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Optimal Pricing for Carbon Dioxide Removal Under Inter-Regional Leakage*

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ABSTRACT

Carbon dioxide removal (CDR) moves atmospheric carbon to geological or land-based sinks. In a first-best setting, the optimal use of CDR is achieved by a removal subsidy that equals the optimal carbon tax and marginal damages. We derive second-best subsidies for CDR when no global carbon price exists but a national government implements a unilateral climate policy. We find that the optimal carbon tax differs from an optimal CDR subsidy because of carbon leakage, terms-of-trade and fossil resource rent dynamics. First, the optimal removal subsidy tends to be larger than the carbon tax because of lower supply-side leakage on fossil resource markets. Second, terms-of-trade effects exacerbate this wedge for net resource exporters, implying even larger removal subsidies. Third, the optimal removal subsidy may fall below the carbon tax for resource-poor countries when marginal environmental damages are small.

Keywords: carbon pricing, trade, unilateral climate policy, terms-of-trade effects, removal subsidies
JEL Codes: F18, H23, Q37, Q5

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1 Introduction

Carbon dioxide removal (CDR) refers to a set of technologies that remove CO_2 from the atmosphere and store it in geological, terrestrial, or ocean reservoirs, or in products. While CDR is not employed at large scale today, the technology is projected to play a substantial role in achieving the Paris climate targets (IPCC, 2018). An extensive literature has investigated its potentials, costs and side effects (Minx et al., 2018; Fuss et al., 2018; Nemet et al., 2018), but research into efficient governance of CDR is in its infancy.

If removed carbon can be stored permanently, mitigation of climate change can be achieved equally by either reducing CO_2 emissions or by employing CDR, or both, as their effect on CO_2 in the atmosphere is the same, and both can be incentivized by carbon pricing. Under idealized conditions, cost-benefit analysis mandates both prices to be equal to the social cost of carbon. However, the general optimality condition may not hold in second-best settings.

In this paper, we reveal an asymmetry between carbon taxes and CDR subsidies for the case of inter-regional carbon leakage and terms-of-trade effects on resource markets. Carbon leakage, recently surveyed in Misch and Wingender (2021), refers to responses to unilateral emissions reductions via three channels (following Schwerhoff et al., 2018): increased emissions in response to reduced climate change damages (Hoel, 1991), increased fossil energy demand in response to falling international prices (Bohm, 1993; Gerlagh and Kuik, 2014), and relocation of emission-intensive production (Siebert, 1979).

We find that *removing* a ton of CO_2 from the atmosphere unilaterally by one region causes less leakage than *reducing* CO_2 emissions by a ton. This is because carbon removal causes leakage only through the first of the three channels. Therefore, the optimal CDR subsidy tends to be higher than the optimal tax but lower than marginal climate damages. Additionally, a country may want to alter the terms-of-trade in international resource markets to their favor – and to increase their fossil resource rent. Both motives interact with the leakage channel and lead to further strategic wedges between the optimal carbon tax and the optimal carbon removal subsidy. In certain cases, the difference between optimal carbon tax and CDR subsidy can be expressed as a function of the supply side leakage rate.

2 Model Setup

We consider a two-region economy consisting of one large region A and a competitive fringe region W. Both are populated by a representative household and perfectly competitive firms, which produce a consumption good using labor and fossil energy as inputs. The large region A takes its own contribution to climate change damages into account when setting a domestic carbon tax and a CDR subsidy to maximize welfare. Because countries in W are small, they have no incentives to contribute to climate change mitigation by implementing domestic carbon prices even though they benefit from reduced global damages (Hoel, 1991).

Representative households maximize utility $u(C)$, which increases with consumption of a private numeraire good C. Numeraire goods are produced in each region with the same technology $F(L^i, E^i)D(\bar{E})$. Here, L is labor input, E denotes fossil energy use and $D(\bar{E})$ the environmental damage function ($D(0) = 1$, $D'(\bar{E}) < 0$) that depends on carbon emissions in the atmosphere $\bar{E}$. We assume F to be homothetic and labor endowments L^i for $i \in \{A, W\}$ to be exogenously given and fixed. Region A can mitigate its emissions by using less fossil energy E^A or by deploying CDR R, i.e. mitigation technologies are part of F. Then, damage-relevant emissions are $\bar{E} = E^W + E^A - R$. Costs for removal are weakly convex and given by $h(R)$.

