ENHANCED OIL RECOVERY (EOR) AS A STEPPING STONE TO CARBON CAPTURE AND SEQUESTRATION (CCS)

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Abstract

Fossil fuels promise continuous domination of the global energy mix with mounting carbon emissions and climate threat for decades to come. While the growth of enhanced oil recovery that utilizes CO_2 (CO_2-EOR), especially in the US, has been curbed primarily because of limits on accessibility to affordable supplies of CO_2. Environmental concerns about carbon emissions coupled with the oil industry's need to secure additional CO_2 for EOR has sparked interest in the potential CO_2-EOR may have in jumpstarting carbon capture and sequestration (CCS). We build on the limited previous work by combining robust engineering and economic policy aspects to investigate the practicality of wide scale implementation of CCS when partnered with CO_2-EOR also focusing on the transition from CO_2-EOR to solely carbon sequestration on a single field level.

We develop a unique two-stage dynamic optimization model that tracks total carbon movements during the CO_2-EOR process and continued sequestration after oil production has ceased. Our model of a profit maximizing producer at a single field level quantifies the impacts of various oil and carbon prices on the timing of the transition from CO_2-EOR to solely carbon sequestration and volumes of carbon sequestration across both stages. Total volumes of captured CO_2 sequestered across both stages is on the order of a hundred thousand tonnes, which is equivalent to 30% to 40% of the emissions from the use of the oil produced as part of the project, resulting in lower emissions level relative to pre-policy implementation levels. Our results show that policies that would promote this transition could enhance profits to producers while benefiting the global community.

I Introduction

The International Energy Agency (IEA) has pointed out that emissions from continued use of fossil fuels at current rates of consumption could increase average global temperature by more than 3.5°C by 2100. CCS' technical viability and capability of abating immense amounts of this CO_2 per year make it a strong contender in mitigating these emissions. Yet, commercial deployment of CCS has been stunted from the lack of any significant carbon price coupled with the high cost of implementation, technological uncertainties in performance for large scale stationary sources and the absence of guaranteed storage sites. At the same time, the oil industry's infrastructure, expertise, and decades of experience in separating, transporting, injecting and sequestering CO_2 in underground oil reservoirs makes it a logical partner in improving commerciality of CCS (IEA, 2014).

Shifting to a world where atmospheric disposal of CO_2 is no longer free, policy makers, who will be influencing CO_2 prices, and oil companies, which will be reacting to them, all need more knowledge of the potential role that CO_2-EOR transitioning to full scale CCS might play. As such, there exists an opportunity for a CO_2 market to develop where carbon capture facilities supply the CO_2 to EOR projects. Then CO_2 typically considered a negative externality that needs to be regulated would have a market that values it as an input in production.

Published work highlighting the viability of CCS when coupled with EOR have generally placed more focus strengthening one aspect: engineering or economic policy. Furthermore, associated modelling efforts presented stop at the end of the productive life of the field. Most engineering studies focus on the technical aspects of the design of the CO_2-EOR project to produce the maximum amount of oil while simultaneously storing the most CO_2 with the economics as an afterthought. While most economic studies found have focused on a singular aspect of the issue such as impacts of exogenously varying injection rates. We found only one study

(Leach et al. (2011)) that simultaneously modeled engineering and economic policy aspects of the co-optimization of CO_2-EOR and CCS in a dynamic optimization framework. Nonetheless, as highlighted by van't Veld et. al (2014), although qualitatively the results of the Leach et al paper was sound the technical assumptions related to the CO_2-EOR process needed enhancing. We build on the limited previous work by combining robust engineering and economic policy aspects to investigate the practicality of wide scale implementation of CCS when partnered with CO_2-EOR also focusing on the transition from CO_2-EOR to solely carbon sequestration on a single field level.

To explore the potential transition from CO_2-EOR to full CO_2 sequestration, we build on Leach et al.'s (2011) dynamic optimization model that evaluates the impacts of a tax policy on producer's profits. Unlike Leach et al's model, our model tracks total carbon movements and profits during the CO_2-EOR process, when the companies first extract from natural accumulations of CO_2 and then transition to captured sources. We also include a second stage beyond oil production activities when the companies are only sequestering captured CO_2. In our model, the government introduces market forces with a carbon tax for emissions and use of CO_2 from natural accumulations as well as a carbon subsidy for sequestration. Our model identifies and quantifies relevant factors that lead to the transition from CO_2-EOR to CCS. This two-stage dynamic optimization enables us to evaluate the producer's responsiveness to oil price and carbon policy, which will dictate how to value optimize use of both oil and pore space. It also allows us to endogenize the time, CO_2 and pore volume usage.

In the first stage, the oil producer maximizes profits by optimizing the choice of using CO_2 extracted from natural CO_2 reservoirs or captured sources to achieve their optimal CO_2 injection rate. The carbon tax penalizes the producer for every unit of CO_2 emitted when their oil is consumed as well as every unit of CO_2 they extract from natural sources during operations. The producer is credited for every unit of CO_2 they sequester in the EOR process. This stage allows us to simulate oil production, CO_2 usage and sequestration by source to the end of the productive life of the field subject to an oil stock constraint, natural CO_2 stock constraint and reservoir capacity constraint. Tracking the consumption of CO_2 from both natural and captured sources under increasing levels of carbon tax shows a transition from usage of natural CO_2, currently the most common and cheapest source of CO_2, to captured CO_2. The second stage involves extending the model beyond oil production activities. The oil producer maximizes profits from selling pore space for sequestration of captured CO_2 via their optimal CO_2 injection rate subject to a reservoir capacity constraint. Our reservoir capacity constraint in this stage is a function of cumulative oil production resulting from our first stage. This stage allows us to simulate CO_2 sequestration beyond oil production activities during which all production wells are capped and CO_2 is injected into the reservoir with no physical outlet.

