2009), and Gao and van 't Veld (2021) show that a "price-pegging"CO2 contract outperforms a fixed price  $CO_2$  contract in terms of reducing the contracting risks, decreasing the sensitivity of supply and demand to small oil-price changes, and increasing efficiency. Our empirical analyses of actual CO<sub>2</sub> contracts shed light on how the "price-pegging" clause responds to changes in market conditions and provides valuable information about how "reasonably clever businessmen and lawyers cope with problems scholars might consider intractable" (Goldberg & Erickson, 1987).

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Third, this paper is closely related to studies examining the cost of  $CO_2$  purchase. Two significant costs hold back the advancement of  $CO_2$  -EOR, the high purchasing cost of  $CO_2$  and the large up-front investment costs associated with  $CO_2$  -EOR projects.<sup>2</sup> These two costs have important economic implications. The large up-front investment gives the  $CO_2$  seller some ex-post bargaining power,<sup>3</sup> resulting in the classic "hold-up" problem (Klein, Crawford, & Alchian, 1978; Williamson, 1979, 1985), where inefficiently low investment or "opportunistic behavoir" seeking to force renegotiation of the contract price may occur.<sup>4</sup> One solution to the "hold-up" problem, is to adopt a long-term contract that specifies the terms and conditions, the pegging price adjustment clause studied in this paper, which allows for adjustment of the contract price when certain conditions are met, is plausible.

The rest of this paper is organized as follows. Sections 2 provides a summary of the contracts and analyzes the structure of the contracts, emphasizing the duration, quantity, and price. Section 3 examines how the pegging coefficients in the contracts are determined, and Section 4 concludes.

#### 2. The structure of long-term CO<sub>2</sub> contracts

 $CO_2$  -EOR has been widely regarded as one of the most economically viable approaches for carbon capture, utilization, and storage (CCUS). The technique of  $CO_2$  -EOR injects  $CO_2$  into the reservoir to make the oil swell and reduce its viscosity. The result is increased reservoir pressure and easier movement of the oil through the reservoir rock to the well. The  $CO_2$  injected gets either sequestered in the reservoir or recycled and re-injected. The injected  $CO_2$  can be permanently contained within the depleted reservoir with proper sealing and maintenance. Specifically, Faltinson & Gunter (2011) have shown that for the majority of the  $CO_2$ -EOR projects in North America, more than half of the injected  $CO_2$  is stored in the reservoir.

The technical  $CO_2$  storage capacity offered by  $CO_2$  -EOR in the U.S. is estimated to be 51 billion metric tons. Using the "next generation"  $CO_2$  -EOR technology, 100 billion barrels of oil are estimated to be economically recoverable,<sup>5</sup> with associated demand for and potential storage of 30 billion metric tons of  $CO_2$  (Kuuskraa, Godec, & Dipietro, 2013). Within the foreseeable future, the U.S. government is likely to adopt some form of regulation of  $CO_2$  emissions, whether in the form of a carbon tax or a cap-and-trade program. The importance of the  $CO_2$  -EOR market, in terms of oil production and carbon sequestration, is likely to keep growing in the coming years. Figure 1 shows the locations of the  $CO_2$  -EOR projects in the U.S., along with the natural  $CO_2$  sources and the pipeline infrastructures that transport  $CO_2$  to the oil fields. We can see that most of the active  $CO_2$  -EOR projects are located in the Permian Basin area. The rest are scattered in Wyoming, Utah, Kansas, Oklahoma, Louisiana, and

<sup>&</sup>lt;sup>2</sup>For the first ten years of operation, the CO<sub>2</sub> purchasing cost could amount to as much as 68% of total costs (Jarrel, Fox, Stein, & Webb, 2002). In addition, investing in CO<sub>2</sub> -EOR involves converting existing production wells to injection wells, drilling new wells, and building a recycling plant to capture, compress and re-inject some of the injected CO<sub>2</sub> (van 't Veld & Phillips, 2010).

<sup>&</sup>lt;sup>3</sup>Williamson (1983) identifies four different types of transaction-specific investments. The up-front investment associated with CO<sub>2</sub> -EOR should be identified as "Physical Asset Specificity" type, since the transaction-specific investment are made in equipment and machinery that are specifically designed for CO<sub>2</sub> -EOR.

<sup>&</sup>lt;sup>4</sup>See Masten (1988) and Hart (2009) for further discussion of such "opportunistic behavoir".

<sup>&</sup>lt;sup>5</sup>Assuming the cost of CO<sub>2</sub> is at \$40/metric ton and the oil price is \$85/barrel.



