Limits to Limiting Greenhouse Gases: Intertemporal Leakage, Spatial Leakage, and Negative Leakage

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Work in Progress

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Abstract

This paper contributes to the recent literature on the Green Paradox (Hoel, 2011 and Harstad, 2012) that distinguishes between regulated and unregulated regions in a Hotelling framework. In our model, different grades of oil are characterized by different costs, emission factors, and underground reserves; furthermore, the clean backstop experiences cost-reducing technical change. As a result, even unregulated consumers may switch from fossil fuels to the backstop before exhausting them. Hence, cumulative emissions reductions can occur in this model, and we identify circumstances in which reducing emissions in the regulating coalition also induces reductions among unregulated consumers—"negative leakage." Increasing an emissions tax, increasing the size of the regulated coalition and accelerating backstop cost reductions are policy substitutes for achieving a target emissions reduction. Given the difficulties in securing international cooperation on global warming, promoting technical change in clean energy sources may be a more effective instrument for reducing carbon emissions.

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), stabilizing carbon dioxide (CO2) concentrations at levels that would avoid the largest risks of climate change could require global emissions to peak in the next 20 years (IPCC 2007). Although several countries are taking significant steps to reduce their own GHG emissions, their efforts may be partially (or completely) offset by the actions of others, resulting in "carbon leakage."

Some leakage results from the lack of comparable emissions regulation among trading partners. Although much attention is paid to the competitiveness of energy-intensive manufacturing, modeling studies show that the larger leakage potential comes through adjustments in global energy prices.[1] If, for example, a regulated region reduces its demand for fossil fuels by imposing emissions taxes, then the reduced demand would depress the world price of oil, which in turn would stimulate oil demand and with it economic activity in parts of the world where carbon emissions are not regulated. This kind of "spatial leakage" has been estimated as falling in the 10-30% range (Babiker and Rutherford 2005 and Boehringer et al. 2012).

Even if every part of the world is regulated, however, leakage can still occur over time. Current oil prices are well above costs for some of the world's largest reserves, leaving ample room for price reductions if consumers begin switching from heavily taxed fossil fuels to clean, increasingly affordable substitutes. Moreover, if climate policies make selling fossil fuels in the distant future less attractive than current sales, suppliers may prefer to extract more in the present, offsetting future emissions reductions.

Sinn (2008) and other early investigations of this type of "intertemporal leakage" (e.g., Strand 2007, Grafton et al. 2010, and Charkravorty et al. 2011) relied on assumptions that imply that all oil would ultimately be extracted; specifically, marginal costs of extraction are independent of the amount previously extracted (and often zero). As a result, the cumulative carbon content of the underground reserves ultimately ends up in the atmosphere, so the primary focus is the timing of emissions and the cost of climate damages discounted to the present. A central issue throughout this debate has been the role of technology policies that lower the costs of an alternative energy backstop. In models where these cost reductions do not reduce cumulative carbon emissions, their only effect is to accelerate emissions and worsen damages in present value terms. Sinn (2008) popularized this notion as the "green paradox."

A second generation of intertemporal models took account of heterogeneity in the extraction costs of different fossil fuel reserves. Once the assumption that reserves were homogeneous was replaced, climate policies such as emissions taxes were predicted to be effective in limiting cumulative carbon emissions. Gerlagh (2011), Van der Ploeg and Withagen (2010), and Fischer and Salant (2012) show that climate policies can render high-cost pools of fossil fuels too expensive to utilize. This second generation of intertemporal models implicitly assumed, however, that policies to mitigate emissions would be applied uniformly around the world, ignoring spatial leakage.

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[1] A variety of studies using *static* computable general equilibrium models (CGE) models have shown the sensitivity of leakage to fossil fuel supply elasticities (e.g. Burniaux and Martins 2000; Mattoo et al. 2009).

In reality, of course, *both* spatial and intertemporal leakage occur at the same time. Even if the marginal cost of extraction is flat at any given time, an increase in emissions taxes in one part of the world can depress the price paid by unregulated consumers elsewhere because the value of oil in the ground (the so-called Hotelling resource rent) falls. Hoel (2011) pointed out that "In almost all of the body of literature referred to above, the economy analyzed is a single unit; in the context of climate policy, it seems reasonable to interpret this as the whole world ... This is in sharp contrast to reality. Carbon taxes and other climate policies differ substantially across countries."

Hoel (2011) initiated a third generation of Hotelling models that allow for different stringencies of climate regulation among regions of the world. In Hoel's model, a homogeneous fossil fuel in fixed global supply is extracted at zero cost, and a perfect substitute is available at constant marginal cost. Consumers are divided into two regions, each of which imposes stationary policies—a tax on fuel consumption and/or a subsidy for using the backstop. He considers the effects of changes in one region's policy, given an unchanged policy in the other region. Hoel did not consider climate policies sufficient to reduce the cumulative amount of carbon eventually going into the atmosphere; his focus instead was on the time profile of these emissions.

Similarly, Eichner and Pethig (2011) distinguish between regulating, nonregulating, and fossil-fuel exporting countries. They use a two-period model to assess the effects of policy timing and rates of intertemporal substitution on the green paradox. They find that increasing the size of the regulating coalition tends to reduce carbon leakage. However, they do not consider a role for a backstop technology.