Our model allows us to evaluate implications of changes to oil price and tax levels on the operator's decisions relating to the co-management of their state variables (non-renewable assets: oil and pore volume). Knowing that their historical oil production methods will influence pore volume availability, of value to us is the evolution of pore space availability across both stages which dictate how much CO_2 they can sequester. We also track the usage and sequestration of CO_2 from various sources to appropriately account for reductions in emissions.

The remainder of the paper is organized as follows: Section II provides a brief background about technical aspects of both stages: CO_2-EOR and continued sequestration after oil production has ceased (which we will designate as CCS). Section III describes and justifies the model used. Section IV details the numerical simulation results and their significance in quantifying CO_2-EOR's contribution to CCS. Conclusions and future work are presented in section V.

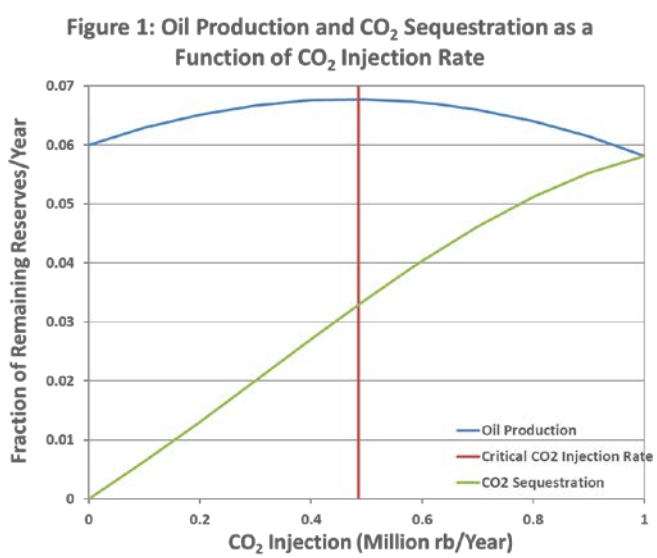
II Background

The three phases of oil recovery are: primary, secondary and tertiary. In the primary phase, no fluids are injected into the reservoir to assist in oil production. Oil produced makes pore space available for future use. In the secondary and tertiary phases, injected fluids provide necessary pressure support and help sweep oil left in the pore space. In our case, CO_2-EOR, injected CO_2 aids in reducing the viscosity of oil, increasing its mobility while providing needed pressure support. Injected CO_2 can dissolve into the oil or reservoir fluid, fill part of the pore space left by the oil produced, or cause a geochemical reaction with the reservoir rock. Since, CO_2 in the reservoir is at a much higher pressure than at the surface its volume can be reduced to about half of its surface volume (Donaldson, 1985).

During the CO_2-EOR process, an injection process called water alternating gas (WAG) is gaining significant popularity for improving oil recovery. The alternating injection of water and CO_2 to enhance oil recovery has the advantage of coupling the improved displacement efficiency of gas flooding with the improved macroscopic sweep efficiency of water injection. The result is an improvement in recovery compared to separate gas or water injection schemes. Water flooding sweeps most of the reservoir leaving a smaller amount of oil behind compared to CO_2, which can finger around some of the oil and leave it behind. On the other hand, CO_2 dissolves into the oil reducing its viscosity and allowing for easier mobility of the oil in the reservoir and subsequently to surface (Verma, 2015). Higher CO_2 injection levels will increase the incremental oil production, relative to the case of no CO_2 injection, until it reaches a critical injection rate beyond which the magnitude of the incremental production declines. We observe diminishing marginal benefits with increases in CO_2 injection resulting from fluid dynamics within the reservoir commonly the CO_2 bypassing the oil in place (Donaldson, 1989).

Oil wells usually reach the height of their production shortly after they are brought on-stream. Soon after a decline in production over time is observed mainly resulting from a depleting pressure drive. The rapidity of decline depends on several factors that include reservoir characteristics and choice of recovery techniques. This observed decline in production can be estimated by a decline rate function that links oil production to remaining reserves (Fetkovich, 1996). In our model we emulate a WAG process thus our total rate of injection, $q_i(t)$, is the summation of both water and CO_2 injected at a given point in time. The decline rate function in the model is represented by δ(c(t)). δ(c(t)), a function of both CO_2 and water injection, allows us to measure the impact of total injection on oil production in each time period. δ(c(t)) can also be viewed as the recoverable fraction of oil resulting from the injection process. Oil production declines over time because we produce a fraction of a declining pool of reserves with time. Our resulting oil production function (δ(c(t))*R(t)) is defined as the product of the decline rate function and remaining reserves at a given point in time.

The injected CO_2 that has not dissolved in the oil will begin to occupy the pore space made available by the oil it displaces. We assume that every reservoir barrel of oil displaced by CO_2 will allow for equivalent volume of CO_2, also measured in rb, to occupy the freed pore space. Assuming that the volume of oil displaced by each of the injected fluids is proportional to the fraction of each fluid in the total injection stream, our resulting CO_2 sequestration function becomes ($\frac{c(t)}{q_i(t)}$*δ(c(t))*R(t)) the product of the fraction of CO_2 in the total injection volume and oil production. It should be noted that all injected and produced volumes have been converted to reservoir barrel equivalent. We also normalized our total injection and production streams to 1 million reservoir barrels per unit of time for modelling purposes. As such, our CO_2 sequestration function becomes c(t)*δ(c(t))*R(t).