**Figure 1.** Location of current  $CO_2$  EOR projects and pipeline infrastructure in the U.S. Source: Carbon dioxide enhanced oil recovery (DOE, 2010)

Mississippi. Most of the CO<sub>2</sub> supplied to the Permian Basin is from three natural CO<sub>2</sub> sources: McElmo Dome, Bravo Dome, and Sheep Mountain. Three pipelines connect the sources to the basin: Cortez Pipeline, Bravo Pipeline, and Sheep Mountain Pipeline. Figure 2 shows the locations of the oil fields from the CO<sub>2</sub> sales contracts. Of the 103 CO<sub>2</sub> sales contracts we are able to obtain, 95 are buying CO<sub>2</sub> for EOR projects in the Permian Basin, 4 for projects in Utah, and 4 for projects in Mississippi. Therefore the sample contracts cover not only most of the CO<sub>2</sub> -EOR fields in the Permian Basin but also some of the fields in other states.

The 103  $CO_2$  sales contracts we investigate are provided by the Department of Economics at the University of Wyoming. The contracts remain proprietary to this day, so details about any specific contract cannot be revealed. Overall, there are six unique sellers and 34 unique buyers. The contract effective dates range from 1982 to 2001.<sup>6</sup> Table 1 shows a summary of the number of contracts and the total quantity supplied from each supplier. In terms of both contract number and total quantity supplied, Company C is, without a doubt the largest supplier in this dataset. The total amount of  $CO_2$  supplied in the 103 contracts is 4545.61 Bcf. Company C alone supplies 3402.74 Bcf of  $CO_2$ , which is 75% of the total  $CO_2$  supplied in all contracts.

It is also useful to look at the contracts that supply  $CO_2$  to the Permian Basin. Three pipelines connect three natural  $CO_2$  sources to the oil fields. This gives the oil fields in the Permian Basin a large advantage over fields in other areas, where there is only one pipeline transporting  $CO_2$  from a single source. Table 2 shows a summary of the number of contracts

<sup>&</sup>lt;sup>6</sup>The effective date of the latest contract is 1 January 2001, which means it was drafted in 2000.



(c) Oil fields in Texas and New Mexico



Supplier	Freq.	Percent	Cum.	Total CO <sub>2</sub> supplied (Bcf)	Percent	Cum.
Company A	7	6.80	6.80	549.83	12.10	12.10
Company B	4	3.88	10.68	202.18	4.45	16.54
Company C	83	80.58	91.26	3402.74	74.86	91.40
Company D	4	3.88	95.15	329.01	7.24	98.64
Company E	1	0.97	96.12	24.50	0.54	99.18
Company F	4	3.88	100	37.35	0.82	100
Total	103	100.00		4545.61	100.00	

Table 1. Summary of number of contracts and total quantity from each supplier.

and the total quantity supplied from each supplier in the Permian Basin. Company C is still the largest supplier with the largest number of contracts and the largest quantity supplied, indicating that the  $CO_2$  market in the Permian Basin is also highly concentrated.

Table 1 and Table 2 indicate that Company C is the dominant player in our sample contracts. Even though our sample does not possibly include all  $CO_2$  sales contracts in the 1980s and 1990s, the dominant position of Company C in our sample generally reflects its actual market position in the Permian Basin and the overall  $CO_2$ -EOR market in the US.<sup>7</sup>

Table 3 shows the summary of three important contract terms, contract duration, total contracted quantity, and the initial contracted  $CO_2$  price. All three terms vary a lot. For total contracted quantity, the smallest value is 0.02 Bcf, while the largest is 720 Bcf. Figure 3 shows the distribution of the total contracted quantity of all contracts. We can see that the majority of contracts have a total contracted quantity of less than 100 Bcf. For the initial  $CO_2$  price, the lowest price is only \$0.2/Mcf, while the highest is \$1.65/Mcf. Figure 4 shows the distribution of the initial  $CO_2$  price of all contracts. Most contracts have an initial  $CO_2$  price between \$0.5 and \$0.8 per Mcf. The shortest contract lasts only 16 days for contract duration, while the longest one lasts 24 years. Figure 5 shows the distribution of the contracts. Table 4 shows a summary of contract types in

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Supplier	Freq.	Percent	Cum.	Total CO <sub>2</sub> supplied (Bcf)	Percent	Cum.
Company A	7	7.37	7.37	549.83	12.43	12.43
Company B	4	4.21	11.58	202.18	4.57	17.00
Company C	75	78.94	90.53	3279.67	74.16	91.16
Company D	4	4.21	94.74	329.01	7.44	98.60
Company E	1	1.05	95.79	24.50	0.55	99.16
Company F	4	4.21	100.00	37.35	0.84	100
Total	95	100.00		4422.54	100	

Table 2. Summary of number of contracts and total quantity from suppliers in the Permian Basin.

Table 3. Summary of contract duration, total contracted quantity and initial CO<sub>2</sub> price.