Recently, Harstad (2012) explored a novel policy that had previously been overlooked. He pointed out that if the unextracted deposits located in the unregulated region could be acquired by governments in the regulated region, these deposits could be sequestered so that they would not leak out and undermine the regulated region's subsequent attempts to raise the prices consumers pay for fossil fuels via taxes imposed on extractors in the regulated region. Harstad's assumption that any such deposit, once acquired, could be sequestered or controlled by the regulated region at zero cost seems extreme. But there may well be some deposits for which the policy he proposed would be practical. Moreover, his focus on the *simultaneous use* of two or more policy instruments is also valuable.

In second-generation models, the equilibrium is unaffected by whether the government collects the tax from demanders or from suppliers. In third generation models, however, only agents in the regulated region can be taxed. In this circumstance, it does matter who pays the tax. In particular, a tax on demanders in the regulated region would cause the price received by suppliers in both regions (and by demanders in the unregulated region) to decline. On the other hand, a tax on suppliers in the regulated region would cause the price paid by demanders in both regions (and received by suppliers in the unregulated region) to rise. The former tax stimulates foreign demand (and reduces foreign supply) while the latter tax has the opposite effects. Hence, in third generation models, one must be careful when specifying tax policies to identify who pays the tax. In Hoel (2011), for example, demanders in the regulated region pay the tax; in the preliminary example in Harstad (2012), suppliers in the regulated region pay the tax. In practice, all existing climate policies focus on energy consumption; no country has yet showed a willingness to disadvantage its own extraction sector by taxing it for the emissions its output of fossil fuel will subsequently generate.[2]

In what follows, we contribute to this third generation of models. We assume that the world is divided into a regulated and an unregulated region, as is common in the static models of spatial leakage. Like Hoel (2011), we consider an emissions tax imposed on consumers, in this case only in the regulated region; we also consider a technology policy that accelerates cost reductions in backstop and a negotiation policy of expanding the coalition of regulating countries. One could also incorporate the approach of Harstad (2012) by assuming that some underground reserves are sequestered initially; in essence, one could regard the heterogeneous pools in our model as those remaining after such a policy is implemented.

Unlike Hoel (2011), we assume that pools differ in extraction costs, and that the marginal costs of energy from a clean backstop, although high initially, decline over time due to exogenous technological change. Our focus differs as well, as we explore the tradeoffs among policy options. We investigate how much each climate policy pursued by the regulated region can reduce global emissions when consumers in the rest of the world are unregulated and extractors are free to lower fossil fuel prices when faced with competition from the backstop. Previous studies made assumptions insuring complete exhaustion which, by definition, always results in 100% carbon leakage—that is, any reductions by the regulated consumers are ultimately offset by the consumers in the unregulated region. In our model, incomplete exhaustion can occur in equilibrium. We identify situations where leakage, although positive, is smaller and even several circumstances where it is *negative.* "Negative leakage" occurs when a given policy induces unregulated consumers to cut back their own emissions, *reinforcing* the emissions reductions of consumers in the regulated region.

To fix ideas at the outset, we assume that there are only two grades of fossil fuel in the world, low cost and high cost. We focus on regimes where one or both of the pools are incompletely exhausted, as this is the relevant case for reducing meeting emission reduction goals.[3] These cases cannot arise in Hoel's model since he assumes a zero extraction cost and the backstop marginal cost is always higher. If the clean backstop is never cheaper than even the highest cost fossil fuel, then combustion of fossil fuels in the unregulated region will eventually result in 100% leakage: an undiminished amount of carbon will be released into the atmosphere even if emissions taxes are high enough to induce regulated consumers to use the clean backstop from the outset.

In the presence of technical change, however, the regulated region can use emissions taxes to reduce cumulative global emissions provided its share of global demand for fossil fuels is sufficiently large. We assume that emissions taxes grow at the real rate of interest and so maintain a constant present value. As we show, cumulative carbon emissions are a decreasing function of (1) emissions taxes, (2) the share of world demand in the regulated region, and (3) the speed of cost-reducing technical change in the backstop. Hence, policies that

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[2] Norway does tax offshore drilling but only for its own CO_2 emissions. Similarly, Alberta has an intensity-based emissions credit trading program for large emitters, primarily oil-sands upgraders.

[3] In the Appendix, we describe the competitive equilibrium if both pools are completely exhausted, which generalizes Hoel (2011) to the case of multiple pools; in this case, the same amount of carbon is released into the atmosphere in all such equilibria.

strictly increase any one of these parameters are substitutes. Typically the same cumulative emissions target can be achieved using any of a set of these three policies. However, the policies can have different implications for leakage.

Furthermore, if the global demand share of the regulating coalition is smaller than some minimal threshold, it cannot reduce cumulative global emissions no matter how high it sets emissions taxes. Similarly, if the regulated coalition share, while bigger than this minimal threshold, is still below some higher threshold, then it cannot reduce emissions from the low-cost pool, although it can eliminate those coming from the higher cost pool.

Our model clarifies the significant benefits which technology-oriented policies can provide. First, accelerating cost reductions in the backstop induces consumers not just from the regulated region but also from the unregulated region to reduce emissons. Second, more rapid cost reductions in the backstop technology reduce the minimum coalition size required to influence cumulative emissions. Thus, rather than exacerbating climate damages, technology policies can serve to create greater scope for climate policy actions. After describing such policy tradeoffs and thresholds theoretically, we calibrate a model to estimate them empirically.