Given the parameterization of our model, figure 1 shows a static snapshot of the resulting oil production and CO_2 sequestration rates associated with different CO_2 injection rates given a reserves value of one. We see increases in oil production associated with higher injection up till the critical value identified by the red line. The critical value of CO_2 injection, for our model setup and parameterization, is 0.485 million rb/year. It should be noted that the optimal CO_2 injection rates considering associated revenues and costs will be lower than this critical value. This indicates that the producer is dynamically optimizing and continuously balancing revenues against cost over the life of the project.

III Methodology

Leach et al (2011) use a field level optimal control model to evaluate how a CO_2-EOR producer can maximize the net present value of an EOR project (π) through the choice of the optimal rate of CO_2 injection (c(t)), constrained by a fixed oil stock (R(t)). They include a tax policy where the producer pays a tax (τ) for produced oil according to the amount of CO_2 emitted when the oil they produce is consumed and credits them for each unit of CO_2 they sequester. Their model determines the economic productive field life along with the optimal CO_2 injection, oil production and sequestration profiles. In doing so, Leach et al.'s model endogenizes oil production decline, which is a function of the CO_2 injection rate as well as the optimal time to terminate the project.

The model used in this paper builds on the Leach et al. model extending it in several ways in addition to tracking usage of CO_2 from multiple sources. We add a second stage to the dynamic optimization modelling activities after oil production stops. This enables us to evaluate the transition to only CCS and the producer's responsiveness to the price of oil and a modified carbon policy through the transition. We use a reservoir simulation model to help us verify and achieve realistic representations of injection, production and sequestration profiles across both stages of our dynamic optimization model. The simulation allows us to appropriately characterize the fluid dynamics in the reservoir; more specifically how CO_2 injection influences oil production and sequestration during the EOR process and continued sequestration once production has ceased. Similarly, we start at an individual field level to develop an appropriate base to later scale up to a regional level.

The reservoir simulation model used in the study is based on the theory of material balance requiring the conservation of energy, mass and momentum. We start with a basic static model assuming a flat homogenous 3D reservoir with rock and fluid properties equal in all grid blocks. The homogeneity of the reservoir will reduce the fingering effects of the CO2 from injector to producer, adding to the efficiency of the system. Eliminating the structural element by having no relief prevent phase segregation effects and eliminates gravity drainage giving us a more representative model and recovery results by eliminating noise from different elements. Translating the static model to a dynamic simulation model was done using Eclipse simulator. The model was subjected to pressure, production and injection rate constraints to produce a more realistic output mimicking observed behavior of actual field performance with a WAG injection process in our productive stage and subsequently assess storage capacity for CO_2 post production activities.

The simulation model's output was used to construct the equations used in the dynamic optimization model. Sensitivity runs with different rock and fluid properties were performed to assist us in the construction of representative equations relating total injection to both our production and sequestration profiles in stage 1. While for stage 2, the simulation model results allowed us to estimate reservoir capacity for sequestration and assess limitations on CO_2 injection rates given the prescribed constraints such as fracture pressure. So even though the general structure of our first stage mirrors that of Leach et al., the coefficients or multipliers used to relate the production and sequestration profiles to CO_2 injection are modified, specifically via the decline rate function $\delta(c(t))$. Our second stage is a completely new construct which we added to the dynamic optimization model.

The oil producer in our first stage maximizes profits by optimizing the choice of using CO_2 from natural (q_{NR}) or captured sources (q_{CAP}) to achieve their optimal CO_2 injection rate which impacts both oil production (q_p^o) and CO_2 sequestration (q_s^c). The carbon tax penalizes the producer for every unit of CO_2 emitted when their oil is consumed as well as every unit of CO_2 they extract from natural sources during operations. The producer is credited for every unit of CO_2 they sequester in the EOR process. This stage allows us to simulate oil production,

CO_2 usage and sequestration by source to the end of the economically productive life of the field subject to a known oil stock constraint (R(t)), natural CO_2 stock constraint (X(t)) and reservoir capacity constraint (S(t)). Tracking the consumption of CO_2 from both natural and captured sources under increasing levels of carbon tax shows a transition from usage of natural CO_2, currently the most common and cheapest source of CO_2, to captured CO_2.

The second stage involves extending the model beyond oil production activities. The oil producer maximizes profits from selling pore space for sequestration of captured CO_2 via their optimal CO_2 injection rate subject to a reservoir capacity constraint. Our reservoir capacity constraint in this stage is a function of cumulative oil production resulting from our first stage. This stage allows us to simulate CO_2 sequestration beyond oil production activities during which all production wells are capped and CO_2 is injected into the reservoir with no physical outlet.

The producer switches from one stage to the next when the total benefits that can be obtained from sequestering CO_2 is more than the total benefits that can be obtained during CO_2-EOR. This decision is affected by the interaction between geological, technical and market conditions. The major findings relate to the optimal time of switch from one stage to the other, total volumes of captured CO_2 sequestered and how both are influenced by the tax and oil price levels set in the first stage. The intent is to be able to inform policy makers how to design policy in the presence of a market for CO_2. Presented below is the optimal control set up for our model as well as a table defining variables and parameters used.

