A Two Sided Carbon Story: Carbon Capture and Storage and Enhanced Oil Recovery[*]

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Abstract

We study the effects of a carbon emission tax on the interaction between carbon capture and storage (CCS) and enhanced oil recovery (EOR). We consider a CO_2 market where CCS firms sell their CO_2 to EOR firms that use this CO_2 as an input to their production process. In this economic environment, we find that the effectiveness of a carbon tax may be hampered. A carbon tax shifts out the supply curve of CO_2 leading to a decline in the market price of CO_2. With lower input price, oil firms are indirectly subsidized and oil production and emissions increase. Nonetheless, we show the total emissions from both CCS and EOR sectors are always decreasing in the carbon tax.

Because the structure of the CO_2 market depends on regional characteristics, we also examine how the distribution of market power across these two sectors influence CO_2 abatement, energy output, and total emissions. Contrary to the standard result in environmental economics, market power can lead to an increase in pollution. Our findings demonstrate that a carbon tax will have differential impacts across regions and that policy needs to be adjusted to control for the idiosyncrasies of each local market situation.

Keywords: Carbon Capture and Storage (CCS), Enhanced Oil Recovery (EOR), carbon emissions tax, climate change.

JEL Codes: H21, L50, Q32, Q40, Q54

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1 Introduction

Demands for cheap energy and a cleaner environment seem hard to reconcile. Fossil fuels production in the United States amounts to 73 quadrillion British thermal units (Btu) and is responsible for 4.6 GtCO2. Carbon capture, utilization, and storage (CCUS) has attracted substantial attention as it could allow for the use of cheap fossil fuels while keeping carbon dioxide emissions into the atmosphere in check (DOE-NETL, 2015). Yet, despite its promising contribution to addressing the perils of climate change, CCUS is one of the most underdeveloped technological paths towards deep decarbonization (Abdulla et al., 2020). While the technology itself is straightforward, there are barriers associated with the technical and financial viability of these CCUS projects that hamper their development (Herzong, 2017). These barriers come from four sources: technical capacity (Grant et al., 2021 (a)) and costs (Budinis et al., 2018, van der Spek et al., 2019), climate and energy regulatory uncertainty (Lipponen et al., 2017, Wang, Akimoto and Nemet 2021), increased availability of cheap renewable energy (Grant et al., 2021 (b)), and incipient industrial demand for CO2 [Martin-Roberts et al., 2021, Wang, Akimoto and Nemet 2021). All these different barriers point to one single outcome: an immature market for the product of the CCUS, namely carbon dioxide (CO2). The fact remains that we need a CCUS sector with the capacity to deal with approximately 1 GtCO2/year in the United States and around 14% of emissions worldwide. For CCUS to be deployed at an industrial scale commensurate with these climate needs, the product of CCUS cannot be waste disposal alone (i.e., geological sequestration), it needs to add value to society beyond emissions reduction [10]. The stream of CO2 needs to be incorporated in the economy as an input in the production process. With this idea in mind, my main research question is under which regulatory, economic and technical circumstances does a robust market for CO2 arise and what are the biggest threats to its development?

The main contribution of this work is exploring the market for CO2 with the goal of envisioning ways to increase the market potential for CCUS. It complements efforts on understanding the barriers in transportations, sequestration and storage (Lane, Greig, and Garnett, 2021) and possible solutions to those barriers (Waxman et al, 2021). This work also relates to the literature on the general equilibrium effects of a carbon tax and its interactions with other taxes in the economy (Bovenberg and Goulder 1996). Unlike the previous literature that concentrates on the distortionary effect of a carbon tax in other markets, here we concentrate on the effects in the market for CO2 as a productive input in the economy (Parry, Williams and Goulder, 1999). More generally, this work contributes to the CCUS research on social sciences, which until now has been dominated by research in engineering and technology leaving important questions unanswered (Buck, 2021).

Carbon capture and storage consists of separating and capturing the CO_2 contained in fossil fuels before they are emitted into the atmosphere and then permanently injecting this CO_2 underground (DOE 2012). The potential for CCS is quite large as technologies needed to separate and capture the CO_2 are constantly changing and improving (Gibbins and Chalmers 2008). CCS can reduce up to 88% of carbon emissions per MWh (Rubin, Chen, Rao 2007). The International Energy Agency has identified CCS as leading to at least 22 percent of the necessary reductions from industrial and power sources (IEA 2012).[1]

The carbon dioxide captured by CCS plants can then be stored and used as an input for Enhance Oil Recovery (EOR), a technique that allows recovering a substantially larger amount of oil in each deposit. For more than 40 years the oil industry has used enhanced oil recovery to increase the output of oil and gas reservoirs. According to the Carbon Capture and Storage Atlas (2012), the benefits of CO_2-enhanced oil recovery (EOR) are substantial: in 2010, “approximately 50 million metric tons of CO_2 per year from naturally occurring sources were used to recover additional oil.” The National Energy Technology Laboratory (NETL) estimated that in the United States, 17 billion metric tons of CO_2 would be needed to produce 60 billion barrels of oil by 2100 using next-generation EOR technology. Moreover, if oil prices continue to increase, the incentives to invest in EOR projects will be stronger (McCoy and Rubin 2009). According to Melzner (2012), however, the natural sources of CO_2 in the proximity of oil fields are quickly drying up; there is an opportunity to replace these shrinking sources with CO_2 captured from electricity and other large fixed sources of CO_2.[2]

As the natural sources of CO_2 used for EOR deplete, it is likely a market for CO_2

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[1] There are several types of storage: oil and gas reservoirs, saline formations, and basalt formations.

[2] Leach, Mason and van’t Veld (2011) provides an excellent overview of the EOR technology. Melzer (2012) also offers technical details of various factors involved in CCUS-EOR.

will develop where carbon capture facilities supply the CO_2 to EOR deposits. The market interaction between CO_2 sellers and its buyers can affect the effectiveness of a carbon tax in achieving environmentally efficient outcomes. Having such circumstance in mind, we address the following questions: How does a carbon tax interfere with the carbon dioxide market? And, how can we design a climate policy that encourages clean production while accounting for this interaction?

To address these questions we develop a parsimonious model where electricity and oil firms interact in a carbon market. Our approach is guided by at least three observations. Naturally occurring CO_2 is already used in EOR activities and pilot projects are being developed to test the techno-economic feasibility of CCS projects. Naturally occurring CO_2 in the proximity of EOR projects is running out while electricity generation occurs everywhere in the US. In addition, given considerable costs in shipping CO_2 to remote sites, the CO_2 market tends to be localized and its market structure will be crucially determined by the proximity of EOR and CCS firms.

Keeping these in mind, we build our model considering several key features. First, oil firms *demand* carbon dioxide for EOR activities while electricity generation firms *supply* this carbon via CCS activities. The CO_2 prices ultimately depend on the overall market structure which is primarily characterized by how many firms operate in each side of the market as sellers and buyers for CO_2. We consider three different market structures: a competitive market, a CCS monopoly and an EOR monopsony. Second, electricity and oil companies produce CO_2 as a by-product of their economic activities. We allow for emissions intensity to differ across sectors. Finally, the two sectors are subject to environmental regulation in the form of a carbon tax. Although the carbon tax is taken as given by the two sectors, it will affect the CO_2 market by altering the abatement decisions of electricity generation firms and the output decisions of oil producers.

