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

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Overview

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

Methods

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. 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.

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 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.

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.

Results and Conclusions

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 to captured sources. Results, from our first stage, show the tax threshold above which we see the oil producer make the switch from using only natural CO_2 to only captured CO_2. We consequently see a significant jump in the sequestration of captured CO_2 at carbon taxes above the tax threshold. The implication for policy is that small increases in the level of a carbon tax can have large and discontinuous impacts on net sequestration. Moreover, because of the credits oil producers receive from sequestering CO_2, relatively high carbon taxes incentivize additional sequestration without impacting supply of oil, a win-win situation for energy security and climate policy.

The producer switches from one stage to the next if 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 especially since pore volume availability in stage 2 is dictated by the results of our first stage. 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 because of the policy implementation will be lower relative to pre-policy implementation levels.

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.

References

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