Variables	
$q_p^o(t)$ = Oil produced at time 't' $q_r^c(t)$ = CO_2 recycled at time 't' $q_s^c(t)$ = CO_2 sequestered at time 't' $q_{NR}^c(t)$ = Amount of CO_2 purchased from natural reservoirs at time 't'. $q_i(t)$ = Total Injection at time 't'.	**Choice Variables:** $c(t)$ = CO_2 injection rate at time 't'. $q_{CAP}^c(t)$ = Amount of CO_2 purchased from captured sources at time 't'. **State Variables:** $R(t)$ = Stock of oil at time 't' $X(t)$ = Stock of natural CO_2 at time 't' $S(t)$ = Amount of CO_2 sequestered at time 't'
Parameters	
p_o = Price of oil p_p = Price of pore space τ = Carbon tax β = induced tax liability for a one dollar increase in the carbon tax.	w_{NR} = Price of CO_2 extracted from natural reservoirs w_{CAP} = Price of CO_2 purchased from captured sources w_r= Cost of a recycled unit of CO_2 F = Total fixed costs include all other costs outside of what is associated with CO_2 purchases and recycling.

Stage 1: CO_2-EOR

$$\max \pi = \int_0^{t_1} e^{-rt}\left([p_o - \beta\tau]q_p^o(t) - w_{CAP}q_{CAP}^c(t) - (w_{NR}+\tau)q_{NR}^c(t) - w_r q_r^c(t) + \tau q_s^c(t) - F\right) dt$$

$$s.t.: \dot{R(t)} = -q_p^o(t) = -\delta\big(c(t)\big)R(t)$$

$$\dot{X(t)} = -q_{NR}^c(t) = -\big(q_s^c(t) - q_{CAP}^c(t)\big) = -\Big(c(t)\delta\big(c(t)\big)R(t) - q_{CAP}^c(t)\Big) = q_{CAP}^c(t) - c(t)\delta\big(c(t)\big)R(t)$$

$$\dot{S(t)} = q_s^c(t) = q_{NR}^c(t) + q_{CAP}^c(t) = c(t)\delta\big(c(t)\big)R(t)$$

$$R(0) = R_o \;\&\; R(T) \geq 0$$

$$X(0) = X_o \;\&\; X(T) \geq 0$$

$$S(0) = 0 \;\&\; S(T) \geq 0$$

$0 \leq c(t) \leq 1$ million reservoir barrels/unit time

2nd Stage: Sequestration after CO_2-EOR

$$\max \pi = \int_{t_1}^{T} e^{-rt}\left((p_p)q_s^c\big(c(t)\big) - Fc(t)\right)dt$$

$$s.t.: \dot{S(t)} = q_s^c\big(c(t)\big) = c(t)$$

$$S(0) = Given \;\&\; S(T) \leq 1.2 * q_p^o(t) = \; 1.2 * \textstyle\sum_0^{t_1} \delta\big(c(t)\big)R(t)$$

$0 \leq c(t) \leq 1$ million rb per unit of time.

Consistent with reservoir engineering studies and the results of our reservoir simulation model, the decline rate function is concave with an interior maximum. It takes on the following quadratic form in the model similar to Leach et. al.: $\delta\big(c(t)\big) = \delta_w + \delta_1 c(t) - \delta_2 c(t)^2$. δ_w is a parameter representing the impact of a pure water flood on oil recovery and *c(t)* represents the rate of CO_2 injection at any given time '*t*'. The parameter values for δ_w, δ_1 and δ_2 are specific to the field being evaluated as the impacts of different recovery mechanisms will differ by reservoir. Our coefficients are based on the results of our reservoir simulation model.

We assume that the cost of captured CO_2 (w_{CAP}) is more expensive than CO_2 from natural sources (w_{NR}). Similar to the Leach et al. model, we assume that the cost of purchase of a unit of CO_2 from either source is more expensive than recycling a unit of CO_2 produced with oil (w_r) incentivizing the producer to recycle all the CO_2 produced with oil. The producer only purchases enough to compensate for the CO_2 sequestered in the EOR process. The tax policy introduced in the model is also an added incentive to recycle the CO_2 rather than vent it. The parameter β, presented in the model, describes the effect that the tax will have on the oil price received by the producer. This parameter absorbs the tax incidence on producers and includes the appropriate conversion reflecting the amount of CO_2 emitted in the usage of a barrel of oil. Prices and costs associated with the project are assumed to be exogenous and constant over the life of the project.

The Leach et al. model also treats non-CO_2 related operational costs as fixed. We carried through this cost characterization to identify the impacts of the model changes we made on CO_2 injection, sequestration and oil production. It should be noted that an upper limit on the sequestration capacity is not implemented during our first stage because the CO_2 sequestered as part of the EOR process will not occupy all the available pore space in the reservoir. But, we do introduce a cap on sequestration in our second stage, which ties to the cumulative production resulting from the first stage. We also introduce q_{CAP}(t), the amount of CO_2 from captured sources purchased and used as a choice variable in addition to the rate of CO_2 injected which was used by Leach et al. We additionally limit CO_2 injection rate to a specific range in both stages. In the first stage, we need to ensure a certain injection rate that will allow for the dissolution of CO_2 in the oil, thus inducing oil production. In the second stage, we need to ensure that our injection rate is capped as not to fracture the reservoir or seal.

In the first stage, the model solves for the producer's optimal usage of CO_2 from each source for the optimal CO_2 injection rate. Upon determining the producer's optimal usage of CO_2 from each source, the model can also determine the amount of CO_2 sequestered from each source along with the optimal time path of oil production. The second stage, allows us to observe how quickly the operator sells and occupies the existing pore space post production activities given the constraints on both injection rate and sequestration capacity. The importance of this model in addition to what each stage gives us on a singular basis is what it tells us in terms of optimal switching times from one stage to the other and total volumes of CO_2 sequestered by source.