We proceed as follows. In Section 2, we describe our model. The model takes as exogenous three parameters: the fraction of world demand subject to regulation, the emissions tax within that sector, and the rate of cost-reducing technical change in the green backstop. In Section 3, we determine the equilibrium effects of changing each of these parameters. We first consider the case where the two pools have the same emissions factor. We then show how strikingly different results can occur if the two pools have sufficiently different emissions factors. In Section 4, we derive two thresholds: the smallest coalition capable of reducing emissions from the high-cost pool and from the low-cost pool. As we show, a much larger coalition is required to reduce emissions from the low-cost pool. These two thresholds are each decreasing functions of the speed of backstop cost reductions. In Section 5, we calibrate a five-pool generalization of our theoretical model and simulate it. Our analysis of the theoretical model illuminates the simulations in the calibrated model. Section 6 concludes the paper.

2 The Two-Pool Model

2.1 Assumptions

In this section, we consider the case in which oil from two pools with different per-unit extraction costs ($c_L < c_H$) is sold in a competitive market. The insights we gain will illuminate behavior that occurs in our 5-pool, calibrated simulation model discussed in Section 5.

Denote the initial size of the underground stocks as S_L and S_H. At time t, a carbon-free backstop technology is available in unlimited capacity at constant marginal cost $B(t; z)$, where z denotes the intensity of cost-reducing technical change. The backstop is initially too expensive to warrant consideration by consumers: $B(0; z) > c_H > c_L$. In the absence of technical change ($z = 0$), the marginal cost of the backstop would remain forever higher than the cost of extracting the most expensive pool: $B(t;0) > c_H$ for all t. Because of technological improvements ($z > 0$), however, the marginal cost of the backstop is assumed to decline exogenously over time toward a long-run cost, B_{LR} $(= \lim_{t\to\infty} B(t;z) < c_L)$.[4] We assume that the parameter z can be increased by government policy. In the baseline scenario, we assume that this per-unit cost declines slowly enough $(z = z_0 > 0)$ that the two pools of oil are completely exhausted before the backstop is utilized.

Demand is split into two regions, regulated (R) and unregulated (U). We assume that the demand per person is stationary and so is the world population. Denote the world demand function at time t as $D(\cdot)$. So if the N consumers in the world have identical demand curves, each has demand $D(\cdot)/N$. If N_U of those demanders are in the unregulated sector and N_R of them are in the regulated sector, the demand in sector i $(i = \{U, R\})$ is $\frac{N_i}{N}D(\cdot)$. Let α denote the fraction of the N consumers who are regulated. Then $\alpha = N_R/N$. Denote the price consumers pay in region i at time t as $p_i(t)$, $i = \{U, R\}$. Then the quantity demanded in region R at time t is $\alpha D(p_R(t))$ and demand in the unregulated region at time t is $(1-\alpha)D(p_U(t))$, where $\alpha \in [0, 1]$. The interest rate is assumed exogenous and is denoted r. A tax with present value τ per unit of emissions is levied at each instant on consumers of fossil fuels in the regulated region, while no emissions tax is imposed on consumers in the unregulated region.[5]

Denote the present value of a barrel of low-cost and high-cost oil in the ground as λ_L and λ_H, respectively. Let π_t be the cost of acquiring a barrel of type i $(i = L, H)$ oil and bringing it to the surface: $\pi_i(t) = c_i + \lambda_i e^{rt}$. Assume that transportation costs are zero. Then $\pi_i(t)$ is also the price consumers in the unregulated region must pay at time t to obtain oil from source i. $\pi_i(t)$ weakly increases over time.

We consider an emissions tax regime in the regulating region in which the tax rises at the interest rate.[6] Let μ_j $(j = \{L, H\})$ denote the emissions factor of each pool. We assume that emissions taxes of $\tau\mu_i e^{rt}$ per barrel are added to the producer price in region R and are collected at time t from regulated consumers. Consumers in each region choose at each instant the least-cost energy source. Thus, consumers in the regulated region pay $p_R(t) = \min(\pi_L(t) + e^{rt}\tau\mu_L, \pi_H(t) + e^{rt}\tau\mu_H, B(t;z))$ while consumers in the unregulated region pay $p_U(t) = \min(\pi_L(t), \pi_H(t), B(t;z))$.

Since no oil is stored aboveground, prices adjust so that in equilibrium everything extracted is purchased by consumers in the two regions. If at time t the low-cost (respectively, high-cost) oil is cheapest of the three energy sources for at least one of the two groups of consumers, then $q_L(t) > 0$ (respectively, $q_H(t) > 0$). The aggregate flow of emissions at time t (denoted $M(t)$) is assumed to be equal to the sum of quantity of oil produced from each pool at time t, multiplied by its emissions factor: $M(t) = \mu_L q_L(t) + \mu_H q_H(t)$. Therefore, cumulative emissions, E, are $E = \int_0^\infty M(t)dt$. Carbon emissions can be reduced only by

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[4] It can be verified that the marginal-cost function used in the simulations, $B(t;z) = B_{LR} + (B_0 - B_{LR})e^{-zt}$, satisfies each of these properties.

[5] A cap-and-trade program with bankable permits would be equivalent if the exogenous quota was set equal to cumulative emissions of the regulated consumers under the emissions tax.

[6] This corresponds to the optimal tax policy for meeting a given cumulative emissions target or more generally if the social cost of carbon rises over time at the interest rate.

reducing cumulative usage of either the high-cost or low-cost pool.