Finally, fossil energy is sold by competitive fossil energy suppliers at a world market price p, maximizing their profits $\pi_R = pE - c(E)$. Extraction costs $c(E)$ are convex and $E = E^W + E^A$ denotes total fossil energy. Region A owns a fraction $\lambda \in [0, 1]$ of the fossil energy suppliers. The first order condition yields

$$p = c'(E). \tag{1}$$

3 Leakage rates

We now discuss the mechanisms by which unilateral emission reductions and deployment of CDR in region A cause leakage. Firms in W maximize profits

$$\pi^W = F(L^W, E^W)D(\bar{E}) - pE^W - w^W L^W \tag{2}$$

utilizing energy up to the point where its price p balances with its marginal productivity:

$$p = \frac{\partial F}{\partial E^W} D =: F_E^W D \tag{3}$$

Combining (1) with (3) yields

$$c'(E^A + E^W) = F_E^W D(E^A + E^W - R) \tag{4}$$

Figure 1 explains the energy market equilibrium (4) graphically for a simplified case with linear marginal cost and benefit curves from the perspective of region W. In the initial equilibrium (point X) energy demand is given by $E^W = E^W_0$. If A reduces its demand for fossil energy E^A by some Δ, this has two effects: First, marginal extraction costs fall, shifting the marginal cost curve c' to the right. Second, climate damages fall, shifting the marginal benefit curve $F^W_E D$ to the right. Now, marginal costs equal marginal benefits in point Y and energy demand in W increases from E^W_0 to $E^W_{E_A}$. Reducing emissions in A causes leakage due to a) the falling price for fossil energy, which stimulates demand in W and b) the reduction of climate damages, which increases marginal benefits of fossil energy in W.

If instead of reducing demand by Δ, region A removes Δ units of CO_2 from the atmosphere, the marginal benefit curve shifts to the right, but marginal extraction costs remain unchanged. Then, the resulting equilibrium is at point Z and emissions in W are only E^W_R. Hence, deploying CDR in A causes leakage only by reducing climate damages for W.

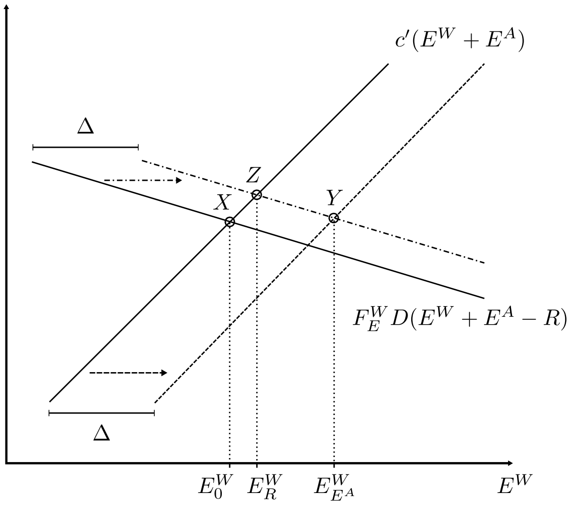

Figure 1: Fossil energy demand E^W in W is such that marginal extraction costs MC are equal to marginal net product $F^W_E D$, i.e. marginal benefits MB. This corresponds to Eq. (4).

We can express the leakage rate of a unilateral emission reduction in region A more precisely by considering that equation (4) implicitly determines region W's response function ϕ to region A's fuel demand, that is, $E^W(E^A, R) =: \phi(E^A, R)$.

Proposition 1 (Emission reduction leakage rate). *A unilateral reduction in region A's emissions, E^A, leads to an increase in region W's emissions E^W by*

$$\frac{dE^W}{dE^A} = \frac{\partial \phi}{\partial E^A} = -\left(1 + \frac{F^W_{EE} D}{F^W_E D' - c''}\right)^{-1} \tag{5}$$

with $-\frac{dE^W}{dE^A}$ *denoting the leakage rate and* $0 < -\frac{dE^W}{dE^A} = -\frac{\partial \phi}{\partial E^A} < 1$

Proof. Substituting $E^W = \phi(E^A, R)$ into (4) and taking the total derivative with respect to E^A, we obtain $c''\left(1+\frac{\partial\phi}{\partial E^A}\right) = F^W_{EE}D\frac{\partial\phi}{\partial E^A} + F^W_E D'\left(1+\frac{\partial\phi}{\partial E^A}\right)$. Re-arranging gives the first result. The second result on the inequality equation follows from $F^W_{EE}D < 0$, $F^W_E D' - c'' < 0$, implying that $-1 < \frac{\partial\phi}{\partial E^A} < 0$. □

The emission reduction leakage rate $-\frac{\partial\phi}{\partial E^A}$ measures how much of the mitigated ton of carbon in region A is off-set by increased energy demand in W. Leakage rates are always between 0 and 100% since $\frac{\partial\phi}{\partial E^A} > -1$. The rate depends on the slopes of the marginal extraction costs and climate damages (cf. Fig. 1). If, ceteris paribus, c'' or D' is large (small) in absolute terms, leakage rates are large (small), too.