IV Results and Discussion

While the policy implementation in the Leach et al. model encourages the producer to sequester CO_2, there is no distinction between CO_2 used from natural reservoirs and captured sources. Sequestration of CO_2 from natural sources provides no net benefit to the environment. By using CO_2 produced from underground reservoirs, we are adding CO_2 to the existing stock that needs to be sequestered. Given the distribution of CO_2 supply in the

US, most active CO_2-EOR projects make sole use of the lower cost CO_2 from natural sources or some combination of natural and captured CO_2 depending on location (NETL, 2014).

The model presented in this paper measures how the producer responds to a tax policy that encourages use and sequestration of captured CO_2. The policy ensures the transition from usage of natural CO_2 to captured CO_2 in the EOR process providing the needed benefit to the environment without significantly impacting the supply of oil. It additionally ensures the transition to continued sequestration beyond oil production activities allowing for the evaluation of changes to oil price and tax levels on the operator's decisions relating to the co-management of their non-renewable assets oil and pore volume. Knowing that their historical oil production methods will influence pore volume availability, of value to us is the evolution of pore space availability across both stages which dictate how much CO_2 they can sequester. We also wanted to track the usage and sequestration of CO_2 from different sources to appropriately account for reductions in emissions.

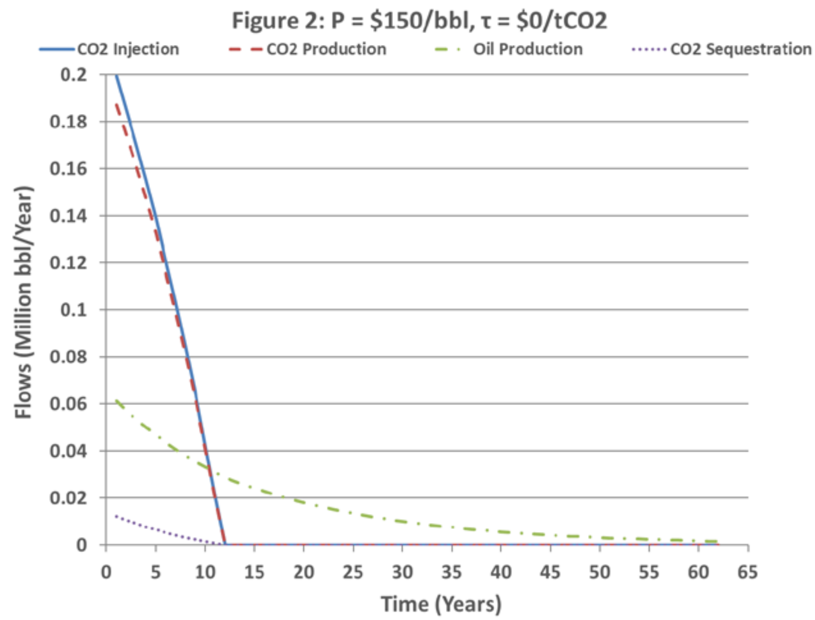
A series of numerical simulations, using the GAMS software, are conducted to solve for the optimal time paths of CO_2 usage from each source, oil production and how much CO_2 is sequestered from each source at various combinations of oil price and tax levels. Our simulation results also allow us to evaluate the timing of the switch from one stage to the next. We consider both oil price and tax level to be exogenous and remain constant over the life of the project. The simulations are run for several scenarios that include oil price levels of $50, $100, $150 and $200 per reservoir barrel of oil (rb) and for carbon tax levels of $0, $19, $20, $21, $80 and $120 per tonne of CO_2 (tCO_2). To ensure consistent units in running the numerical simulations quantities of oil and CO_2 are represented in reservoir barrels. Our results are obtained by running the simulations with the base case parameters tabulated below.

Base Case Parameter Values		
R_o	1	Initial stock of oil in reservoir (million reservoir barrels)
X_o	1	Initial stock of CO_2 in reservoir (million reservoir barrels)
W_{ind}	6	Per reservoir barrel cost of CO_2 obtained from captured sources ($)
W_{nr}	4	Per reservoir barrel cost of CO_2 obtained from natural reservoirs ($)
w_r	1	Per reservoir barrel cost of recycled CO_2 ($)
F	0.1	Fixed Costs (million dollars)
β	2.2	Incidence of the carbon tax on the oil producer
r	0.05	Discount rate
δ_w	0.06	Intercept of $\delta(c)$ function
δ_1	0.0329	First coefficient of $\delta(c)$ function
δ_2	0.0348	Second coefficient of $\delta(c)$ function

Initial stocks of both oil and natural CO_2 are both normalized to one for modelling purposes. Given the current distribution of CO_2 supply, we assumed that the cost used by Leach et al. was a reasonable estimate of costs related to the handling of natural CO_2 (w_{NR}). We also introduce two new parameters: cost of captured CO_2 (w_{CAP}) and a natural CO_2 stock ($X(t)$). We assume that the cost of captured CO_2 is about 1.5 times the cost of natural CO_2 for lack of defined estimates of that cost.

