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

Dana M Abdulbaqi, Saudi Aramco, Dhahran, Saudi Arabia, Phone: +966505922276, Email: dana.abdulbaqi@gmail.com
Carol Dahl, Colorado School of Mines and Luleo Technical University, Phone: +1-303-273-3921, Email: cadahl@mines.edu
Mohammed AlShaikh, Saudi Aramco, Dhahran, Saudi Arabia, Phone: +96658534388, Email: moalalshaikh@gmail.com

Overview

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 CCS. We build on the study the practicality of wide scale implementation of CCS partnered with CO2-EOR to full scale CCS. We apply a unique two-stage dynamic optimization model that includes a carbon tax for emissions, which becomes a subsidy for sequestration. Our model tracks the response of total carbon movements and oil production, for a single field, during the CO_2-EOR process and continued sequestration after oil production has ceased.

Our model results suggest that small increases in the level of carbon tax can have large and discontinuous impacts on net sequestration. Total volumes of captured CO_2 sequestered across both stages is equivalent to 30% to 40% of the emissions from the use of the oil produced as part of the project. Moreover, because of the credits oil producers receive from sequestering CO_2, relatively high carbon taxes incentivize additional sequestration without significantly impacting the supply of oil and maintaining a steady stream of profits, a win-win situation for energy security and the climate.

Methods

We start with a basic static model assuming a flat homogenous 3D reservoir. We subsequently translate the static model to a dynamic simulation model using Schlumberger's simulator Eclipse. The inability to nest our reservoir simulation model in our dynamic optimization model because of the structural and time scale differences in both models necessitates an intermediate step. From the simulator's resulting production streams, we construct the equations used in our two-stage dynamic optimization model such as the equations relating total injection to both our production and sequestration profiles in stage 1. While for stage 2, the results allow us to estimate reservoir capacity for sequestration and assess limitations on CO2 injection rates given the prescribed constraints such as fracture pressure.

The reservoir simulation model allows us to predict the interaction and flow of fluids through the reservoir; mimicking observed behavior from actual field performance. Our simulation model was subjected to pressure, production and injection rate constraints to produce a more realistic output mirroring 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. We can predict more accurately how CO_2 injection influences oil production and sequestration during the EOR process as well as continued sequestration once production has ceased.

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 ($c(t)$) 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 also 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 ($S(t)$) that tracks pore volume availability. These variables also represent our state variables. 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 ($S(t)$). 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 and shed light on how inherent physical production constraints impact the producer's response to market mechanisms.

Results

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.

Higher tax levels induce higher CO_2 injection rates early on as compared to lower tax rates. But, will also induce a more rapid decline in CO_2 injection and thus an accelerated switch to pure water flood. As a result, we will see higher production early on at higher tax levels, resulting in a faster depletion of our reserves. So even though we may be injecting at a higher rate inducing higher recovery, after a period of time, we will be producing from a relatively smaller pool of reserves. This induces the producer to optimize their CO_2 injection rates and switch to water flood sooner, thus leading to lower production levels later in the life field for higher tax rates relative to lower tax rates or the no tax case. This results in a reduction in cumulative production at higher tax rates even though we were initially injecting more CO_2. Nonetheless, we will still see a positive impact on net CO_2 sequestration at higher tax rates above the threshold.

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 substantial 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.

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.

Conclusions

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.

References

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