In what follows we disaggregate cumulative emissions according to the fossil fuel which generates them. If the two sources are the low-cost and high-cost pools, we would denote the cumulative emissions resulting from the oil extracted from each pool as E_L and E_H, where $E_L + E_H = E$. We also focus on the emissions per consumer in each region, E_U and E_R. Since $N_U E_U + N_R E_R = E$, emissions per capita in the world are $\alpha E_R + (1-\alpha)E_U = E/N$.

Gaudet, Moreaux and Salant (2001) generalize Hotelling's (1931) exhaustible resource model for the case where extractors and consumers are spatially separated. The GMS framework assumes that there is an endogenous, pool-specific cost (the shadow price of a unit of underground oil in a given pool) and an exogenous cost per unit to get oil from that pool to a given consumer. This exogenous, region-specific cost of a pool is the sum of three components: the per-unit cost of (1) extraction, (2) transportation, and (3) taxes. In the case we consider here, there are two sets of consumers, regulated and unregulated. The GMS framework, however, permits disaggregation of the regulated region into an *arbitrary number* of countries with different types of CO_2 regulation. Since we assume $c_H > c_L$, zero transportation costs, and $\mu_H \geq \mu_L$, pool L has a lower per-unit cost sum than pool H for each region.

GMS (2001) establish that no consumer in one region will abandon a pool with a higher per-unit cost sum and subsequently use a pool with a lower per-unit cost sum. In this sense, consumers in each region will use pools in order of their region-specific per-unit cost sums. GMS (2001, p.1153) refer to this as the "Generalized Herfindahl Principle." Unlike Herfindahl's nonspatial case, however, consumers in one region may switch to a higher cost resource *before* the lower cost resource is exhausted.[7] For when the consumers in one region are indifferent between two resources, consumers in the other region will find one resource strictly cheaper unless the difference in the exogenous per-unit cost sums of the two pools happens to be the same in the two regions.[8] Since the backstop becomes cheaper over time, the only temporal sequences that are possible for each region are: $L \to H \to B$ or $L \to B$ or $H \to B$ or B. We denote the date when regulated and unregulated consumers switch to the high-cost fossil fuel (respectively, to the backstop) as x_H^R, x_H^U (x_B^R, x_B^U).

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[7] The Hotelling model is often criticized because of its implication, noted by Herfindahl (1967), that no consumer will touch a higher cost resource until a lower cost resource is exhausted. This should not be taken as a basis for discarding the Hotelling framework but for dispensing with its most unrealistic assumption—that the exogenous cost of getting each resource to users is the same no matter where the users are located. In reality, consumers in different regions pay different prices for oil from the same pool. Although the cost of a barrel underground and the cost of bringing it to the surface (π_i) are the same for all users, there are *other* costs that are region-specific: in particular, the cost of transporting oil to a given region and the taxes specific to that region. Once these are taken into account, the Hotelling model *no longer* predicts that users will all exploit the same energy source at the same time, switching to the next resource only when the first one is exhausted.

[8] The difference in the per-unit cost sums of two pools is the same for all users in Herfindahl's model because there are no transport costs or emissions taxes. Hence, the difference in the per-unit cost sums of the two pools is simply the difference in their extraction costs. Even if only one of the two regions was taxed, the difference in the per-unit cost sums of the two pools would be the same in the two regions as long as the two pools had the same emissions factors. In that case, the transition from one pool to the next would still occur at the same time for both regions. For a more extensive discussion, see GMS (2001, pp. 1153-55).

In a model with any number of pools, we can distinguish two types of equilibria, referred to as regime A and regime B in Fischer and Salant (2012). In regime A, all pools that are utilized are fully exhausted and the scarcity rent on each of them is, therefore, positive. In regime B, part of the highest cost pool which is utilized is left in the ground and its scarcity rent is zero. Since marginal changes in policy affect cumulative emissions in regime B but not regime A, we focus here on regime B and relegate discussion of regime A to the Appendix.

2.2 Equilibria with incomplete extraction

Consider the situation where pool L is fully exhausted and pool H is partially exhausted ($\lambda_L > 0, \lambda_H = 0$). Given the Generalized Herfindahl Principle established in GMS, we know that each region will select one of the following four orders: $L \to H \to B$ ("LHB"), $L \to B$ ("LB"), $H \to B$ ("HB"), and B ("B"). Of these 16 possible pairs of orders, however, 7 can be eliminated because some pool is untouched by both regions (for example, if each region used only B); and another 4 can be eliminated because they would reflect suboptimal behavior. Thus, the unregulated consumers cannot use L initially while the regulated consumers use H since if L is cheaper for the unregulated users it must also be cheaper for the regulated users; this eliminates two pairs of sequences (LHB, HB) and (LB, HB), where first component is the sequence chosen in equilibrium by the unregulated consumers. Similarly, the unregulated consumers cannot use B initially while the regulated consumers use L since since if the unregulated consumers find L more expensive so will the regulated consumers, who must pay taxes on their emissions; this eliminates one more pair of sequences (B, LHB). Finally, we can eliminate the pair of sequences (LB,LHB) provided $\mu_H > \mu_L$. For at x_H^R the regulated consumers find L and H equally attractive and cheaper than B. It follows that the unregulated consumers would at that time find H cheapest, followed by L, and then B. Thus, it could not be cost-minimizing for the unregulated consumers to choose L or B instead of H.[9]

We conclude, therefore, that there are five possible patterns of resource use in the two regions when emissions factors differ: either the unregulated region uses the resources in the order (LHB) while the regulated region uses them in one of the following three orders (1) LHB, (2) LB, or (3) B; alternatively, the unregulated region uses them in the order HB and the regulated region can use them in the following two orders (4) LHB (5) LB.[10] In what follows, we focus on the first three of these cases. As the regulation becomes more stringent the equilibrium would shift from case (1) to case (2) to case (3).