Within this framework we identify several interesting results. Under the competitive market structure we find that the effectiveness of a carbon tax in reducing emissions is limited by the interaction between EOR firms and CCS firms. The introduction of a carbon tax creates incentives for CCS firms to increase their abatement activities which in turn results in an increase in the supply of carbon dioxide for EOR activities. Thus, a carbon tax introduces distortions in EOR firms' production activities *beyond* the direct tax effects associated with CO_2 capture and storage. In other words, a carbon tax may work as a subsidy to EOR firms by lowering the price of CO_2 used as an essential input by EOR firms. In addition, we find that whether or not this indirect subsidy results in higher emissions from EOR firms depends on the magnitude of the output response of EOR to changes in the carbon price and the emissions intensity of oil production. Nonetheless, we find that total emissions are always decreasing in the carbon tax.

Under the CCS monopoly, the electricity company reduces the supply of CO_2 in order to induce a higher price as EOR firms compete to obtain the scarce input. As in any monopoly situation, the price is higher under this scenario than under the competitive market structure. In terms of total emissions, we compare the total emissions in the CCS monopoly with those in the competitive market and find that a CCS monopoly, by restricting input to EOR firms, can help reduce total emissions. But, contrary to the standard result in environmental economics (Perman et al., 2003 pp 142-143 Figure 5.15), it can also increase emissions if the emissions intensity of the oil industry is high and the oil industry is not very effective at using CO_2.

We also consider an EOR monopsony, a single buyer of CO_2. In this case, the monopsonist reduces its oil output reducing its demand for CO_2. This, in turn, increases the value of its storage. CCS firms now compete for this scarce storage by reducing the price they charge to the EOR firm. As in a typical monopsony case, the CO_2 price is lower relative to the competitive market price. The effects on emissions are again ambiguous. CCS firms reduce their abatement efforts due to the low CO_2 price, which in turn increases emissions. In contrast, the EOR firm reduces its output, thus, reducing emissions. The net effect depends on which of the two forces is greater and it again depends on the productivity of EOR firms and the emissions intensity of the oil sector.

While traditional industrial organization results presume that market power yields a lower social welfare compared to a competitive market, we find such a relationship is not firmly established when it comes to emissions for both the CCS monopoly and the EOR monopsony scenarios. The focus on market structure reveals very important issues that will become apparent once a market for CO_2 is fully established. Our findings demonstrate that a carbon tax will have differential impacts across regions and that policy needs to be adjusted to control for the idiosyncrasies of each local market situation.

Our work is of course related to previous contributions on environmental economics and energy economics and has benefited from literature in Industrial Organization. Because of the long-term effects of climate change and the time-dependent extraction of natural resources the link between CCS and EOR has been studied mostly in a dynamic context (see Gerlagh and van der Zwaan (2006); Leach, Mason and van't Klass (2011) and Amigues, Lafforgue and Moreaux (2012)). The complexity of the dynamic approach makes it very difficult to study market structure and most dynamic approaches consider a social planer or a single actor economy. Although we believe dynamic aspects are important, we purposefully suppress the role of time in the model; instead, we try to concentrate on the interaction between carbon dioxide markets and energy markets under different market structures. Our work also relates to the literature on the general equilibrium effects of a carbon tax and its interactions with other taxes in the economy (e.g., Bovenberg and Goulder 1996, Goulder 2013). Unlike the previous literature that concentrates on the distortionary effect of a carbon tax in other markets, here we concentrate on the effects in the market for CO_2 as a productive input in the economy. In this sense, factor markets are distorted more in line with Parry, Williams and Goulder (1999).

The rest of the paper proceeds as follows. In section 2 we introduce the model. First we present the supply side of the CO_2 market represented by electricity generating utilities that maximize profits while accounting for abatement costs. We then present the demand side of the CO_2 market represented by oil producing firms that require enhanced oil recovery to extract more oil out of their reservoirs. We close this section by defining the market clearing condition for equilibrium in the CO_2 market. In the following three sections we analyze different market structures. In section 3 we study the competitive market structure where there are several firms in both sides of the market. In section 4 we study the CCS monopoly where only one CCS firm supplies carbon to several EOR firms. In section 5 we study the EOR monopsony case where only one EOR firm buys CO_2 form several CCS firms. We finish the paper with a brief concluding section.

2 The Model

2.1 Electricity firms

We start by describing the CCS firms, the supply side of the CO_2 market. There are many sources of anthropogenic CO_2 that could adopt CCS techniques, e.g., coal based power plants, natural gas processing, ammonia production, and fertilizer production. We consider here the case of power plants as CO_2 suppliers, although the analysis can be readily expanded to other possible sources of highly localized CO_2 production. The number of firms in the electricity sector is n_e. We assume that each unit of electricity sells at an exogenously given price p_e. Let $c_e(q_e) = \frac{k_e}{2}q_e^2$ denote total production cost of q_e units of electricity; the cost is convex with a constant $k_e > 0$ that measures a constant unit marginal (and average) cost, i.e., $c_e'(q_e) = k_e q_e$ and $c_e''(q_e) = k_e$. Each firm e can mitigate emissions of a units of CO_2 at a cost given by $m(a) = \frac{k_a}{2}a^2$. Again the mitigation cost is convex with a constant $k_a > 0$ that represents the efficiency of the emission-mitigation technology.

Electricity firms capture CO_2 to reduce their emissions and thus their carbon tax cost of compliance. Then, they feed this CO_2 to EOR firms. Denote the carbon tax by $\tau \in \mathbb{R}$ which firms take as given.[3] Denote the price of CO_2 by p_c which is endogenously determined in the CO_2 market equilibrium. While a competitive electricity firm takes p_c as given, a firm with market power will consider it a function of its abatement level, a. In general, firm e's optimization problem is characterized as follows:

$$\max_{q_e, a \geq 0} \ \pi_e = p_e q_e - c_e(q_e) - \tau(\alpha q_e - a) + p_c(a)a - m(a) \tag{1}$$

where the parameter $\alpha \geq 0$ denotes the amount of CO_2 generated per unit of electricity output. On top of the standard profit expression, $p_e q_e - c_e(q_e)$, firm e pays a per unit carbon tax τ for its net emissions of CO_2, $\alpha q_e - a$. When CO_2 is sold in the market, it generates the sales revenue $p_c(a)a$ but the mitigation of a units of CO_2 costs the firm $m(a)$. Rearranging (1) into

$$\pi_e = (p_e - \alpha\tau)q_e - c_e(q_e) + (p_c(a) + \tau)a - m(a), \tag{2}$$

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[3] Note that τ is a policy instrument at disposal of the regulator (social planner) who presumably aims to maximize social welfare.

we see an alternative interpretation: the effective price of a unit of electricity is $p_e - \alpha\tau$ due to the carbon tax on the electricity output. The profit associated with the electricity production is $(p_e - \alpha\tau)q_e - c_e(q_e)$. Because a unit of CO_2 capture not only saves the carbon tax τ per unit but also generates the per unit revenue p_c from the CO_2 market, the profit associated with CO_2 capture is given by $(p_c(a) + \tau)a - m(a)$.