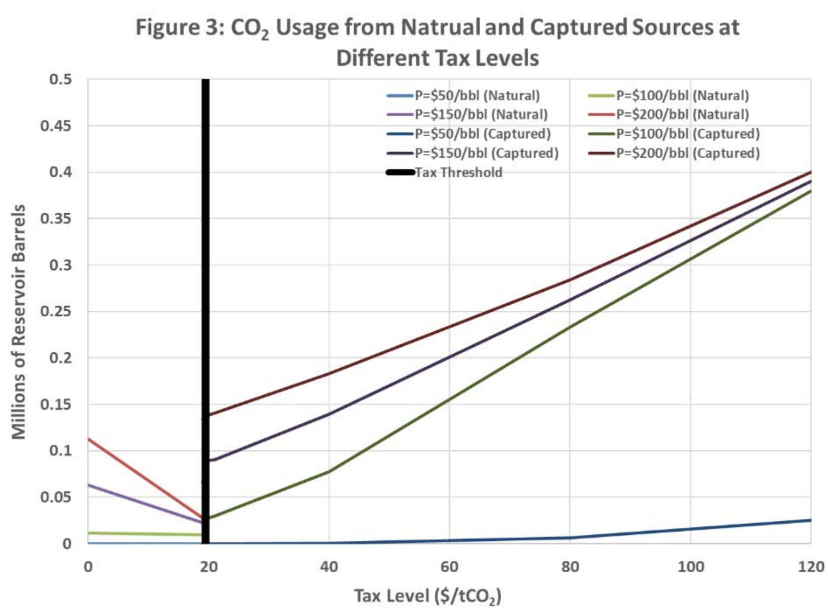
We start with the characterization of the resulting time paths of CO_2 injection, sequestration and oil production in stage one. The trends we observe for these profiles will remain the same but the magnitudes observed for each will be impacted by price, costs and policy. CO_2 injection rates will decline with time until it reaches zero at which point the producer will continue extracting oil via a pure water flood scheme until their economic limit is reached. The reduction in the CO_2 injection rates with time can also be viewed as a reduction in the marginal product of CO_2 because of reduced associated oil production.

Oil production declines over time because we produce lower fractions of a declining reserves pool at subsequent points in time. This necessary decline in oil production leads to less pore volume available to be occupied by CO_2, resulting in less CO_2 sequestration during the CO_2-EOR process. The decline in oil production and CO_2 sequestration also necessitates decline in the CO_2 injection rate. Figure 2 shows CO_2 injection, sequestration and oil production rates over the life of the project at an oil price level of $150/bbl and no carbon tax.

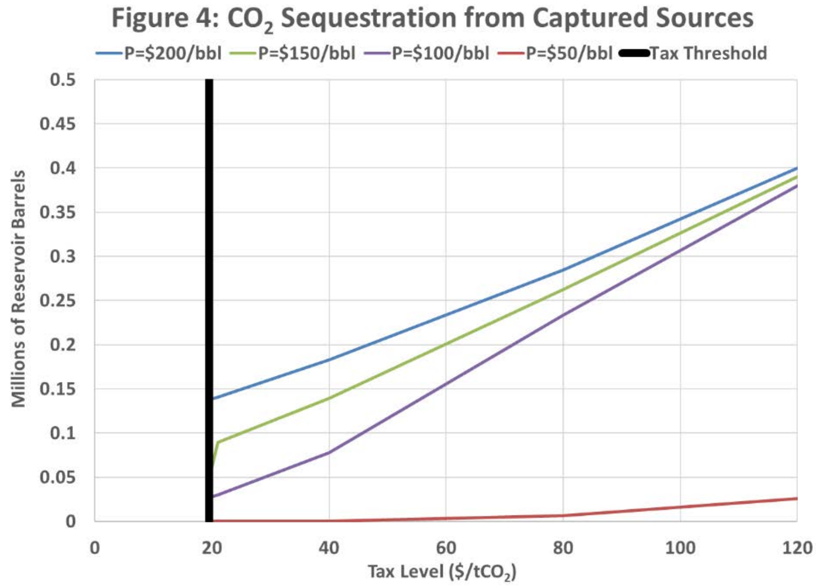


Impact on Timing of Switch, CO_2 Usage and Sequestration across Both Stages

Adjusting the Leach et al policy to penalize the producer for every unit of natural CO_2 used is effective in encouraging the producer to transition from sole use of natural CO_2 to sole use of captured CO_2 in stage 1. Under the assumption that CO_2 from both sources are perfect substitutes, the tax threshold above which the producer switches from sole use of natural CO_2 to sole use of captured CO_2 is equal to the difference in price between captured and natural CO_2. Figure 3 shows the change in CO2 usage from each source at different price levels and varying tax values. Natural CO_2 usage declines with increases in tax levels up to the tax threshold because the credit they receive for sequestering CO_2 gets negated by the tax they have to pay for every unit of natural CO_2 they use. Above the threshold captured CO_2 usage increases with higher tax levels. The revenues accrued to the producer from CO_2 sequestration provide the needed incentive to increase CO_2 usage which will positively impact sequestration.