Let $\theta_H \in (0, 1)$ denote the fraction of the high-cost pool that is depleted in the equilibrium. Thus, we have six equations defining the six endogenous variables $(\lambda_L, \theta_H, x_H^R, x_B^R, x_H^U, x_B^U)$:

$$\alpha \int_{t=0}^{\min(x_H^R, x_B^R)} D(c_L + e^{rt}[\lambda_L + \tau\mu_L])dt \quad + \quad (1-\alpha)\int_{t=0}^{x_H^U} D(c_L + \lambda_L e^{rt})dt = S_L \qquad (1)$$

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[9] When $\mu_H = \mu_L$, we cannot eliminate this last case but can still eliminate the other four.

[10] Equilibria in regime A (see Appendix) must also exhibit one of these five patterns.

$$\alpha \int_{t=\min(x_H^R, x_B^R)}^{x_B^R} D(c_H + e^{rt}\tau\mu_H)dt \; + \; (1-\alpha)\int_{t=x_H^U}^{x_B^U} D(c_H)dt = \theta_H S_H \tag{2}$$

$$c_H + e^{rx_H^R}\tau\mu_H \; = \; c_L + e^{rx_H^R}[\lambda_L + \tau\mu_L] \tag{3}$$

$$c_H \; = \; (c_L + \lambda_L e^{rx_H^U}) \tag{4}$$

$$B(x_B^U; z) \; = \; \min(c_H, c_L + \lambda_L e^{x_B^U}) \tag{5}$$

$$x_B^R \geq 0,\ B(x_B^R; z) - \min\{c_L + e^{rx_B^R}[\lambda_L \; + \; \tau\mu_L], c_H + e^{rx_B^R}\tau\mu_H\} \leq 0,\ c.s. \tag{6}$$

The transition dates always exhibit distinctive patterns.[11] If $\mu_L = \mu_H$ and the regulated and unregulated regions each utilize both pools, then they must switch to the higher cost pool at the *identical* time ($x_H^R = x_H^U$). For on the date when the regulated consumers find the two pools equally attractive, so will consumers who pay no taxes. However, if $\mu_L < \mu_H$, the regulated consumers would be paying a strictly higher tax per barrel on the high-cost pool. Consequently, on the date when the unregulated consumers find the two fossil fuels equally costly, the regulated consumers will find the lower cost pool cheaper, implying that they switch later to the high-cost pool ($x_H^U < x_H^R$).

More formally, if both regions switch from the low-cost to the high-cost pool ($x_H^U > 0, x_H^R > 0$), then equation (**??**) and (**??**) imply

$$c_L + \lambda_L e^{rx_H^U} \; = \; c_H \tag{7}$$

$$c_L + (\lambda_L + \tau\mu_L)e^{rx_H^R} \; = \; c_H + \tau\mu_H e^{rx_H^R}. \tag{8}$$

If the two pools have the same emissions factor ($\mu_L = \mu_H = \mu$), the terms involving τ on the left and the right-hand side of equation (**??**) cancel, and these two equations each must be solved by the same date of transition to the high-cost pool (x_H); that is, $x_H = x_H^U = x_H^R$. Hence, consumers in the two regions switch on the same date. Moreover, each of these equations implies that $x_H(\lambda_L)$ is strictly decreasing: the lower the rent on the low-cost pool, the later will be the transition to the high-cost pool. If instead the high-cost pool had a strictly higher emissions factor, then at x_H^U the unregulated consumers would switch to the high-cost pool but since the tax on it is higher ($\tau\mu_L e^{rx_H^U} < \tau\mu_H e^{rx_H^U}$), the right-hand side of (**??**) would be strictly larger than the left-hand side and the regulated consumers would continue to use the low-cost pool. Hence, $x_H^U < x_H^R$.

Similarly, when the regulated consumers eventually switch to the backstop ($x_B^R > 0$), the unregulated consumers will still be using fossil fuel ($x_B^R < x_B^U$). For, if the cost of the backstop is at that instant were equal to the cost of the taxed fossil fuel, then consumers not obliged to pay an emissions tax will find the fossil fuel cheaper than the backstop.

More formally, at $x_B^R > 0$, equation (**??**) reduces to $B(x_B^R; z) = c_i + (\lambda_i + \tau\mu_i e^{rx_B^R})$, where i denotes the fossil fuel the regulated consumers use just prior to switching to the backstop. Clearly, $B(x_B^R; z) > c_i + \lambda_i e^{rx_B^R}$, so at that date the unregulated consumers would continue to use fossil fuel.

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[11] These arguments apply equally to complete exhaustion case in the Appendix.

Together these two observations ($x_H^U \leq x_H^R$ and $x_B^R < x_B^U$) imply that if each region utilizes all three sources and $\mu_H \geq \mu_L$, the regulated consumers will begin weakly later and end strictly earlier their extraction from the high-cost pool.

3 Comparative Statics

We now consider the consequences of varying exogenous policy parameters. We first consider the case where the two emissions factors are the same; then we consider the more realistic case where the higher cost pool has a higher emissions factor. As we will see, the effects of these policies on emissions and transition dates depend on the change they induce in the rent on the low-cost pool.