Leakage as characterized in Prop. 1 thus occurs via the conventional supply-side channel and the channel that affects energy demand in W through reduced climate damages. The latter channel is also relevant for CDR:

Proposition 2 (CDR leakage rate)**.** *A marginal carbon removal in A affects energy demand, and thus, emissions in W as follows:*

$$\frac{dE^W}{dR} = \frac{\partial\phi}{\partial R} = \left(1 + \frac{F^W_{EE}D - c''}{F^W_E D'}\right)^{-1} > 0 \tag{6}$$

Proof. Substituting $E_W = \phi(E_A, R)$ back into (4) and taking the total derivative with respect to R, we obtain $c''\frac{\partial\phi}{\partial R} = F^W_{EE}D\frac{\partial\phi}{\partial R} + F^W_E D'(\frac{\partial\phi}{\partial R} - 1)$. The inequality follows from $\frac{F^W_{EE}D - c''}{F^W_E D'} > 0$. □

Carbon removal leakage is induced by reduced climate damages, which increase productivity in W and, thus, demand for (fossil) energy: When damages are flat and D' is small, $\frac{\partial\phi}{\partial R}$ converges to zero and CDR in region A has almost no effect on fuel use in W. When damages are steep and D' is very large, $\frac{\partial\phi}{\partial R}$ converges to one, implying an almost perfect crowding out of CDR by increased emissions abroad. In this case, CDR leads to substantially lower climate damages implying a large increase in fuel demand. Accordingly, in Fig. 1, a given marginal increase of CDR leads to a small (large) distance between E^W_0 and E^W_R for a flat (steep) marginal benefit curve $F^W_E D$. Thus, while CDR induces demand-side leakage through reduced climate damages it does not trigger supply-side leakage.

Combining (6) and (5) reveals the link between both leakage rates.

Corollary 1. *Emission reduction leakage and CDR leakage are linked by*

$$\frac{\partial\phi}{\partial R} = \alpha\left(-\frac{\partial\phi}{\partial E^A}\right) \tag{7}$$

where $\alpha := \left(1 - \frac{c''}{F_E^W D'}\right)^{-1}$. *The CDR leakage rate is smaller than the emission reduction leakage rate,*

$$\frac{\partial \phi}{\partial R} < -\frac{\partial \phi}{\partial E^A} \tag{8}$$

Proof. Follows directly from (7) as $0 < \left(1 - \frac{c''}{F_E^W D'}\right)^{-1} < 1$. □

4 Optimal unilateral carbon prices

The differences in carbon leakage according to Prop. 1 and 2 have consequences for region A's optimal carbon tax and removal subsidy. We first derive a 'command-and-control' equilibrium where A sets quantities for fossil energy use and CDR directly, then we use this to solve for the two carbon prices.

4.1 Command-and-control optimum in A

The government of A maximizes consumption, i.e. maximize

$$C = F(L^A, E^A) D(E^A + E^W - R) + \lambda p (E^A + E^W) - pE^A - h(R) \tag{9}$$

subject to:

$$E^W = \phi(E^A, R) \tag{10}$$

$$p = c'(E^W + E^A) \tag{11}$$

where $\lambda \in [0,1]$ is the fraction of shares of the fossil resource extracting firm held in region A. We substitute (10) and (11) into (9) and obtain

$$\begin{aligned} C = {} & F(L^A, E^A) D(E^A + \phi(E^A, R) - R) + \lambda c'(E^A + \phi(E^A, R))(E^A + \phi(E^A, R)) \\ & - pE^A - h(R) \end{aligned} \tag{12}$$

Maximizing over (E^A, R) gives the first order conditions:

$$F_E^A D - p = \left(1 + \frac{\partial \phi}{\partial E^A}\right) \left[-FD' + \Omega\right] \tag{13}$$

$$h' = \left(1 + \alpha \frac{\partial \phi}{\partial E^A}\right) \left[-FD' + \Omega\right] - \Omega \tag{14}$$

where we used (7) for deriving equation (14) and define $\Omega := -c'' \bar{E}(\lambda - E^A/\bar{E}) - \lambda p$.