Duration of Contract (Year)         103         7.74         6.28         0.02           Total Contract Quantity (Ref)         102         44.13         100.95         0.03	Max	Min	Std. Dev.	Mean	Obs.	Contract term
Total Contracted Quantity (Pcf) 102 44.12 100.85 0.02	24	0.02	6.28	7.74	103	Duration of Contract (Year)
Total Contracted Qualitity (bcf) Tos 44.15 Tot.65 0.02	720	0.02	100.85	44.13	103	Total Contracted Quantity (Bcf)
Initial CO <sub>2</sub> Price (\$/Mcf) 103 0.68 0.27 0.2	1.65	0.2	0.27	0.68	103	Initial CO <sub>2</sub> Price (\$/Mcf)

<sup>7</sup>This is not surprising as Company C is the earliest company entering the CO<sub>2</sub> -EOR market and the biggest promoter of the CO<sub>2</sub> -EOR technology. It also owns a large portion of the natural CO<sub>2</sub> deposits and the pipeline network.



Figure 3. Oil fields in Mississippi.



Figure 4. Oil fields in Texas and New Mexico.

terms of contract duration. Short-term contracts (one year or shorter) comprise only 24% of all contracts, while long-term contracts (longer than five years) comprise 55% of all contracts. This suggests that long-term contracts might be more prevalent than short-term contracts in the  $CO_2$ -EOR industry.



Figure 5. Location of the oil fields from the CO<sub>2</sub> sales contracts.

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Contract duration	Freq.	Percent	Cum.
Short-term contract (T $\leq$ 1 year)	25	24.27	24.27
Intermediate-term contract (1 year $\leq T \leq 5$ years)	21	20.39	44.66
Long-term contract (T $>$ 5 years)	57	55.34	100.00
Total	103	100.00	

Table 4. Summary of different contract types in terms of duration.

Other than the prevalence of long-term contracts, we also notice the frequent usage of price-pegging in the  $CO_2$  sales contracts. The contracted  $CO_2$  price consists of two elements: a commodity price and a transportation cost. The transportation cost can be bid on flat and escalated but is usually not pegged to a specific index. On the other hand, the commodity price is commonly pegged to an index and adjusted based on the changes of the index. Of the 103 contracts, 69 contracts use one or more indexes to auto-adjust the  $CO_2$  prices. That is about two-thirds of all the contracts. The indexes used include the West Texas Intermediate (WTI) price, the Producer Price Index (PPI)<sup>8</sup> for industrial commodities and the natural gas price. Table 5 shows a summary of the indexes used. Note that there are a few contracts that utilize both the WTI and PPI indexes. In this case, the two indexes are used separately when calculating the adjusted  $CO_2$  price, and the higher adjusted price is used. Knowing there are three different possible indexes, an interesting question is how an index is chosen. Unfortunately, we have no concrete answer to this question. It may just come down to the preferences of the parties involved.<sup>9</sup> Lastly, there is a possible positive correlation between the contract duration and the probability of

<sup>&</sup>lt;sup>8</sup>The Producer Price Index, which the Bureau of Labor Statistics publishes, measures the average change over time in the selling prices received by domestic producers for their output.

<sup>&</sup>lt;sup>9</sup>A possible explanation for the wide usage of WTI as the index is that the industry is following the leader. The early long-term contracts in our sample all use WTI as the index, with Company C being the seller.

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Table 5. Summary of indexes used in contracts.

Index type	Freq.	Percent	Cum.
WTI	57	82.61	82.61
PPI	1	1.45	84.06
WTI & PPI	9	13.04	97.10
Natural Gas Price	2	2.90	100.00
Total	69	100.00	

using price-pegging. As is shown in Figure 6, as the contract duration increases, the proportion of indexed contracts within each category increases significantly. For the 57 long-term contracts, 52 contracts peg their  $CO_2$  price to some index types.

#### 3. Analyses on the Price-pegging Mechanism

Theoretical studies have shown that it is optimal to use a pegged  $CO_2$  price instead of a fixed one, regardless of the contract duration (Agarwal, 2014; Gao & van 't Veld, 2021). However, Figure 6 shows that while the price-pegging mechanism is widely used in intermediate and long-term contracts, it is rarely used in short-term contracts. One possible explanation is that although theoretically, the seller earns a higher expected profit by using a pegged price instead of a fixed one, in reality, this profit gain is rather small in a short period. The pegged  $CO_2$  price could be almost identical to the fixed price because the change in the oil price is very small. Additionally, writing a price-pegging contract can be more costly to the parties involved.<sup>10</sup>



Figure 6. Different contracts by duration and indexing.

<sup>&</sup>lt;sup>10</sup>We do find that price-pegging contracts are generally much longer than fixed-price contracts. This may imply that it is more costly to write a price-pegging contract.