Since the impact of environmental policies on the oil industry sometimes seems to determine its political viability, we note that the present discounted value of profits earned by the low-cost extractors is $\lambda_L S_L = (p(0) - c_L)S_L$. Hence any policy that raises λ_L raises the wealth of the owners of the low-cost reserves.

3.1 Equal Emissions Factors ($\mu_H = \mu_L = \mu$)

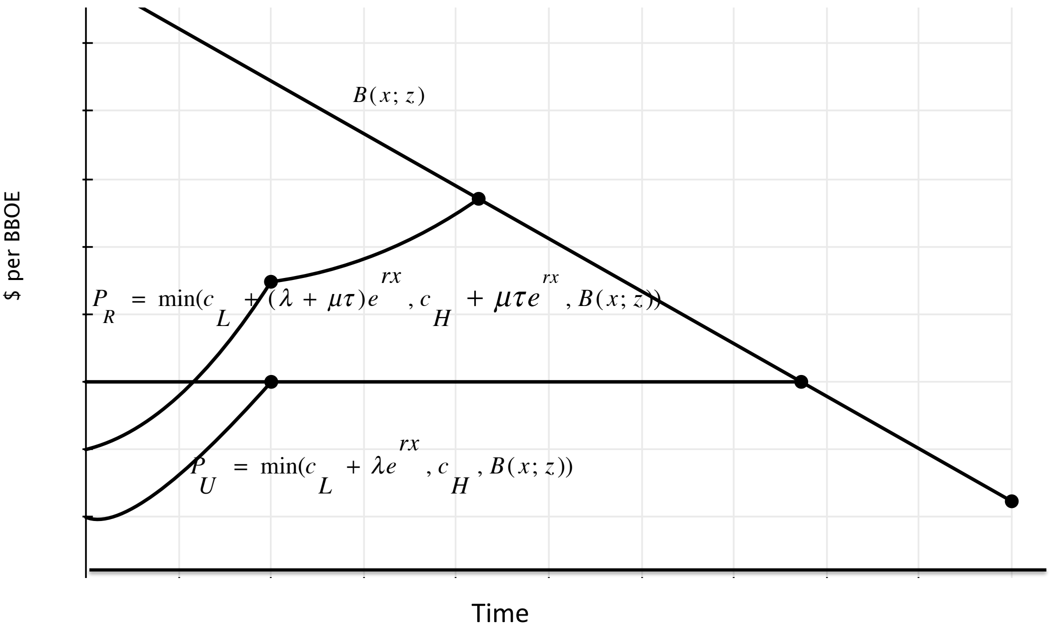
Assume the emissions per unit output is the same for the two pools ($\mu_L = \mu_H = \mu$). Cumulative global emissions and the other endogenous variables depend on the three exogenous policy parameters: the emissions tax (τ), the speed of technological change in the backstop (z), and the share of world demand that is regulated (α). We consider how an increase in each policy affects the equilibrium in our model. For each policy, we first consider the case where consumers in the regulated region, like those in the unregulated one, use both the low-cost and the high-cost pool before switching to the backstop (LHB, LHB). Then we consider the case where both regions exhaust the low-cost pool but only the unregulated consumers use the high-cost pool; the regulated consumers switch directly to the backstop (LHB,LB). Equation (1) holds in each case. Moreover, in the former case, $x_H^U = x_H^R = x_H(\lambda) < x_B^R$, and equation (1) simplifies to:

$$\alpha \int_{t=0}^{x_H(\lambda)} D(c_L + e^{rt}[\lambda_L + \tau\mu_L])dt + (1-\alpha) \int_{t=0}^{x_H(\lambda)} D(c_L + \lambda_L e^{rt})dt = S_L \tag{9}$$

3.1.1 An Increase in the Emissions Tax Rate

We first consider the case where the regulated region, like the unregulated one, uses both the low-cost and the high-cost pool before switching to the backstop (LHB, LHB). If λ_L were to rise in response to an increase in the emissions tax, then each integrand would fall and the upper limits of integration would fall. In that case, cumulative demand would be strictly smaller than the unchanged stock (S_L). If instead, λ_L were to remain unchanged, then the second integrand would fall while the upper limits and the first integrand would remain unchanged. Again cumulative demand would no longer equal the unchanged stock.

Figure 1: Equal Emissions Factors and (LHB, LHB)



It follows that λ_L must fall. However, if the decrease in λ_L were to outweigh the increase in $\mu\tau$ so that $\lambda_L + \mu\tau$ fell, then both integrands would strictly increase as would both upper limits of integration. In that case, cumulative demand for the low-cost pool would exceed the unchanged reserve stock.

Therefore to restore equilibrium when the tax rate increases, λ_L must fall but $\lambda_L + \mu\tau$ must rise. As a result, regulated consumers will use the low-cost resource less intensively while the unregulated consumers will use it more intensively before switching to the higher-cost pool. Furthermore, both users will simultaneously switch to the high-cost pool at a later date. After that point, unregulated consumers will utilize the high-cost pool at the same rate ($(1 - \alpha)D(c_H)$) and until the same date as before, while the regulated consumers utilize less and switch to the backstop sooner. Hence, the unregulated consumers extract more than before the tax increase and have larger cumulative emissions (positive leakage), while the regulated consumers extract less of both pools and have lower emissions.

Although the cumulative emissions of the unregulated users increase, they do not fully offset the reductions of the regulated users. Since the low-cost pool is fully extracted, emissions from it are unchanged. But both regulated and unregulated consumers use the high-cost pool less intensively and for a shorter time interval. Hence, more of the high-cost reserves are left in the ground and cumulative emissions from the high-cost pool are smaller.