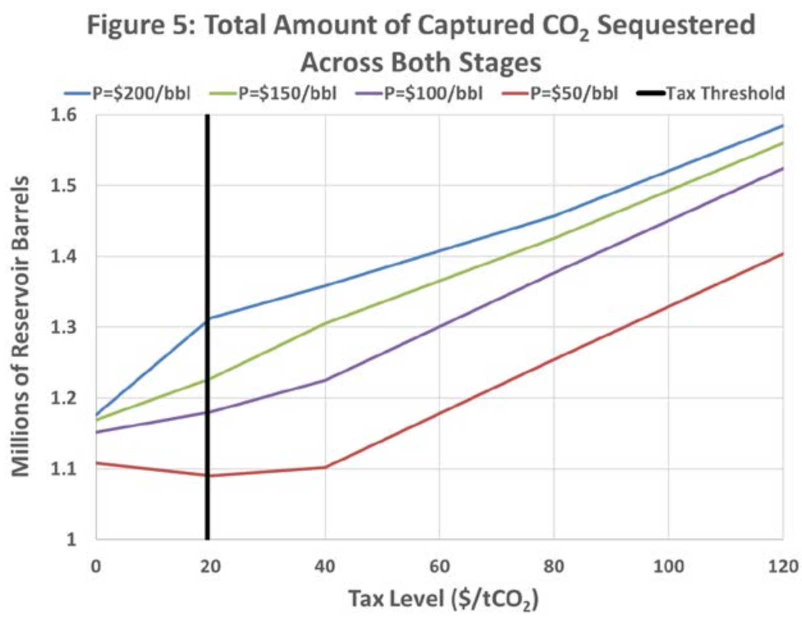


We consequently see a significant jump in net sequestration above the tax threshold. Figure 4 shows sequestration of captured CO_2 at different price levels and varying tax values. The jump in sequestration of captured CO_2 at tax levels above the threshold is attributed to the transition to sole use of captured CO_2 at those tax levels. Model results suggest that the amount of captured CO_2 sequestered in the EOR process, stage 1, is on the order of hundreds of thousands of barrels which equates to tens of thousands of tonnes. Mirroring the Leach et al. results, we observe that at higher oil prices resulting in higher revenues make it optimal to increase CO_2 injection levels over the life of the project leading to increases in cumulative sequestration. With higher tax rates, initial CO_2 injection rates are increased but we also observe a more rapid decline in the injection rates over time which results in an accelerated switch to water flood. Nonetheless, the impact on cumulative sequestration is positive because the amount of CO_2 sequestered early on when injection rates were higher more than compensates for the lower sequestration later on due to reduced injection and earlier switch to water flood.



Leach et al. show that cumulative CO_2 sequestration does increase with increased oil price and tax levels, the main takeaway of their paper is that CO_2 injection and sequestration are more responsive to oil price than their carbon tax. The obvious implication is that policies raising the cost of CO_2 emissions may not induce the expected increase in magnitudes of CO_2 sequestration in the EOR process. Our model gives us the ability to track both sources of CO_2 usage and sequestration in the EOR process which has not been done before. As a result, comparisons of the amount of captured CO_2 sequestered resulting from our model with the status quo cannot be shown. Nonetheless, our model shows that small increases in the level of carbon tax can have a large impact on the amount of captured CO_2 sequestration. We will see a benefit, from a total carbon accounting point of view from making use of captured CO_2 in the EOR process. This quantification is necessary to give us a clear direction with regards to policy implementation.

The amount of CO_2 we can sequester in our second stage is a function of cumulative oil production resulting from the first stage. We assume in the second stage that the producer sells available pore space to facilities in need of storage space for their captured CO_2. As expected, total volumes of sequestered CO_2 across both stages eventually increases with higher tax rates as seen in figure 5. But at lower oil prices, we see the trend in volumes of captured CO_2 sequestered over both stages decrease until the tax threshold and then increase post the tax threshold. This can be explained by the fact that the burden of the tax at lower oil prices induces limited or no use of CO_2 in the production process leading to less cumulative oil production. Thus, leading to less sequestration across both stages because of the limited use of CO_2 and less cumulative oil production in stage one; releasing less space for sequestration in stage two.



Oil price and tax levels will also influence the timing of the switch from our first stage to the second. We find that at fixed price levels, but increasing tax rates the time of switch from one stage to the next is accelerated.

Increased tax accelerates oil production in the first stage which results in a quicker decline in oil production thus inducing the accelerated switch to the second stage where the operator can accrue greater profits from just sequestration. On the other hand at fixed tax levels, but increasing prices the time of the switch from stage one to two is delayed. Higher oil prices encourage longer production periods coupled with the volumes of oil produced and CO_2 sequestered outweigh potential benefits from our second stage for longer periods of time.

Results from applying the model to a single field show that sequestration of captured CO_2 is on the order of a hundred thousand tonnes across both stages. These results are from a single field, but when aggregated across all fields on a national or global level it can be significant relative to annual CO_2 emissions. Quantifying impacts of implemented policy are necessary in establishing that CO_2-EOR will have a positive role in promoting carbon capture and sequestration with minimal impact on oil production and associated economic activity.

V Conclusions and Future Work

We see a minimal impact on cumulative oil production because of our tax implementation as compared to the pre-tax levels. But we do observe an acceleration in oil production as a result of the trend of CO_2 injection at higher tax levels above the threshold described above. This raises the concern about whether this will negate the objective of the policy implementation by increasing associated CO_2 emissions levels relative to the pre-policy implementation. Our results show that even though we do see acceleration in oil production at higher tax levels above the threshold, net CO_2 emissions as a result of the policy implementation will be lower relative to pre-policy implementation levels. These results in conjunction with the minimal impact on oil production are a win-win situation for both the producer and the environment.

The results of the modelling work done on one field indicate that given the appropriate economic environment, CO_2-EOR can contribute to the promotion of CCS. The model developed appropriately values CO_2 emissions and reservoir pore space. The results of the model in conjunction with estimates of CO_2 demand for EOR purposes provide an appropriate foundation for future work. We aim to continue bridging the gap between engineering and economic policy aspects whilst providing an easy to use tool that allows for evaluation the practicality of wide scale implementation of CCS when partnered with CO_2-EOR.