To estimate what variables could affect the decision to include price-pegging in the contract, we run a Probit regression of the contract type (1 = price-pegging contract,0 = fixed-price contract) against some key contract terms. The estimation results are given in Table 6. The "Affiliation" and "Area" variables are two dummy variables controlling for whether the buyer and seller are affiliated and whether the contracted oil field is located in the Permian Basin or not. Although not statistically significant, the result suggests that being affiliated increases the probability of price-pegging being used, while the contracted oil field in the Permian Basin reduces the probability. The contract duration has a statistically significant positive effect on the decision to use price-pegging. The other two variables, "Initial Oil Price" (the average oil price of the month before the contract effective date) and "Total Contracted Quantity", both positively affect the probability of price-pegging being used. However, the coefficients of these two estimators are not statistically significant, so not too much should be read into it. The coefficient of the initial oil price may seem weakly statistically significant. Nevertheless, this significance goes away when we replace it with the average oil price of two months or three months prior to the contract effective date.

We further investigate the determinants of the price-pegging coefficient. Our analysis directly follows the theoretical work by Gao and van 't Veld (2021). For contracts that use crude oil prices as the index, the  $CO_2$  price is calculated as the product of the pegging coefficient and the oil price. The theoretical model implies that the pegging coefficient is affected by a number of variables, namely the discounted cumulative incremental oil production,<sup>11</sup> the discounted cumulative added cost,<sup>12</sup> net  $CO_2$  utilization,<sup>13</sup> up-front investment, the initial oil price, and the oil price volatility. We confront the implications

	(1)
	Price-pegging Contract
Affiliation	0.175
	(0.373)
Area	-0.569
	(0.550)
Contract Duration	0.202 ***
	(0.0464)
Initial Oil Price	0.0601 *
(Past Month)	(0.0362)
Total Contracted Quantity	0.000181
	(0.00187)
Constant	-1.658 *
	(0.996)
Ν	103
pseudo R <sup>2</sup>	0.377
Standard errors in parentheses	

## **Table 6.** Probit regression of the contract type (y = 1).

\* *p* < 0.10, \*\* *p* < 0.05, \*\*\* *p* < 0.01

<sup>&</sup>lt;sup>11</sup>Incremental oil production is defined as the volume of oil produced as a direct result of CO<sub>2</sub> injected into the reservoir that would not otherwise be produced by currently available primary and secondary recovery techniques.

<sup>&</sup>lt;sup>12</sup>CO<sub>2</sub> -EOR incurs both a higher transportation cost and a higher operating cost than waterflooding. The reason for the higher operating cost is the additional cost of recycling CO<sub>2</sub>.

<sup>&</sup>lt;sup>13</sup>Net CO<sub>2</sub> utilization is defined as the cumulative net CO<sub>2</sub> volume purchased divided by the incremental CO<sub>2</sub> -EOR oil production.

of the theoretical model with the data. Of all the contracts that peg the  $CO_2$  price to the oil price, 46 contracts have well-defined pegging coefficients. These 46 contracts have  $CO_2$ supplied to 19 different fields. Although we do not know how each contract was negotiated, there are patterns of contract features, which suggest that each seller is offering a standardized contract as a starting point in the negotiations. Those standardized contracts tend to include a provision for pegging. This fact allows us to focus on key contract terms such as the pegging coefficient without worrying about the differences between the sellers. Because the incremental oil production, added cost (including added transportation cost and added operating cost), net  $CO_2$  utilization, and up-front investment all vary greatly for different fields, having data on these variables is crucial to the empirical analysis. Unfortunately, we are not able to locate usable data regarding these variables. Based on the data at hand, there are still a few implications of the model that can be tested.

First of all, the theoretical model predicts that a higher initial oil price leads to a higher pegging coefficient. To test this prediction, we define three different initial oil prices as the average oil price for the past one, two, or three months before the contract effective date, respectively. Secondly, simulation based on the theoretical model suggests that the optimal pegging coefficient is not sensitive to changes in the oil price volatility. Assuming that the oil price follows a random walk described by Geometric Brownian motion, for a T year contract, the oil price volatility is the product of an annualized *log* oil price standard deviation and the square root of the contract duration,  $\sqrt{T}$ . Therefore, we must first calculate the annualized log oil price standard deviation to test whether the pegging coefficient is insensitive to the oil price volatility. Based on "adaptive expectations," we calculate the log oil price standard deviation using monthly log oil prices for the past one year prior to the contract effective date. Since we do not know how "backward-looking" the sellers are, we also calculate the standard deviation using monthly log oil prices for the past two and three years.<sup>14</sup>

Thirdly, the theoretical model predicts that a higher net  $CO_2$  utilization leads to a lower pegging coefficient. We calculate the net  $CO_2$  utilization by dividing the daily contracted  $CO_2$  volume by the daily enhanced oil production based on the EOR surveys published by the Oil & Gas Journal.<sup>15</sup>