If the emissions tax is sufficiently stringent, the regulated region might skip the high-cost pool entirely and switch from the low-cost pool directly to the backstop. The effect of an increase in the emissions tax in this (LHB, LB) case is exactly the same as in the previous (LHB, LHB) case.[12]

3.1.2 An Increase in the Speed of Technological Change in the Backstop

Next, we consider the case where the per-unit cost of the backstop falls faster (an increase in z). As before, we first consider the case where the regulated region, like the unregulated one, uses both the low-cost and the high-cost pool before switching to the backstop. In this (LHB, LHB) case, both the regulated and unregulated consumers switch to the backstop sooner (both x_B^R and x_B^U decrease), but rents on the low-cost resource do not change. Consequently both the regulated and unregulated consumers deplete the low-cost pool at unchanged rates and switch simultaneously at an unchanged time to the high-cost pool; each group also consumes that pool as before but each group switches earlier to the backstop. In short, cumulative usage of the low-cost pool continues to equal the unchanged reserves and since more of the high-cost pool is left in the ground, cumulative emissions from the two pools fall. In this case, we have negative leakage, as the unregulated consumers use the low-cost pool exactly as before but consume less of the high-cost pool.

If the emissions tax is sufficiently high, consumers in the regulated region switch directly from the low-cost pool to the backstop while those in the unregulated region utilize each of the three energy sources in sequence (LHB, LB). In the previous case (LHB, LHB), a marginal increase in the speed of backstop cost reductions had no effect on rents or transition dates since consumers in both regions switched from a pool with zero rent (the high-cost pool) to the backstop. But when the regulated region switches from a pool with strictly positive rent (the low-cost pool) to the backstop, the Hotelling rent on the low-cost pool must decline or the earlier abandonment of that pool by the regulated consumers would result in insufficient cumulative demand for the unchanged low-cost stock. Because the rent on the low-cost pool declines, each sector uses it more intensively. Since the unregulated consumers switch to the high-cost pool at a later date, they use more of the low-cost pool. Consequently, the regulated consumers must deplete less of it despite consuming it at a faster rate. This occurs because the regulated consumers switch *earlier* from the low-cost pool to the backstop (i.e. x_B^R decreases). Because low-cost extractors still charge unregulated consumers (c_H) per barrel but the faster technological change is making the clean substitute more attractive, the

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[12] An increase in the emissions tax must depress the Hotelling rent on the low-cost pool but by less than the increase in the emissions tax per barrel. Therefore, the regulated consumers use less of that pool and the unregulated consumers use more of it. The regulated users therefore switch to the backstop earlier than before while the unregulated users switch to the high-cost pool later but switch to the backstop at an unchanged time. Since the low-cost pool is completely exhausted, emissions from it do not change but since the unregulated consumers deplete the high cost pool at the same rate but for a shorter time interval, emissions from it decline. Consequently the tax increase results in reduced aggregate emisisons. Emissions from the regulated users fall and emissions from the unregulated users increase, partially offsetting the carbon reductions of the regulated consumers.

unregulated consumers switch sooner to the backstop (x_B^U decreases). Cumulative emissions fall because, although there is no change in emissions from the low-cost pool, emissions from the high-cost pool decline. Emissions from the regulated sector decline since it uses less of the low-cost pool. Unregulated consumers, as before, deplete less of the high-cost pool when backstop-cost reductions accelerate; but since—in contrast to the (LHB, LHB) case—they deplete more of the low-cost pool, the change in their cumulative emissions (E_U) is indeterminate.[13]

3.1.3 An Increase in the Coalition Share

Finally, suppose a larger share of world demand is regulated. Consider first the case where the regulated region, like the unregulated one, uses both the low-cost and the high-cost pool before switching to the backstop: (LHB, LHB). Recall that in this case, consumers in each region switch from the low-cost to the high-cost pool at the same time. Since the regulated consumers must pay tax on the low-cost pool, they deplete it at a slower rate until the common date x_H and hence have smaller cumulative demand. When the fraction of world demand subject to regulation increases, cumulative demand for the low-cost pool would fall short of the unchanged stock unless the Hotelling rent on that pool declined. The decline in that rent means that both groups switch later to the high-cost pool (x_H increases). Since rents on the high-cost pool remain zero, each group switches to the backstop at the same dates as before. Emissions from the low-cost pool remain the same. But since each group uses the high-cost pool at unchanged rates and for a shorter time interval and since a greater share of world demand comes from the sector with the smaller demand, total emissions must fall.

As a result, the regulated consumers increase their cumulative depletion of the low cost pool because (1) they face uniformly lower prices, (2) they spend longer on that pool than before, and (3) there are more regulated consumers. Unregulated consumers deplete less of the low-cost pool but, in aggregate, emissions remain μS_L. As for the high-cost pool, both regulated and unregulated consumers begin to simultaneously utilize it later since λ_L is smaller. The two groups switch to the backstop at the same two dates as before. Members of each group actually *increase* their emissions, since their price path is uniformly lower; however, emissions from the high-cost pool (and hence cumulative emissions) decline, since more consumers are made subject to the regulation, lowering their emissions.