2.2 EOR firms

Now we turn to EOR firms, the demand side of CO_2 market. In particular, we consider the EOR firms that operate in oil fields located over underground reservoirs where CO_2 from power plants and industrial facilities can be safely and securely stored. The EOR firms are price-takers in the oil market and sell their output at a price $p_o > 0$. Each EOR firm makes its production choice to maximize its own profit. We denote EOR-related variables with subscript o. The number of EOR firms is n_o. Let $c_o(q_o) = \frac{k_o}{2}q_o^2$ denote oil production cost, with $k_o > 0$ constant. We assume $q_c(q_o) = \sigma q_o$ where $q_c(q_o)$ measures the amount of CO_2 required to produce q_o units of oil.[4] A high σ implies more CO_2 is needed per unit of output; that is, σ is a measure of the productivity of EOR. This set-up is convenient because it allows us to characterize the EOR firm's optimization problem as an output choice problem.

Firm o's optimization problem is characterized as follows:

$$\max_{q_o \geq 0} \ \pi_o = (p_o - \beta\tau)q_o - c_o(q_o) - p_c q_c(q_o). \tag{3}$$

where the parameter $\beta > 0$ denotes the amount of CO_2 generated per unit of oil output; firm o pays a per unit carbon tax τ for its net emissions of CO_2, $\tau\beta q_o$. We could allow for EOR firms to also abate their emissions, but our results are independent of such an assumption so we refrain from adding this feature to the model.[5]

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[4] Here we focus on a static analysis of the problem. Excellent accounts of the dynamic interplay between EOR and CCS are in Leach et al. (2011). Despite their significance, our inclusion of such dynamic aspects may obscure the main focus of this paper.

[5] We can additionally consider a carbon tax credit to the EOR firms to incentivize CO_2 sequestration. This tax credit plays a crucial role in the dynamic set-up considered by Leach et al. (2010).

2.3 Market Clearing Condition

To complete the description of our model we add the CO_2 market clearing condition:

$$n_e a = n_o q_c(q_o) \tag{4}$$

This condition connects the two sides of the market by equating CO_2 supply to CO_2 demand.

We do not deal with entry into the carbon dioxide market. Instead, we assume the exact number of firms n_e and n_o determines the nature of the market structure. In the *competitive market* a number of firms act as price-takers in both sides in the CO_2 market. Another plausible case is a *CCS monopoly* where many EOR firms play as competitive buyers for the limited supply of CO_2. When there are only a few EOR firms and many CCS firms, the market can be characterized as an *EOR monopsony.* In this case, all market power goes to the EOR firms because they become a competitive bottleneck vis-a-vis CCS firms who want to buy limited storage space at the EOR sites. These possibilities are shown in Figure 1. We start by analyzing the competitive market case where both n_e and n_o are large. We then relax this assumption and allow for market power in either side of the market. In the EOR monopsony $n_o = 1$ and n_e is large. In the CCS monopoly $n_e = 1$ and n_o is large.

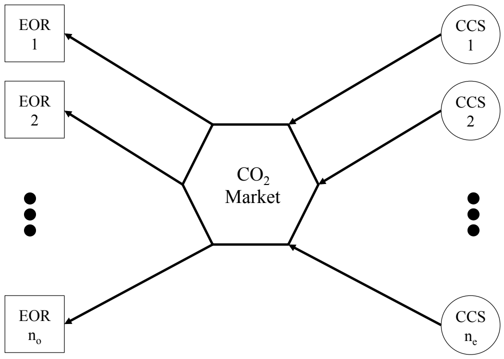
3 Competitive CO_2 Markets

We begin by considering the competitive market scenario where the number of firms is large in both industries. All firms take the CO_2 price p_c as given and maximize their own profits. This situation is represented in Panel 1(a).

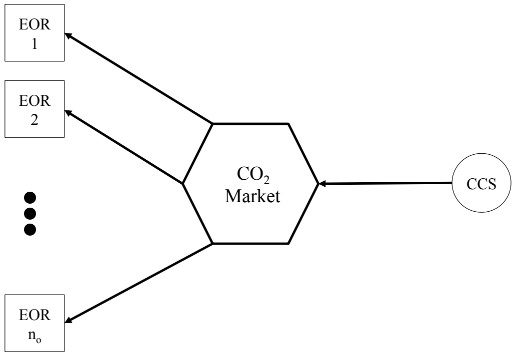
3.1 Market outcomes

We first consider the choices of electricity production and CO_2 abatement for the electricity firms given in problem (1). From the first order condition with respect to electricity output, q_e, we find

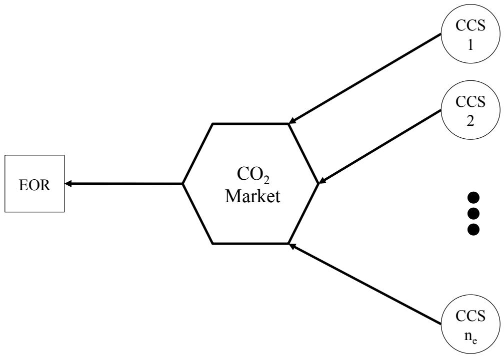
$$\frac{\partial \pi_e}{\partial q_e} = 0 \Rightarrow p_e - \alpha\tau = k_e q_e. \tag{5}$$



(a) Competitive Market Structure



(b) CCS Monopoly



(c) EOR Monopsony

Figure 1: Alternative market structures

The electricity production decision is simple. Given a competitive market price p_e, each power plant will produce up to the point where its marginal cost of electricity production is equal to its effective marginal revenue per unit of electricity, $p_e - \alpha\tau$. Note that equation (5) identifies the optimal production of electricity q_e^* as a function of only parameters, p_e, α, k_e, and τ.

Electricity firms also choose the amount of CCS they want to implement. The first order condition with respect to abatement, a, is given by

$$\frac{\partial \pi_e}{\partial a} = 0 \Rightarrow p_c + \tau = k_a a. \tag{6}$$

Optimal abatement is determined when the marginal benefit of the last unit of abatement, $p_c + \tau$, is equal to its marginal abatement cost, $k_a a$.

We consider now the output decision of the oil producers, given in problem (3). From the first order condition with respect to oil output, q_o, we find

$$\frac{\partial \pi_o}{\partial q_o} = 0 \Rightarrow p_o - \beta\tau = k_o q_o + \sigma p_c. \tag{7}$$

The left-hand side of equation (7) is the effective marginal revenue after the carbon tax, while the right-hand side captures the two different sources of marginal costs. In addition to the basic marginal cost of production $k_o q_o$, the EOR firm must buy CO_2 to extract more oil out of the reservoir, thus adding to the marginal input cost σp_c. The optimal level of oil production must satisfy the equality between the marginal revenue $p_o - \beta\tau$ and the marginal cost $k_o q_o + \sigma p_c$.

3.2 The General Equilibrium Effects of a Carbon Tax

The supply of CO_2 is simply the amount of abatement implemented by each firm, a^*, times the number of electricity firms:

$$S(p_c) \equiv n_e a^* = \frac{n_e}{k_a}(p_c + \tau). \tag{8}$$

where the last equality follows from substituting (6) for a^*. The demand for CO_2 is given by the EOR demanded by each firm times the number of oil producing firms:

$$D(p_c) \equiv n_c q_c^* = \frac{n_o \sigma}{k_o}(p_o - \beta\tau - \sigma p_c). \tag{9}$$

where the last equality follows from (7) combined with $q_c = \sigma q_o$.[6] The market clearing condition for an interior equilibrium in the CO_2 market, $S(p_c) = D(p_c)$, identifies the price of CO_2 as a function of parameters:

$$p_c^* = \frac{k_a n_o \sigma(p_o - \beta\tau) - k_o n_e \tau}{k_o n_e + k_a n_o \sigma^2}. \tag{10}$$

The equilibrium price derived in (10) shows several intuitive comparative statics of how the market CO_2 price changes in response to other exogenous variables. First, the CO_2 price is increasing with the price of oil, that is, $\frac{\partial p_c^*}{\partial p_o} > 0$. The higher oil price shifts the demand for CO_2 rightward, which results in the higher CO_2 price through movement along the supply curve. This result shows the connection between the CO_2 market and the oil market; more importantly, it is consistent with a general notion that the oil price is critical for understanding the EOR-CCS interaction (Leach et al. 2011). We can also see that the CO_2 price decreases with σ. This means that the more effective use of CO_2 in EOR sites (by requiring less CO_2 to produce one unit of oil) increases CO_2 prices because the demand shifts to right, other things being equal.