Proposition 3. *Leakage due to emission reduction and carbon removal effectively reduces the impact of marginal climate damages on the optimal choice of domestic emissions and CDR.*

Proof. Because $-1 < \frac{\partial \phi}{\partial E^A} < 0$ and $0 < \alpha < 1$, leakage due to emission reduction and carbon removal effectively reduces the impact of marginal climate damages on the optimal choice of domestic emissions and CDR. $\square$

4.2 Policy instruments

We now derive the optimal unilateral carbon tax τ and CDR subsidy ς of region A, and thus, consider a decentralized economy. Firms in A maximize

$$\pi_A = F(L^A, E^A)D(\bar{E}) - (p+\tau)E^A + \varsigma R - h(R) - w^A L^A \tag{15}$$

implying the first order conditions:

$$F_E^A D = p + \tau \tag{16}$$

$$h' = \varsigma \tag{17}$$

$$F_L^A D = w^A \tag{18}$$

Comparing these first order conditions with the optimality conditions (13) and (14) allows to derive optimal carbon prices for emissions and their removal:

Proposition 4. *The optimal carbon tax for carbon emissions τ^* and the optimal subsidy for carbon removal ς^* that maximize region A's welfare are in general not equal. They are given by*

$$\tau^* = \left(1 + \frac{\partial \phi}{\partial E^A}\right)\left[-FD' + \Omega\right] \tag{19}$$

$$\varsigma^* = \left(1 + \alpha \frac{\partial \phi}{\partial E^A}\right)\left[-FD' + \Omega\right] - \Omega \tag{20}$$

with

$$\Omega = \underbrace{-c''\bar{E}(\lambda - E^A/\bar{E})}_{\textit{Terms-of-Trade Effect}} \qquad \underbrace{-\lambda p}_{\textit{Domestic Resource Rent Effect}} \tag{21}$$

Hence, the optimal carbon tax equals marginal damages $-FD'$ plus a resource price component Ω, which consists of two channels: The resource rent effect is always negative while the terms-of-trade effect is negative for a net resource exporter (i.e. $\lambda > E^A/\bar{E}$).

The resource rent effect describes that a country with large fossil resource ownership wants to reduce carbon taxes below marginal damages (to conserve domestic resource rent income). The terms of trade effect describes that a net exporting (importing) country has an incentive to lower (increase) the carbon tax to influence international prices, and thus, the terms-of-trade in their interest. However, both marginal damages and resource price component, are adjusted for the emission reduction leakage rate $0 < 1 + \frac{\partial \phi}{\partial E^A} < 1$.

The optimal CDR subsidy has a similar structure as the optimal carbon tax, but is adjusted for the CDR leakage rate $\left(1 + \alpha \frac{\partial \phi}{\partial E^A}\right) = \left(1 - \frac{\partial \phi}{\partial R}\right)$ that takes into account increased fossil energy use abroad due to lowered climate damages. Additionally, the resource price component enters in opposite sign again and independent from the leakage effect. The optimal subsidy differs from the optimal carbon tax:

$$\tau^* - \varsigma^* = \underbrace{(1-\alpha)\frac{\partial \phi}{\partial E^A}(-FD')}_{<0} + \underbrace{\left[(1-\alpha)\frac{\partial \phi}{\partial E^A} + 1\right]\Omega}_{>0} \tag{22}$$

Without the resource price effect, Ω, the optimal carbon tax whould be lower than the optimal carbon removal subsidy because the latter has a lower carbon leakage rate (expressed by $\alpha < 1$). Whether the resource price effect Ω is able to reverse this depends on the following cases:

a) If region A is a net exporter, then $\lambda \geq E^A/\bar{E}$, $\Omega < 0$ and, thus, $\tau^* < \varsigma^*$. The CDR subsidy is then always larger than the tax on carbon emissions.

b) If region A is an importer, then $\lambda < E^A/\bar{E}$, the sign of Ω is ambiguous. In particular, there is a threshold for λ below which Ω becomes positive.

In case a), region A benefits from higher energy prices due to increasing resource rents and terms-of-trade effects; it therefore sets the carbon tax below the removal subsidy to increase international resource prices. In case b), since region A imports fossil energy, it has an incentive to use the carbon tax to appropriate region W's resource rent. In particular, when resource ownership in A is sufficiently low, the terms-of-trade effect dominates the domestic resource rent effect and $\Omega > 0$. In that case, region A implements a carbon tax that is larger than the CDR subsidy when marginal damages $-FD'$ are sufficiently small, such that the terms-of-trade effect dominates the environmental motive.