We hope to expand this modelling work focusing on the nuances of how the producers co-manage both oil production activities and pore volume capacity resulting from the impacts of varying both market and reservoir parameters (i.e. reservoir maturity, size, and quality). We assume a regional modelling effort or analysis will inform us on how to allocate both natural and captured CO_2 volumes across a portfolio of hydrocarbon producing assets allowing us to evaluate the dynamics between both the oil and CO_2 markets now tied together by pore volume management. This future study includes the evaluation of the mechanics of supply and demand of CO_2 on a regional and global scale providing the basis for creating an international CO_2 market.

The possible investigations addressed above highlight the flexibility of the model constructed. The potential studies suggested go beyond quantifying CO_2-EOR's contribution to CCS. Those studies allow us to investigate whether there is sufficient storage capacity on a global scale to allow for the capture and sequestration of enough CO_2 to sustain current and future levels of human and industrial activity. The research highlights the importance of using existing knowledge and infrastructure in the pursuit of our environmental objectives. Significant technical and engineering study, in addition to data collection, will be required to investigate these possibilities and formulate the functional forms of the equations in the model.

References

Amigues, J., Lafforgue, G., Moreaux, M., 2014. Optimal Timing of Carbon Capture and Storage Policies Under Learning-By-Doing. IDEI Working Papers 824, Institut d'Économie Industrielle (IDEI), Toulouse.

Amigues, J., Lafforgue, G., Moreaux, M., 2014. Triggering the Technological Revolution Carbon Capture and Sequestration Costs. TSE Working Papers 14-479, Toulouse School of Economics (TSE).

Bandza, A. J., Vajjhala, S. P., 2008. Long-Term Risks and Short-Term Regulations: Modeling the Transition from Enhanced Oil Recovery to Geologic Carbon Sequestration. Resources for the Future RFF DP 08-29.

DiPietro, P., Balash, P., Wallace, M., 2012. A Note on Sources of CO_2 Supply for Enhanced Oil Recovery Operations. SPE Economics and Management.

Godec, M., Kusskraa, V., Van Leeuwen, T., Melzer, L. S., Wildgust, N., 2011. CO_2 Storage in Depleted Oil Fields: The Worldwide Potential for Carbon Dioxide Enhanced Oil Recovery. Energy Procedia 4, 2162 – 2169.

IEA Greenhouse Gas R&D Programme, 2005. A Review of Natural CO_2 Occurrences and Releases and their Relevance to CO_2 Storage. Report Number 2005/8.

Jessen, K., Kovscek, A.R., Orr Jr., F.M., 2005. Increasing CO_2 storage in recovery. Energy Conversion and Management 46, 293 – 311.

Manaar Energy Consulting and Project Management, 2013. EOR and IOR in the Middle East. Available at:http://www.manaarco.com/images/presentations/Fleming%20Gulf%20Manaar%20EOR%20Abu%20Dhabi%20March%202013.pdf (Accessed May 2015).

Moreno-Cruz, J., Kim, B., 2014. A Two Sided Carbon Story: Carbon Capture and Storage Enhanced Oil Recovery. The Selected Works of Juan B. Moreno-Cruz. Available at: http://works.bepress.com/morenocruz/17.

Kovscek, A.R., Cakici, M.D., 2005. Geological storage of carbon dioxide and enhanced oil recovery. II. Cooptimization of storage and recovery. Energy Conversion and Management 46, 1941 – 1956.

Kusskraa, V., Godec, M., Dipietro, P., 2013. CO_2 Utilization from "Next Generation" CO_2 Enhanced Oil Recovery Technology. Energy Procedia 37, 6854 – 6866.

Leach, A., Mason, C. F., van't Veld K., 2011. Co-optimization of Enhanced Oil Recovery and Carbon Sequestration. Resource and Energy Economics 33, 892 – 912.

Melzer, L. S., 2012. Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery. National Enhanced Oil Recovery Initiative, Center for Climate and Energy Solutions.

National Energy Technology Laboratory (NETL), 2014. Near-Term Projections of CO_2 Utilization for Enhanced Oil Recovery.

Nissen, D., 2008. Pricing and Policy for Carbon Capture and Sequestration with Learning by Doing. USAEE Working Paper No. 08-013. Available at: http://dx.doi.org/10.2139/ssrn.1302578.

Stigson, P., Hansson, A., Lind, M., 2012. Obstacles for CCS Deployment: An Analysis of Discrepancies of Perceptions. Mitigation and Adaptation Strategies for Global Change 17, 601 – 619.

Thronicker, D., Lange, I., 2014. Determining the Success of Carbon Capture and Storage Projects. Working Papers 2014-14, Colorado School of Mines, Division of Economics and Business.

U.S. Energy Information Administration (EIA), 2015. Annual Energy Outlook 2015. http://www.eia.gov/forecasts/aeo/. (Accessed on April 16, 2015).

van't Veld, K., Phillips, O. R., 2010. The Economics of Enhanced Oil Recovery: Estimating Incremental Oil Supply and CO_2 Demand in the Powder River Basin. The Energy Journal 31-3.

van't Veld, K., Phillips, O. R., 2009. Pegging Input Prices to Output Prices in Long-Term Contracts: CO_2 Purchase Agreements in Enhanced Oil Recovery. http://www.uwyo.edu/owenphillips/papers/co2pegging071509.pdf.

van't Veld, K, Wang, X., Alvarado, V., 2014. Economic Co-optimization of Enhanced Oil Recovery and CO_2 Sequestration. Paper SPE-170880-MS presented at the 2014 SPE AT&CE, The Netherlands. https://doi.org/10.2118/170880-MS