Here we also see that τ and p_c^* are inversely related: an increase in the carbon tax reduces the price of carbon. Consider Figure 2. Starting at equilibrium E, the EOR firms will produce less oil directly due to the higher carbon tax applied to oil output, shifting the demand curve to the left. In addition, higher taxes incentivize electricity companies to to capture more CO_2, shifting the supply curve to the right. The new equilibrium is now denoted by E'. This analysis shows how an increase in carbon taxes can create indirect

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[6] To ensure an interior equilibrium exists, we need to impose a condition that the carbon tax is not too large. If the carbon tax is very large, then there both electricity and oil companies will reduce output and increase abatement driving the equilibrium price to zero. Specifically, we need $\tau < \bar{\tau}$, where $\bar{\tau} = \frac{n_o \sigma p_o}{(k_o/k_a)n_e + n_o \sigma \beta}$. The condition is relaxed as the price of oil increases, and the number of oil firms increases or as the number of electricity firms decreases.

subsidies to EOR companies.

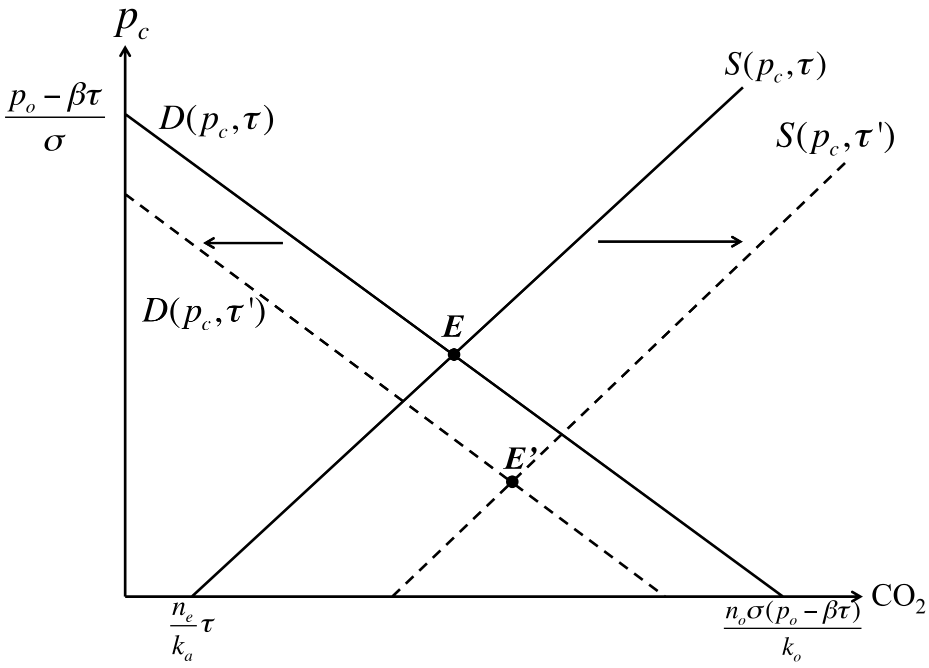

Figure 2: Competitive Equilibrium

We summarize thus far results as following:

Proposition 1 *Consider competitive CCS-EOR industries. Then, we find*

(a) The equilibrium carbon price increases in oil price and EOR technology efficiency, i.e., $\frac{\partial p_c^*}{\partial p_o} > 0$ *and* $\frac{\partial p_c^*}{\partial \sigma} < 0$.

(b) A carbon tax lowers the equilibrium CO$_2$ *price, working as an indirect subsidy to EOR firms, i.e.,* $\frac{\partial p_c^*}{\partial \tau} < 0$.

Next, we consider the effects of an increase in the carbon tax on abatement. Substituting (10) into (7), we derive the equilibrium quantity of oil produced:

$$q_o^* = \frac{n_e[\tau\sigma + (p_o - \beta\tau)]}{k_o n_e + k_a n_o \sigma^2}. \tag{11}$$

Similarly, substituting (10) into (6) and solving for a, we can derive the level of abatement in equilibrium:

$$a^* = \frac{\tau\sigma^2 n_o + (p_o - \beta\tau)\sigma n_o}{k_o n_e + k_a n_o \sigma^2}. \tag{12}$$

Then, using (11) and (12) we can easily see how the carbon tax would affect CCS firms' abatement decision and EOR firms' oil production decision.

First, consider the effect of a change in the carbon tax on oil production:

$$\frac{\partial q_o^*}{\partial \tau} = \frac{n_e(\sigma - \beta)}{k_o n_e + k_a n_o \sigma^2}. \tag{13}$$

The expression in equation (13) shows that output increases with an increase in the carbon tax, if $\sigma > \beta$. The intuition for this result is simple. By increasing the tax, there is a direct response by oil firms to reduce output. This direct tax effect on oil production is mediated by the emissions intensity parameter β. However, as we showed in Proposition 1(b), the price of CO_2 falls when the carbon tax increases. This indirect subsidy, as mediated by the EOR productivity parameter σ, causes oil production to increase. If the indirect subsidy effect dominates the direct tax effect, then oil production will increase.

The effect of an increase in the carbon tax on abatement levels is given by

$$\frac{\partial a^*}{\partial \tau} = \frac{\sigma n_o(\sigma - \beta)}{k_o n_e + k_a n_o \sigma^2}. \tag{14}$$

implying that abatement will also increase in the carbon tax, if $\sigma > \beta$. As we discussed above, for $\sigma > \beta$, oil production increases with the carbon tax. This implies that the demand curve will shift only slightly to the left. By contrast, the CCS firms' incentives to increase abatement will increase. The supply curve will move to the right. This is shown in Figure 2 were the equilibrium E' is to the right of the equilibrium E. We summarize these results in the next proposition.

Proposition 2 *In competitive CCS-EOR industries, the relative magnitude of β and σ determines whether the carbon tax would increase or decrease the equilibrium CO_2 abatement and EOR-associated oil production. If $\sigma > \beta$, the carbon tax results in more oil production and more abatement; otherwise, the carbon tax results in less oil output and less abatement.*

3.3 Emissions

Our preceding analysis shows that both abatement and oil output increase due to an increase in the carbon tax. The combined effects are, however, ambiguous.