Fourthly, the theoretical model assumes a monopolistic seller. This implies that the timing of the contracts may have important effects on the pegging coefficients. Intuitively, the buyer's expected profits from the  $CO_2$  -EOR project must at least cover the up-front investment cost. Once the project has started, the up-front investment becomes a sunk cost. As a result, the initial contract needs to be attractive enough for the buyer to participate in the  $CO_2$  -EOR project. However, once the project has started, any follow-up contract only needs to guarantee a positive profit stream for the buyer to continue the EOR project. We construct a "Contract Timing" variable for the empirical analysis to indicate the lag between the initial injection date and the contract effective date for the same field. Last but not least, it is necessary to control the buyer-seller

<sup>&</sup>lt;sup>14</sup>The oil prices are adjusted for inflation, and the base month is March 2017. Moreover, if the effective date for a contract is 15<sup>th</sup> or earlier, the monthly oil prices used to calculate the standard deviation will include this month. If the effective date, however, is the 16<sup>th</sup> or later, the monthly oil prices used to calculate the standard deviation will exclude this month.

<sup>&</sup>lt;sup>15</sup>We use the natural logarithm of the net CO<sub>2</sub> utilization because the untreated data are too skewed.

relation and the general areas where the oil fields are located. To do so, two dummy variables are introduced. One is the "Affiliation" dummy variable, used to indicate whether the buyer and seller are affiliated or not. Of the 46 contracts, there are 22 contracts whose buyer and seller are affiliated. The other is the "Area" dummy variable, used to indicate whether the oil fields are located in the Permian Basin or not. Of the 46 contracts, only one contract has  $CO_2$  supplied to an area other than the Permian Basin. Table 7 shows a summary of the variables.

It is important to note that the theoretical model assumes that the seller has full information about the oil field's net  $CO_2$  utilization and the oil price distribution for the contract duration. Realistically speaking, since the seller at best has limited knowledge about this information, it may lead to some discrepancy when testing the predictions of the theoretical model using real-world contract data.

In general terms, the model we estimate can be written as

$$b_i = \alpha_0 + \alpha_1 \text{Affiliation}_i + \alpha_2 \text{Area}_i + \alpha_3 p_i + \alpha_4 \text{Vol}_i + \alpha_5 T_i + \alpha_6 \log \delta_i + \epsilon_i, \quad (1)$$

	peggg e.				
Variable	Obs.	Mean	Std. Dev.	Min	Max
Pegging Coefficient	46	.0189043	.0093721	.0061	.04
Std. Dev. – Past One Year	46	.2974696	.2563329	.108	1.428
Std. Dev. – Past Two Year	46	.3615478	.2413624	.1798	1.1966
Std. Dev. – Past Three Year	46	.4898609	.2226204	.3005	1.105
Net CO <sub>2</sub> Utilization (Mcf/bbl)	39	7.336428	10.77578	.000119	45.93607
Contract Timing (year)	46	6.717391	6.094307	0	24
Contract Duration (year)	46	10.69565	5.206276	2	21
Total Contracted Quantity (Bcf)	46	122.5407	114.7132	.02	398
Daily Contracted Quantity (Mcf)	46	34,265.59	40,639.72	3.652968	191,506.8

Table 7. Summary of the price-pegging contracts.

Table 8. OLS regression of the pegging coefficient, against different initial oil prices.