The optimal prices simplify significantly, if we assume that region A owns no fossil resources ($\lambda = 0$) and that the government does not try to appropriate the resource rent (e.g. because it wants be a fair player on global resource markets), implying $\Omega = 0$.

Corollary 2. *When $\lambda = 0$ and region A takes the global resource price as given, that is, it ignores (11), the optimal carbon tax and CDR subsidy are*

$$\hat{\tau} = -\left(1 + \frac{\partial \phi}{\partial E^A}\right) F D' \tag{23}$$

$$\hat{\varsigma} = -\left(1 + \alpha \frac{\partial \phi}{\partial E^A}\right) F D' = -\left(1 - \frac{\partial \phi}{\partial R}\right) F D' \tag{24}$$

Proof. In this case, the government of A maximizes a simpler version of (9), namely

$$C = F(L^A, E^A) D(E^A + E^W - R) - pE^A - h(R) \tag{25}$$

where p is treated as a constant. The rest of the proof is the same as in Proposition 4. $\square$

With Corollary 2 we can put the wedge between removal subsidy and carbon tax into perspective with respect to prior studies on carbon leakage. Consider the supply-side leakage rate $LR_s := -\frac{dE^W}{dE^A}|_{D'=0}$, which disregards the impacts of climate change. This is common in this literature (e.g. in Branger and Quirion, 2014), and various numerical or empirical models on carbon leakage provide estimates of LR_s (which corresponds to our emission reduction leakage rate).

Proposition 5. *If the motive to capture the resource rent is disregarded and region A owns no fossil resources ($\lambda = 0$), the wedge between the optimal CDR subsidy and the optimal carbon tax depends only on the supply-side leakage rate LR_s.*

$$\frac{\hat{\varsigma}}{\hat{\tau}} = \frac{1}{1 - LR_s} \tag{26}$$

Proof. Following from (23) and (24), we have to calculate $\frac{1-\frac{\partial \phi}{\partial R}}{1+\frac{\partial \phi}{\partial E^A}}$. With $LR_s := -\frac{dE^W}{dE^A}|_{D'=0} = \frac{c''}{c'' - F^W_{EE} D}$, we obtain by re-arranging $c'' = \frac{F^W_{EE} D}{1 - LR_s^{-1}}$. Substituting this into (5) and (6) we get the result. $\square$

Eq. (26) provides a clear intuition on the optimal wedge between carbon taxes and CDR subsidies, which is determined only by the supply-side leakage rate. If supply side leakage is very high, the optimal CDR subsidy becomes a multiple of the carbon tax, without any upper bound. If supply-side leakage is very small, the CDR subsidy rate converges to the carbon tax rate. Table 1 shows optimal subsidy/tax wedges for selected empirical estimates of supply-side leakage rates. From this literature follows that optimal carbon removal subsidies could be significantly higher than carbon taxes (when resource price effects are disregarded).

LR	$\hat{\varsigma}/\hat{\tau}$	Source
0.1-0.3	1.11-1.42	(Böhringer et al., 2012)
0.07-0.46	1.07-1.85	(Misch and Wingender, 2021)
1.0	∞	(Sinn, 2008)

Table 1: Optimal subsidy/tax wedges for selected empirical estimates of supply-side leakage rates when resource price effects are disregarded ($\Omega \approx 0$).

5 Conclusions

Our results challenge the intuition of equal carbon prices for positive and negative emissions by considering the more realistic setting of an internationally fragmented climate policy regime. To the best of our knowledge, our study is the first to shed light on the question of how a pricing policy for CDR in more realistic second-best settings should be designed.

Our stylized static model generated the following insights: The optimal carbon tax differs from an optimal CDR subsidy because of different carbon leakage, terms-of-trade and fossil resource rent motives. With respect to the carbon leakage channel, the optimal removal subsidy tends to be larger than the carbon tax because of lower supply-side leakage on fossil resource markets. This is reinforced for resource owning countries which aim to set removal subsidies higher than carbon taxes to increase resource prices and, thus, resource rent income. Finally, the terms-of-trade effect is ambiguous and depends on the resource trade balance: Net resource exporters aim to increase international resource prices by lower carbon taxes and larger removal subsidies. A resource-poor country may even find it optimal to have a larger carbon tax than a removal subsidy when marginal environmental damages are small – as the gains from altering the terms-of-trade may outweigh environmental benefits.

Future research may explore further aspects that imply a separate price for removing carbon versus reducing carbon emissions. Examples include distortive tax systems; geological storage sites that are open-access and thus suffer from inefficient dynamic allocation; or when carbon removal is not permanent but small amounts of CO_2 leak out of storage sites over time.

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