First, denote electricity sector emissions as $\omega_e = \alpha q_e^* - a^*$. So, the change in the equilibrium emissions of CCS sector driven by the carbon tax change will be given by

$$\frac{\partial \omega_e}{\partial \tau} = \underbrace{-\frac{\alpha^2}{k_e}}_{\substack{\text{direct carbon tax effect} \\ \text{on electricity production}}} \underbrace{-n_e \frac{(\sigma - \beta)\, \sigma n_o}{k_o n_e + k_a n_o \sigma^2}}_{\substack{\text{general equilibrium effect} \\ \text{due to EOR firms' demand}}} . \tag{15}$$

The first term in equation (15) is the direct effect of the carbon tax on electricity production, and is negative. The second term is a general equilibrium effect due to EOR firm's CO_2 demand. As we examined in Proposition 2, if $\sigma > \beta$, the carbon tax increases the abatement and thus contribute to emission reduction in the electricity sector. Hence, when $\sigma > \beta$, the carbon tax clearly decreases the emissions from the electricity sector. For the opposite case of $\sigma < \beta$, two countering forces coexist as the carbon tax decreases the CO_2 abatement. As a result, we cannot rule out the possibility that the carbon tax increases emissions in the CCS sector due to reduced incentives to abate.

Total emissions, the sum of the emissions from the electricity sector and those from the oil sector, are given by

$$\omega = n_e \omega_e + n_o \beta q_o.$$

The change in total emissions due to a change in the carbon tax is given by

$$\frac{\partial \omega}{\partial \tau} = -n_e \frac{\alpha^2}{k_e} - \frac{(\sigma - \beta)^2 n_e n_o}{k_o n_e + k_a n_o \sigma^2} < 0. \tag{16}$$

Emissions in the electricity sector are strictly decreasing in the emissions tax. The explanation for this result is intuitive. When $\sigma > \beta$, the negative general equilirbium effect outweighs the positive EOR firms' production (demand for CO_2) effect. In the other case of $\sigma < \beta$, an increment in the carbon tax will increase the emission in the CCS sector because of the EOR's low demand for the captured CO_2. But, now the EOR's reduced oil production ends up with less emission from the EOR sector. The former CCS sector effect is weighted by σ (that is smaller than β), while the latter EOR sector effect is weighted by β. Again, the combination of these two reduces the overall emissions. Therefore, we sum up thus far results as follows:

Proposition 3 *Consider competitive CCS-EOR industries. For CO_2 emissions, we find*

(a) *Emissions from the CCS sector are decreasing in the carbon tax if and only if $\sigma > \beta$. However, for $\sigma < \beta$, we cannot rule out the possiblity of $\frac{\partial \omega_e}{\partial \tau} > 0$.*

(b) *Emissions from the EOR sector are increasing in the carbon tax if and only if $\sigma > \beta$. For the opposite case of $\sigma < \beta$, it is decreasing in τ.*

(c) *Total emissions from both sectors are always decreasing in τ.*

4 CCS Monopoly

As we mentioned earlier, the market structure governing CO_2 markets is primarily determined by geography. Here we consider a case in which multiple EOR firms compete for a limited supply of CO_2 provided by a CCS power plant that acts like a monopolist. This situation is presented in Panel 1(b). This CCS monopoly is likely to arise when naturally occurring CO_2 sources dry-up and there is a CCS power plant near the EOR firms.[7]

4.1 CCS Monopoly Market Outcomes

The CCS monopolist considers the demand for CO_2 from EOR firms in its decision process. From equation (9) we can solve for the inverse demand of CO_2 as a function of the level of abatement, using $q^c = a$, as follows:

$$p_c(a) = \frac{p_o - \beta\tau}{\sigma} - \frac{k_o}{n_o\sigma^2}a, \tag{17}$$

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[7] Our analysis can be easily extended to an oligopoly market structure if the oligopolistic firms jointly choose their joint profit maximizing abatements. If they non-cooperatively choose their individual profit-maximizing abatement levels, strategic behavior would become an important consideration. That analysis is beyond the scope of the this paper.

which is a decreasing function of abatement, i.e., $p_c'(a) < 0$. The amount of CO_2 abatement is then determined at a point where its marginal revenue from an additional unit of CO_2 is equalized to its marginal abatement cost.

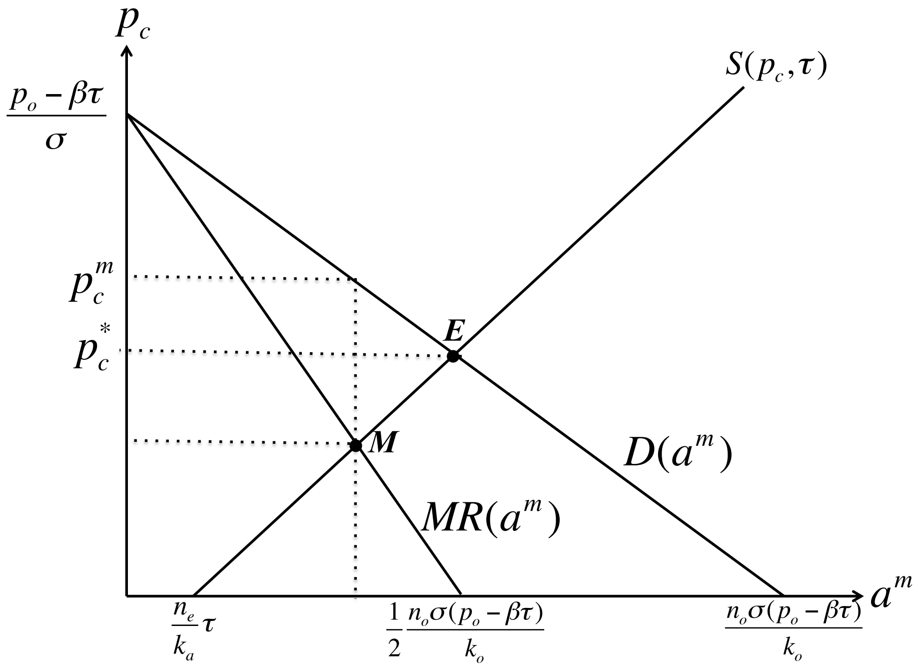

Figure 3: Monopoly

The CCS monopolist's profit expression is given by:

$$\pi_e^m = (p_e^m - \alpha\tau)q_e^m + (p_c(a^m) + \tau)a^m - c(q_e^m) - m(a^m).$$

where the superscript m denotes monopolistic outcomes. The first-order condition with respect to abatement a^m is

$$\frac{\partial \pi_e^m}{\partial a^m} = 0 \Rightarrow p_c(a^m) + p_c'(a^m)a^m + \tau = k_a a^m. \tag{18}$$

Evaluating the left-hand side of equation (18) at the abatement level found in the competitive equilibrium a^* and using equation (6) we find $\left.\frac{\partial \pi_e^m}{\partial a^m}\right|_{a^*} = p_c'(a^*)a^* < 0$, which implies in equilibrium $a^m < a^*$ given the concavity of the profit function (which is ensured by our assumption on convex cost functions in production and abatement). The explicit expression for the abatement level under the CCS monopoly is given by

$$a^m = \frac{k_o n_e + k_a n_o \sigma^2}{k_o n_e + k_a n_o \sigma^2 - p_c'(a)\sigma^2 n_o} a^*, \tag{19}$$

which confirms the relationship of $a^m < a^*$.[8] The intuition is simple; CCS firms will reduce the amount of CO_2 they capture in order to sustain a higher CO_2 price relative to the competitive market level. Accordingly, we find that the EOR firms also decrease their overall oil production compared to the competitive market level, i.e.,

$$q_o^m = \frac{k_o n_e + k_a n_o \sigma^2}{k_o n_e + k_a n_o \sigma^2 - p_c'(a)\sigma^2 n_o} q_o^* < q_o^*. \tag{20}$$