$\begin{array}{c c c c c c c } (1) & (2) & (3) \\ \hline Pegging & Pegging & Pegging \\ Coefficient & Coefficient & Coefficient \\ Affiliation & 0.000252 & 0.000350 & 0.000275 \\ & (0.00316) & (0.00314) & (0.00317) \\ Area & -0.0242 ** & -0.0239 ** & -0.0239 ** \\ & (0.00950) & (0.00943) & (0.00950) \\ Contract Timing & 0.000145 & 0.000195 & 0.000186 \\ & (0.000298) & (0.000304) & (0.000308) \\ Log Net CO _2 Utilization & -0.000529 & -0.000478 & -0.000598 \\ & (0.000690) & (0.000689) & (0.000689) \\ Oil Price Volatility & 0.00146 & 0.00162 & 0.00184 \\ (Past Year Appual Volatility) & (0.00186) & (0.00187) \\ \end{array}$	2	1 33 3		
$\begin{array}{c c c c c c c } & \begin{tabular}{ c c c c } & \begin{tabular}{ c c c c c } & \begin{tabular}{ c c c } & \begin{tabular}{ c c $		(1)	(2)	(3)
$\begin{array}{c cccc} & Coefficient & Coefficient & Coefficient \\ Affiliation & 0.000252 & 0.000350 & 0.000275 \\ & (0.00316) & (0.00314) & (0.00317) \\ Area & -0.0242^{**} & -0.0239^{**} & -0.0239^{**} \\ & (0.00950) & (0.00943) & (0.00950) \\ Contract Timing & 0.000145 & 0.000195 & 0.000186 \\ & (0.000298) & (0.000304) & (0.000308) \\ Log Net CO _2 Utilization & -0.00529 & -0.000478 & -0.00598 \\ & (0.000690) & (0.000689) & (0.000689) \\ Oil Price Volatility & 0.00146 & 0.00162 & 0.00184 \\ (Past Year Appulal Volatility) & (0.00186) & (0.00187) \\ \end{array}$		Pegging	Pegging	Pegging
Affiliation $0.000252$ $0.000350$ $0.000275$ $(0.00316)$ $(0.00314)$ $(0.00317)$ Area $-0.0242^{**}$ $-0.0239^{**}$ $-0.0239^{**}$ $(0.00950)$ $(0.00943)$ $(0.00950)$ Contract Timing $0.000145$ $0.000195$ $0.000186$ $(0.000298)$ $(0.000304)$ $(0.000308)$ Log Net CO 2 Utilization $-0.00529$ $-0.000478$ $-0.00598$ $(0.000690)$ $(0.000689)$ $(0.000680)$ $(0.000680)$ Oil Price Volatility $0.00146$ $0.00182$ $0.00184$ (Past Year Appual Volatility) $(0.00186)$ $(0.00187)$ $(0.00187)$		Coefficient	Coefficient	Coefficient
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Affiliation	0.000252	0.000350	0.000275
Area         -0.0242 **         -0.0239 **         -0.0239 **           Contract Timing         0.00950)         (0.00943)         (0.00950)           Contract Timing         0.000145         0.000195         0.000186           (0.000298)         (0.000304)         (0.000308)           Log Net CO 2 Utilization         -0.00529         -0.000478         -0.00598           (0.000690)         (0.000689)         (0.000680)         (0.00080)           Oil Price Volatility         0.00146         0.00162         0.00184           (Past Year Appual Volatility)         (0.00186)         (0.00187)         (0.00187)		(0.00316)	(0.00314)	(0.00317)
(0.00950)         (0.00943)         (0.00950)           Contract Timing         0.000145         0.000195         0.000186           (0.000298)         (0.000304)         (0.000308)           Log Net CO 2 Utilization         -0.000529         -0.000478         -0.000598           (0.000690)         (0.000689)         (0.000689)         (0.000689)           Oil Price Volatility         0.00146         0.00162         0.00184           (Past Year Appual Volatility)         (0.00186)         (0.00187)         (0.00187)	Area	-0.0242 **	-0.0239 **	-0.0239 **
Contract Timing         0.000145         0.000195         0.000186           (0.000298)         (0.000304)         (0.000308)           Log Net CO 2 Utilization         -0.000529         -0.000478         -0.000598           (0.000690)         (0.000689)         (0.000680)         (0.000680)           Oil Price Volatility         0.00146         0.00162         0.00184           (Past Year Appual Volatility)         (0.00186)         (0.00187)         (0.00197)		(0.00950)	(0.00943)	(0.00950)
(0.000298)         (0.000304)         (0.000308)           Log Net CO 2 Utilization         -0.000529         -0.000478         -0.000598           (0.000690)         (0.000689)         (0.000680)         (0.000680)           Oil Price Volatility         0.00146         0.00162         0.00184           (Past Year Appual Volatility)         (0.00186)         (0.00186)         (0.00187)	Contract Timing	0.000145	0.000195	0.000186
Log Net CO 2 Utilization         -0.000529         -0.000478         -0.000598           0.000690)         (0.000689)         (0.000680)         (0.000680)           Oil Price Volatility         0.00146         0.00162         0.00184           (Past Year Appulal Volatility)         (0.00186)         (0.00186)         (0.00197)	2	(0.000298)	(0.000304)	(0.000308)
(0.000690)         (0.000689)         (0.000680)           Oil Price Volatility         0.00146         0.00162         0.00184           (Past Year Appulat Volatility)         (0.00186)         (0.00186)         (0.00197)	Log Net CO 2 Utilization	-0.000529	-0.000478	-0.000598
Oil Price Volatility         0.00146         0.00162         0.00184           (Pact Year Appulat Volatility)         (0.00186)         (0.00186)         (0.00197)	<u> </u>	(0.000690)	(0.000689)	(0.000680)
(Past Year Appual Volatility) (0.00186) (0.00186) (0.00197)	Oil Price Volatility	0.00146	0.00162	0.00184
(0.00100) $(0.00100)$ $(0.00100)$ $(0.00100)$	(Past Year Annual Volatility)	(0.00186)	(0.00186)	(0.00197)
Initial Oil Price 0.00108 **	Initial Oil Price	0.00108 **		
(One Month Average) (0.000468)	(One Month Average)	(0.000468)		
Initial Oil Price 0.00111 **	Initial Oil Price		0.00111 **	
(Two Month Average) (0.000459)	(Two Month Average)		(0.000459)	
Initial Oil Price 0.00105 **	Initial Oil Price			0.00105 **
(Three Month Average) (0.000457)	(Three Month Average)			(0.000457)
Constant 0.0183 0.0165 0.0182	Constant	0.0183	0.0165	0.0182
(0.0157) (0.0157) (0.0157)		(0.0157)	(0.0157)	(0.0157)
N 39 39 39	Ν	39	39	39
adj. R <sup>2</sup> 0.191 0.202 0.190	adj. R <sup>2</sup>	0.191	0.202	0.190