4.2 CCS Monopoly Emissions

We now consider the influence of a CCS monopoly on overall CO_2 emissions. Define ω^m as the total emissions in the monopoly case. Then, the change in emissions introduced by the monopoly is equal to:

$$\omega^m - \omega^* = \frac{-p_c'(a)\sigma^2 n_o}{k_o n_e + k_a n_o \sigma^2 - p_c'(a)\sigma^2 n_o} \cdot (a^* - n_o \beta q_o^*) \tag{21}$$

where the second line follows from setting $n_e = 1$ and $q_e^* = q_e^m$ from (5). The first factor in (21) is positive so that the relative magnitude of ω^m and ω^* depends on the sign of the second factor, $a^* - n_o \beta q_o^*$. Using (11) and (12), we express it in terms of primitives as

$$a^* - n_o \beta q_o^* = \frac{n_o (\tau\sigma + p_o - \beta\tau)(\sigma - \beta)}{k_o n_e + k_a n_o \sigma^2}.$$

If $\sigma > \beta$, then total emissions under CCS monopoly are greater than those under the competitive market, i.e., $\omega^m - \omega^* > 0$. The reduction in abatement exceeds the countering effect of smaller EOR oil production due to the higher CO_2 price. If $\sigma < \beta$, in contrast, the monopoly power wielded by the capturer leads to smaller total emissions.

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[8] See more detailed derivation process in the Appendix.

Proposition 4 *Consider the monopoly situation in the CCS sector. Then, we find*

- *(a) The CCS monopolist captures a smaller amount of CO_2 compared to the competitive case. As a result, the CO_2 price increases and its traded volume decreases.*
- *(b) Total emissions are greater in the CCS monopoly relative to the competitive case if $\sigma > \beta$; otherwise, emissions are smaller in the CCS monopoly.*

The result in (a) is a standard monopoly result. The result in (b) reflects the standard result in environmental economics that monopoly power results in a cleaner environment due to a reduction in output. For $\sigma < \beta$ we find the opposite is true and monopoly power increases emissions due to the genial equilibrium effect of the CO_2 market.

5 EOR Monopsony

We now consider an alternative market structure in which multiple CCS firms compete for a limited demand of CO_2 requested by a EOR firm who acts like a monopsonist. Here,the price of CO_2 is determined by the EOR firm's level of oil production and its associated demand for CO_2. This situation is likely to occur when a depleted oil well is surrounded by many CCS power plants that have no alternative storage capacity. We illustrate this case in Panel 1(c).

5.1 Monopsony Market Outcome

We start by expressing the supply of CO_2 as a function of q_o using equation (8),

$$p_c(q_o) = \frac{\sigma k_a}{n_e} q_o - \tau.$$

The main departure from the competitive EOR firm is that now the CO_2 price is an increasing function of the EOR firm's input demand q_o, i.e., $p_c'(q_o) > 0$. In contrast to the competitive oil producer, the EOR monopsonist will take the effect of its output choice on the CO_2 price into account. The EOR monopsonist's profit expression is modified as follows:

$$\max_{q_o^s \geq 0} \; \pi_o^s = (p_o - \beta\tau) q_o^s - c_o(q_o^s) - p_c(q_o^s) q_c(q_o).$$

where the superscript s denotes outcomes for the monopsony. The first order condition with respect to q_o^s is given by

$$\frac{\partial \pi_o^s}{\partial q_o^s} = 0 \Rightarrow p_o - \beta\tau = k_o q_o + \sigma p_c + \sigma p_c'(q_o) q_o. \tag{22}$$

Compared to the optimality condition (7) in the competitive market, the third term in the right hand side of (22), $\sigma p_c'(q_o) q_o > 0$, represents an additional marginal cost. As this new term is positive, the EOR monopsonist will decrease it CO_2 demand compared to the competitive market. That is

$$q_o^s = \frac{k_o n_e + k_a n_o \sigma^2}{k_o n_e + k_a n_o \sigma^2 + \sigma p_c'(a)} q_o^*. \tag{23}$$

implying $q_o^s < q_o^*$.[9] The intuition for this result is presented using Figure 4. Note that the EOR monopsonist must pay a higher price for all the CO_2 that it already employs when it buys an extra unit of CO_2. This implies the marginal expenditure on CO_2 increases in CO_2 and is always above the competitive supply curve. The optimal input level is determined by the intersection of the marginal expenditure curve and the monopsonist's CO_2 demand. Now market power is tilted towards the EOR monopsony, the CO_2 price p_c^s is lower than the competitive price, i.e., $p_c^s < p_c^*$. It is even possible for the EOR monopsonist to receive payment for its underground storage by allowing the CCS firms to sequester their captured CO_2.

From the system of equations composed of the optimality condition for a^s and the market clearing condition, we can derive the level of abatement under the monopsony structure as follows:

$$a^s = \frac{k_o n_e + k_a n_o \sigma^2}{k_o n_e + k_a n_o \sigma^2 + \sigma p_c'(a)} a^* \tag{24}$$

Hence, we find that the monopsony EOR firm also reduces the abatement compared to the competitive market level, i.e., $a^s < a^*$.

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[9] See detailed derivation processes in the Appendix.

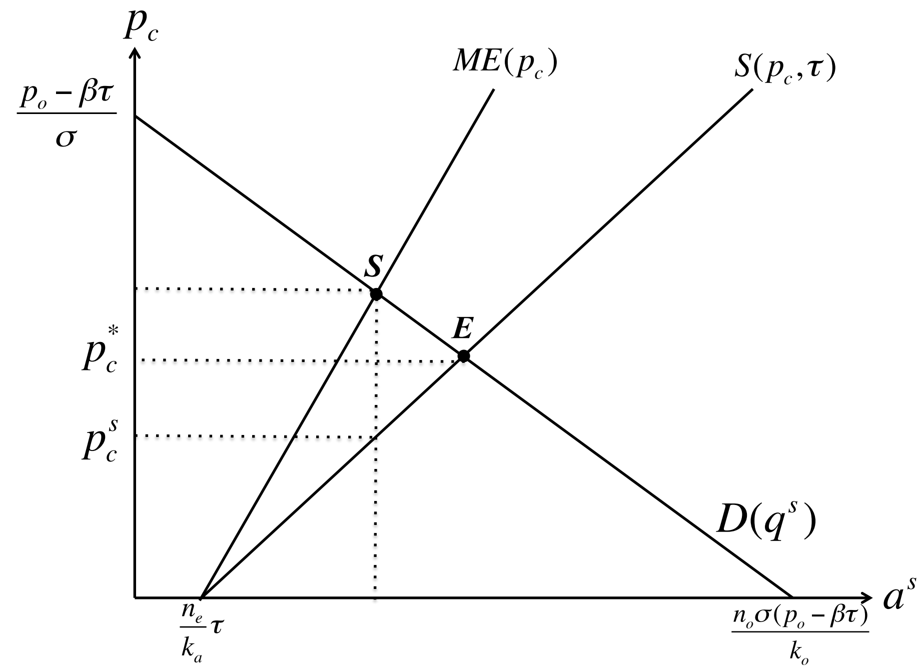

Figure 4: Monopsony

5.2 EOR Monopsony Emissions

Again, let us examine the effects of the market power held by the EOR oil producer on the overall CO$_2$ emissions. Define total emissions under the monopsony case as ω^s. Comparing to the emissions under the competitive outcome we find

$$\begin{aligned}\omega^s - \omega^* &= [n_e(\alpha q_e^s - a^s) + \beta q_o^s] - [n_e(\alpha q_e^* - a^*) + n_o\beta q_o^*] \\ &= \left(\frac{\sigma p_c'(a)}{k_o n_e + k_a n_o \sigma^2 + \sigma p_c'(a)}\right)\frac{(\tau\sigma + p_o - \beta\tau)(\sigma - \beta)}{k_o n_e + k_a n_o \sigma^2} \qquad (25)\end{aligned}$$

Again, if $\sigma > \beta$, then total emissions under EOR monopsony are greater those that under the competitive market, i.e., $\omega^s - \omega^* > 0$.