Standard errors in parentheses

\* *p* < 0.10, \*\* *p* < 0.05

where  $b_i$  is the pegging coefficient specified in the contracts, "Affiliation" is a dummy variable indicating whether the buyer and seller are affiliated, "Area" is a dummy variable indicating whether the CO<sub>2</sub> is supplied to the Permian Basin or not,  $p_i$  is the initial oil price and *Vol<sub>i</sub>* is the oil price volatility,<sup>16</sup>  $T_i$  is the time difference between the contract effective date and the initial injection date for the contracted field, and  $\delta_i$  is the net CO<sub>2</sub> utilization of the oil field associated with any specific contract.

Tables 8 and Tables 9 report the results of the OLS estimation of equation (1) with different initial oil prices and different oil price volatility. In both tables, the signs of the coefficients on the "Initial Oil Price" variable are consistent with the theoretical prediction that an increase in the initial oil price will result in a higher pegging coefficient. Specifically, when the oil price goes up by one dollar per barrel, the pegging coefficient increases by approximately 0.001. Considering that the average pegging coefficient is only 0.0189, this is a rather significant impact. If the real oil price goes up by 10 dollars per barrel, the regression result suggests that the pegging coefficient could go from 2% to almost 3% of the oil price. The significant impact of the initial oil price is also consistent with the theoretical study.

The signs of the coefficients on the "Oil Price Volatility" variable are positive when the annual oil price volatility is calculated based on the one or two years of oil prices prior to the contract effective date. The signs become negative when the annual oil price volatility is calculated based on the past three years of oil prices before the contract effective date. (Although not shown in Table 9, the signs are the same when using average oil price calculated based on the past one or two months of the oil prices before the contract effective date.) The theoretical model predicts that higher oil price volatility should have a positive effect on the

	(1)	(2)	(3)
	Pegging	Pegging	Pegging
	Coefficient	Coefficient	Coefficient
Affiliation	0.000275	0.000230	0.0000322
	(0.00317)	(0.00328)	(0.00313)
Area	-0.0239 **	-0.0232 **	-0.0217 **
	(0.00950)	(0.00966)	(0.00937)
Contract Timing	0.000186	0.000107	-0.000163
	(0.000308)	(0.000339)	(0.000320)
Log Net CO <sub>2</sub> Utilization	-0.000598	-0.000670	-0.000711
	(0.000680)	(0.000684)	(0.000667)
Initial Oil Price	0.00105 **	0.000872 *	0.000473
(Three Month Average)	(0.000457)	(0.000491)	(0.000425)
Oil Price Volatility	0.00184		
(Past Year Annual Volatility)	(0.00197)		
Oil Price Volatility		0.000774	
(Past Two Years Annual Volatility)		(0.00261)	
Oil Price Volatility			-0.00289
(Past Three Years Annual Volatility)			(0.00238)
Constant	0.0182	0.0228	0.0369 **
	(0.0157)	(0.0171)	(0.0162)
Ν	39	39	39
adj. R <sup>2</sup>	0.190	0.170	0.204

Table 9. OLS regression of the pegging coefficient, against different annual oil price volatility.

Standard errors in parentheses

<sup>16</sup>The theoretical work assume the changes of oil price can be described by Geometric Brownian motion, and is lognormally distributed (Agarwal, 2014; Gao & van 't Veld, 2021). The volatility of oil price therefore should increase as the contract duration increases.

<sup>\*</sup> *p* < 0.10,\*\* *p* < 0.05

pegging coefficient. The regression result may suggest that the seller focuses more on recent oil price volatility. However, since the estimated coefficients on volatility are not statistically significant, not too much should be read into them.

The signs of the coefficients on the "Log Net  $CO_2$  Utilization" are negative, consistent with the theoretical model's prediction. However, the estimated coefficients are not statistically significant. This may be largely due to the way the net  $CO_2$  utilization is calculated. Firstly, both the enhanced oil production given in the EOR surveys and the daily contracted  $CO_2$  is the average of the actual numbers. Secondly, as mentioned earlier, it is common for an oil field to have several active  $CO_2$  sales contracts simultaneously. Since we do not have access to all the active contracts for a certain period, this leads to an underestimated net  $CO_2$  utilization.