Proposition 5 *Consider the EOR monopsony situation. Then, we find*

(a) The EOR monopsonist captures less CO$_2$ compared to the competitive case and the CO$_2$ price decreases.

(b) *Total emissions are greater in the EOR monopsony relative to the competitive case if $\sigma > \beta$; otherwise, emissions are smaller in the EOR monopsony.*

As we discussed above for the CCS monopoly case, under this monopsony structure, market power has an ambiguous effect on emissions. Under the EOR monopsony emissions increase if the oil industry is effective in using CO_2 and emissions from oil output is relatively clean.

6 Concluding Remarks

This paper has shown that the effectiveness of a carbon emissions tax can be limited in the presence of a market for CO_2. In fact, it is possible that the increase in a carbon emissions tax can lead to an increase in emissions in the EOR sector and a reduction in CCS abatement. As natural deposits of CO_2 dry up, alternative sources will be needed for productive activities. The distortionary effects of a carbon tax in the CO_2 market is of key importance when discussing the implications of carbon policy.

We developed a simple two-sector model to deliver our messages with simple analyses. By doing so, we were able to compare different market outcomes across various market structures of the CO_2 market. Market power, as determined by geography and location, may play a major role in determining the effectiveness of a carbon tax. In particular, the presence of market power in the CO_2 market can influence the general equilibrium effects of the carbon tax in the carbon market. Contrary to the standard result in environmental economics, market power can lead to an increase in emissions from polluting firms.

Our study shows that a serious understanding of the interaction between the carbon market and climate policy, both theoretically and empirically, is necessary to be able to determine the welfare effects of the distortions of a carbon tax on CO_2 markets. This paper is a step towards this understanding.

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A Appendix

Here we offer a more detailed mathematical derivation of the main results in the paper.

A.1 Competitive Market

Recall that the cost of energy (electricity, gas) production and the cost of abatement are all convex, i.e., $c_e(q_e) = \frac{k_e}{2}q_e^2$, $c_o(q_o) = \frac{k_o}{2}q_o^2$, and $m(a) = \frac{k_a}{2}a^2$, where k_e, k_o, and k_a are respectively capture the efficiency of each activity. In addition, we assume that one unit of oil production requires s unit of CO_2, i.e., $q_c(q_o) = \sigma \cdot q_o$.

A.1.1 Market outcomes

Using the optimality conditions characterized by the first-order conditions and the market clearing condition, for the competitive market we have:

$$\begin{aligned} p_e - \alpha\tau &= k_e q_e; \\ p_c + \tau &= k_a a; \\ p_o - \beta\tau &= k_o q_o + \sigma p_c; \\ n_e a &= n_o \sigma q_o. \end{aligned}$$

The first optimality condition regarding q_e is independently determined without involving other endogenous variables (a, q_o, p_c). Thus, we set up a system of equations composed of three remaining equilibrium conditions as the following matrix form:

$$A\mathbf{x} = \mathbf{b} \Rightarrow \begin{bmatrix} k_a & 0 & -1 \\ 0 & k_o & \sigma \\ n_e & -\sigma n_o & 0 \end{bmatrix} \begin{bmatrix} a \\ q_o \\ p_c \end{bmatrix} = \begin{bmatrix} \tau \\ p_o - \beta\tau \\ 0 \end{bmatrix}$$

where the coefficient matrix is $A \equiv \begin{bmatrix} k_a & 0 & -1 \\ 0 & k_o & \sigma \\ n_e & -\sigma n_o & 0 \end{bmatrix}$. The determinant of matrix A is computed as $|A| = k_a\sigma^2 n_o + k_o n_e > 0$, which warrants a unique solution for the optimal choices. Using Cramer's rule, we can derive explicit solutions for each choice variable. The optimal CO_2 abatement is given by

$$a^* = \frac{1}{|A|}\begin{vmatrix} \tau & 0 & -1 \\ p_o - \beta\tau & k_o & \sigma \\ 0 & -\sigma n_o & 0 \end{vmatrix} = \frac{1}{|A|}[\tau\sigma^2 n_o + (p_o - \beta\tau)\sigma n_o]$$

Similarly, we can derive q_o^* and p_c^* as follows:

$$q_o^* = \frac{1}{|A|}\begin{vmatrix} k_a & \tau & -1 \\ 0 & p_o - \beta\tau & \sigma \\ n_e & 0 & 0 \end{vmatrix} = \frac{1}{|A|}[n_e(\tau\sigma + (p_o - \beta\tau))]$$

and

$$p_c^* = \frac{1}{|A|}\begin{vmatrix} k_a & 0 & \tau \\ 0 & k_o & p_o - \beta\tau \\ n_e & -\sigma n_o & 0 \end{vmatrix} = \frac{1}{|A|}[k_a\sigma n_o(p_o - \beta\tau) - \tau n_e k_o].$$

Now we can do some comparative statics analysis of a change in the carbon tax:

$$\frac{\partial a^*}{\partial \tau} = \frac{1}{|A|}\left(\sigma - \beta\right)\sigma n_o,$$

$$\frac{\partial q_o^*}{\partial \tau} = \frac{1}{|A|} n_e\left(\sigma - \beta\right),$$

and

$$\frac{\partial p_c^*}{\partial \tau} = \frac{1}{|A|}(-k_a\sigma n_o\beta - n_e k_o) < 0.$$

A.1.2 Emissions

Recall that the electricity sector emissions are measured by $\omega_e = \alpha q_e - a$. So, the change in emissions resulting from a change in the carbon tax change is

$$\frac{\partial \omega_e}{\partial \tau} = \alpha\frac{\partial q_e}{\partial \tau} - \frac{\partial a}{\partial \tau} = \alpha\left(-\frac{\alpha}{k_e}\right) - \frac{1}{|A|}\left(\sigma - \beta\right)\sigma n_o.$$

Total emissions, the sum of the emissions from the electricity sector and those from the oil sector, are given by

$$\omega = n_e\omega_e + n_o\beta q_o.$$

Thus, the change in total emissions due to a change in the carbon tax is given by

$$\begin{aligned}\frac{\partial \omega}{\partial \tau} &= n_e \frac{\partial \omega_e}{\partial \tau} + n_o \beta \frac{\partial q_o}{\partial \tau} \\ &= n_e \left[\alpha \left(-\frac{\alpha}{k_e} \right) - \frac{1}{|A|} (\sigma - \beta) s n_o \right] + n_o \beta \frac{1}{|A|} n_e (\sigma - \beta) \\ &= -n_e \frac{\alpha^2}{k_e} - \frac{1}{|A|} (\sigma - \beta)^2 n_e n_o < 0.\end{aligned}$$