The signs of the coefficients on the "Contract Timing" variable are positive in most cases, suggesting that early  $CO_2$  supply contracts tend to have lower pegging coefficients. This result is consistent with the implication of the theoretical model. The coefficient to the "Affiliation" dummy variable suggests that the pegging coefficient would be marginally larger if the buyer and seller are affiliated. Although the estimated coefficient is not statistically significant, the sign does seem counter-intuitive, as one would expect affiliated firms to offer a price closer to the product's production cost to mitigate the double marginalization problem. The coefficient to the "Area" dummy variable suggests that the pegging coefficient in the Permian Basin is significantly lower compared with other regions. However, not too much should be read since there is only one contract outside the Permian Basin region.

#### 4. Conclusions

 $CO_2$  sales contracts used in the enhanced oil recovery industry vary greatly in various terms, such as the contracted quantity and price, contract length, effective date. Some contracts include a special price adjustment mechanism that pegs the  $CO_2$  price to the oil price. In other words, the  $CO_2$  price is defined as a percentage of the oil price. Using 103  $CO_2$  sales contracts, this article investigates when this price-pegging price adjustment mechanism is used and how the price pegging is affected by other contract terms. A probit regression shows that contract terms' length significantly increases the probability of price pegging being used. A shorter contract term implies that the oil price is less likely to have disruptive fluctuations. For price-pegging contracts, regression analysis of the pegging coefficients shows that higher initial oil prices, more volatile historical oil prices, and smaller net  $CO_2$  utilization are associated with high pegging coefficients. The regressions also suggest that contracts signed at the early stages of  $CO_2$  flooding tend to have lower pegging coefficients.

The  $CO_2$  -EOR industry has always been a niche market in the energy section. Nevertheless, it never stops growing over the years. Even under the shadow of the shale revolution, the number of  $CO_2$  -EOR projects in the U.S. has increased from 136 in 2014 to 150 in 2018 (EIA, 2018; Koottungal, 2014). Compared with other EOR techniques, its role in CCUS gives  $CO_2$  -EOR a special advantage. This is especially true once anthropogenic  $CO_2$  becomes a viable source for  $CO_2$  -EOR, which will likely happen given high enough oil prices or the right amount of policy support. 816 🕒 S. GAO ET AL.

Currently, about 80% of the  $CO_2$  supplied to the Permian Basin is from natural sources that are rapidly depleting. The gap between the growing demand and the declining supply of natural  $CO_2$  can only be filled by anthropogenic sources (GCCSI, 2011; Kuuskraa & Wallace, 2014). There are 12 industrial  $CO_2$  sources supplying 0.7 Bcf per day or about 20% of  $CO_2$  used for EOR. Anthropogenic  $CO_2$  is expected to increase to 2.1 Bcf per day, accounting for more than 40% of  $CO_2$  used for EOR. With the huge coal reserves in the U.S. and the growing interests in clean coal energy,  $CO_2$  captured from coal-fired power plants may be the most promising anthropogenic source of  $CO_2$  for EOR.<sup>17</sup>

The transition from natural CO<sub>2</sub> to anthropogenic CO<sub>2</sub> has several important implications. Firstly, the increased number of CO<sub>2</sub> sellers will reduce the market concentration and thus reduce sellers' bargaining power. Secondly, a large up-front investment for CO<sub>2</sub> capturing equipment is needed to produce anthropogenic CO<sub>2</sub>. This transaction-specific investment becomes a sunk cost and weakens the CO<sub>2</sub> seller's ex-post bargaining power. Thirdly, anthropogenic CO<sub>2</sub> captured from the air or biomass combustion has a significantly larger production cost per unit than CO<sub>2</sub> extracted from natural deposits. Therefore, the break-even prices of anthropogenic CO<sub>2</sub> sellers will be higher than those of natural CO<sub>2</sub> sellers. All things considered, compared with sellers of CO<sub>2</sub> from natural sources, the sellers of anthropogenic CO<sub>2</sub> will most likely be in a much weaker position in terms of bargaining power. Consequently, long-term contracts that peg the CO<sub>2</sub> price to the oil price should still be favored during and after this transition because of the reduced contract breaching risk and increased efficiency. However, the weaker bargaining position and the higher production cost suggest possibly lower pegging coefficients for anthropogenic CO<sub>2</sub>, complemented by a high price floor.

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<sup>&</sup>lt;sup>17</sup>The Petra Nova project in Texas is currently the only coal-fired power plant that captures CO<sub>2</sub> from coal combustion. According to its owners, NRG Energy and JX Nippon Oil & Gas Exploration Corp., the plant can capture over 90% of its CO<sub>2</sub> emitted or over one million tons per year. The captured CO<sub>2</sub> is transported to the West Ranch oil field 80 miles away, where it is used for CO<sub>2</sub> -EOR.

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