A.2 CCS Monopoly

A.2.1 CCS Monopoly outcomes

Now, the first row in the system of equilibrium equations changes from $k_a a - p_c(a) = \tau$ to $(k_a - p_c'(a))a - p_c(a) = \tau$ and thus the new system becomes

$$A^m \mathbf{x} = \mathbf{b} \Rightarrow \begin{bmatrix} k_a - p_c' & 0 & -1 \\ 0 & k_o & \sigma \\ n_e & -\sigma n_o & 0 \end{bmatrix} \begin{bmatrix} a \\ q_o \\ p_c \end{bmatrix} = \begin{bmatrix} \tau \\ p_o - \beta \tau \\ 0 \end{bmatrix}.$$

The determinant of matrix A^m is computed as

$$|A^m| = |A| - p_c'(a) \sigma^2 n_o > |A|.$$

Using Cramer's rule, we can derive explicit solutions for each choice variable. The optimal CO_2 abatement is given by

$$a^m = \frac{1}{|A^m|} \begin{vmatrix} \tau & 0 & -1 \\ p_o - \beta \tau & k_o & \sigma \\ 0 & -\sigma n_o & 0 \end{vmatrix} = \frac{|A|}{|A^m|} a^*,$$

from which we find

$$a^m < a^*$$

because $|A^m| > |A|$ (i.e., $\frac{|A|}{|A^m|} < 1$).

EOR sector's oil production, q_o^m, under CCS monopoly is given by:

$$\begin{aligned} q_o^m &= \frac{1}{|A^m|}\begin{vmatrix} k_a - p_c' & \tau & -1 \\ 0 & p_o - \beta\tau & \sigma \\ n_e & 0 & 0 \end{vmatrix} \\ &= \frac{1}{|A^m|}\left[(k_a - p_c')\begin{vmatrix} p_o - \beta\tau & \sigma \\ 0 & 0 \end{vmatrix} - \tau\begin{vmatrix} 0 & \sigma \\ n_e & 0 \end{vmatrix} - \begin{vmatrix} 0 & p_o - \beta\tau \\ n_e & 0 \end{vmatrix}\right] \\ &= \frac{1}{|A^m|}\left[\tau\sigma n_e + n_e(p_o - \beta\tau)\right] = \frac{|A|}{|A^m|}q_o^* \ . \end{aligned}$$

where the third equality is derived using $q_o^* = \frac{1}{|A|}[\tau\sigma n_e + n_e(p_o - \beta\tau)]$. Thus, find $q_o^m < q_o^*$.

A.2.2 Emissions

Using the same notation as before we find:

$$\begin{aligned} \omega^m - \omega^* &= [(\alpha q_e^m - a^m) + n_o\beta q_o^m] - [n_e(\alpha q_e^* - a^*) + n_o\beta q_o^*] \\ &= (a^* - a^m) + n_o\beta(q_o^m - q_o^*) \ \ (n_e = 1 \text{ for normalization; } q_e^* = q_e^m) \\ &= \left(1 - \frac{|A|}{|A^m|}\right)a^* + n_o\beta\left(1 - \frac{|A|}{|A^m|}\right)q_o^* \\ &= \underbrace{\left(1 - \frac{|A|}{|A^m|}\right)}_{(+)}(a^* - n_o\beta q_o^*) \end{aligned}$$

Thus, the relative magnitude of ω^m and ω^* depends on the sign of

$$a^* - n_o\beta q_o^* = \frac{n_o\left(\tau\sigma + p_o - \beta\tau\right)\left(\sigma - \beta\right)}{|A|}.$$

If $\sigma > \beta$, then the total emissions under CCS monopoly are greater than those under the competitive case, i.e., $\omega^m - \omega^* > 0$.

A.3 EOR Monopsony

For the EOR monopsony, the analysis proceeds in a similar fashion applied to the CCS monopoly but the first order condition with respect to q_o^s will be changed into

$$p_o - \beta\tau = k_o q_o + \sigma p_c + \sigma p_c'(q_o)q_o.$$

The system reflecting this change will be given by

$$A^s\mathbf{x} = \mathbf{b} \Rightarrow \begin{bmatrix} k_a & 0 & -1 \\ 0 & k_o + \sigma p_c' & \sigma \\ n_e & -\sigma n_o & 0 \end{bmatrix} \begin{bmatrix} a \\ q_o \\ p_c \end{bmatrix} = \begin{bmatrix} \tau \\ p_o - \beta\tau \\ 0 \end{bmatrix}.$$

using $n_o = 1$. Then, we can derive the determinant of matrix A^s as

$$\begin{aligned} |A^s| &= k_a\sigma^2 n_o + n_e(k_o + \sigma p_c') \\ &= |A| + \sigma p_c'(a) > |A| \quad \because p_c'(a) > 0. \end{aligned}$$

A.3.1 EOR monopsony outcomes

Using Cramer's rule we find:

$$\begin{aligned} a^s &= \frac{1}{|A^s|} \begin{vmatrix} \tau & 0 & -1 \\ p_o - \beta\tau & k_o + \sigma p_c' & \sigma \\ 0 & -\sigma n_o & 0 \end{vmatrix} \\ &= \frac{1}{|A^s|} \left[\tau \begin{vmatrix} k_o + \sigma p_c' & \sigma \\ -\sigma n_o & 0 \end{vmatrix} - \begin{vmatrix} p_o - \beta\tau & k_o + \sigma p_c' \\ 0 & -\sigma n_o \end{vmatrix} \right] \\ &= \frac{1}{|A^s|} \left[\tau\sigma^2 n_o + (p_o - \beta\tau)\sigma n_o \right] = \frac{|A|}{|A^s|} a^* \end{aligned}$$

Hence, $a^s < a^*$ because $|A^s| > |A|$. We also confirm our intuition that the EOR monopsony results in a lower price of CO$_2$ by limiting its use of CO$_2$ for oil production.

$$\begin{aligned} q_o^s &= \frac{1}{|A^s|} \begin{vmatrix} k_a & \tau & -1 \\ 0 & p_o - \beta\tau & \sigma \\ n_e & 0 & 0 \end{vmatrix} = \frac{1}{|A^s|} \left[-\tau \begin{vmatrix} 0 & \sigma \\ n_e & 0 \end{vmatrix} - \begin{vmatrix} 0 & p_o - \beta\tau \\ n_e & 0 \end{vmatrix} \right] \\ &= \frac{1}{|A^s|} [n_e\tau\sigma + n_e(p_o - \beta\tau)] = \frac{|A|}{|A^s|} q_o^* \end{aligned}$$

Thus, $q_o^s < q_o^*$.

A.3.2 Emissions

Finally, we can compare ω^s and ω^* :

$$\begin{aligned}
\omega^s - \omega^* &= [n_e(\alpha q_e^s - a^s) + \beta q_o^s] - [n_e(\alpha q_e^* - a^*) + n_o \beta q_o^*] \\
&= n_e(a^* - a^s) + \beta(q_o^s - q_o^*) \quad (n_o = 1 \text{ for normalization}) \\
&= \left(1 - \frac{|A|}{|A^s|}\right) a^* + \beta \left(\frac{|A|}{|A^s|} - 1\right) q_o^* \\
&= \underbrace{\left(1 - \frac{|A|}{|A^s|}\right)}_{(+)} (a^* - \beta q_o^*) = \left(1 - \frac{|A|}{|A^s|}\right) \frac{(\tau\sigma + p_o - \beta\tau)(\sigma - \beta)}{|A|}
\end{aligned}$$

Again, if $\sigma > \beta$, then the total emission under EOR monopsoly is greater than that under the competitive market, i.e., $\omega^s - \omega^* > 0$.