If the emissions tax is sufficiently high, the regulated consumers may switch directly from the low-cost pool to the backstop (LHB, LB). In this case, when more consumers become subject to the regulation, the rent on the low-cost pool again declines and the resulting changes differ from the (LHB, LHB) case in only one respect. In the (LHB, LB) case, when more consumers become subject to regulation, the reduced rent on the low-cost pool leads the regulated consumers to switch later to the backstop (x_B^R increases).

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[13] If the unregulated region is sufficiently large, of course, its emissions must fall since total emissions fall.

3.1.4 Comparison of Policy Effects

We summarize these results in the following table, where E_R, E_U denote cumulative emissions per consumer from each region:

Table 1
Comparative Statics: (LHB, LHB) Case with $\mu_H = \mu_L$

	Prices		Switch Dates			Emissions		
Policy	λ_L	$(\lambda_L + \mu\tau)$	x_H	x_B^R	x_B^U	E	E_R	E_U
τ	$-$	$+$	$+$	$-$	0	$-$	$-$	$+$
z	0	0	0	$-$	$-$	$-$	$-$	$-$
α	$-$	$-$	$+$	0	0	$-$	$+$	$+$

Table 2
Comparative Statics: (LHB, LB) Case with $\mu_H = \mu_L$

	Prices		Switch Dates			Emissions		
Policy	λ_L	$(\lambda_L + \mu\tau)$	x_H^U	x_B^R	x_B^U	E	E_R	E_U
τ	$-$	$+$	$+$	$-$	0	$-$	$-$	$+$
z	$-$	$-$	$+$	$-$	$-$	$-$	$-$	?
α	$-$	$-$	$+$	$+$	0	$-$	$+$	$+$

When emissions factors are the same, an increase in any of the policy variables can lower total emissions. The emissions tax hike and coalition expansion policies result in emissions leakage, as lower rents for the low-cost pool drive down prices paid by unregulated consumers. The technology policy, on the other hand, always results in negative leakage in the (LHB, LHB) case; its effect in the (LHB, LB) case is indeterminate.

3.2 Unequal Emissions Factors ($\mu_H > \mu_L$)

In reality, resources that are more costly to extract often have higher emissions factors. If the difference in these factors is trivial, the results in the previous subsection still hold. But if the difference is sufficiently large, strikingly different results emerge.

3.2.1 An Increase in the Emissions Tax Rate

When regulated consumers use some of the high-cost pool (LHB, LHB), an increase in the emissions tax would, in the absence of a change in λ_L, raise what the regulated consumers must pay for oil from the high-cost pool by more than it raises the price of oil from the low-cost pool. As a result, regulated consumers would use the low-cost pool longer, although they would consume it uniformly more slowly because it is more expensive. In this circumstance, it is *possible* for the cumulative demand of the regulated consumers for the low-cost oil to increase.[14]

**Whenever an increase in the emissions tax causes regulated consumers to demand more low-cost oil, λ_L will increase, raising the price for the unregulated consumers as well. They will then use it more slowly, switching earlier to the high-cost pool (since it continues to sell for c_H). Since they switch to the backstop at the same time as before but commence consuming the high-cost pool sooner, unregulated consumption of the higher intensity pool increases. The net effect on emissions from unregulated consumers is ambiguous, since they consume less low-cost oil but more high-cost oil; indeed, if the relative intensity of the latter

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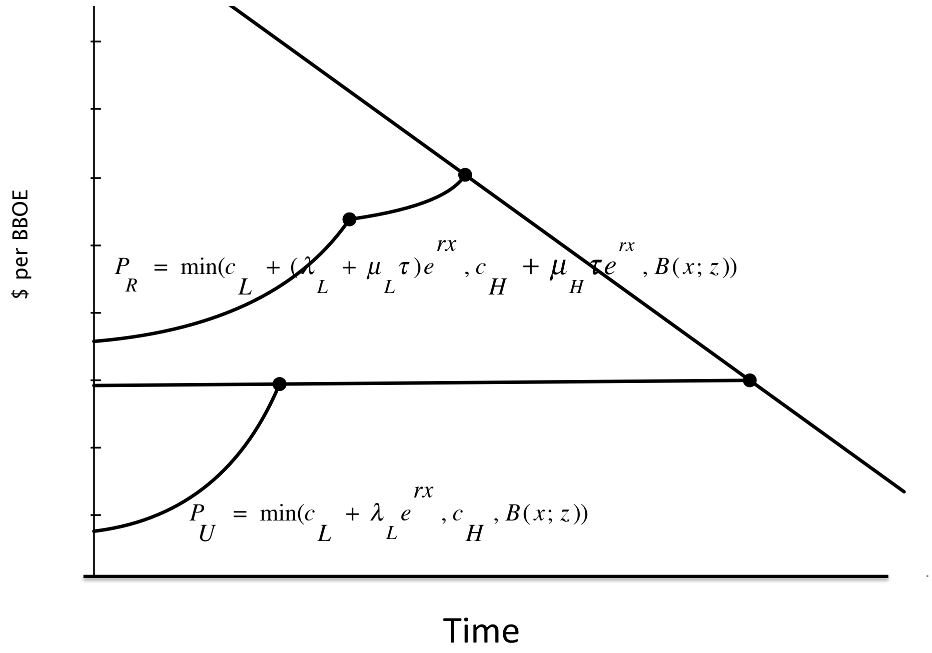
[14] To see this, consider the extreme case where the low-cost pool has a *zero* emissions factor ($\mu_H > \mu_L = 0$). Consumers in both regions would then pay the *same* rising price of low-cost oil but regulated consumers would continue to use it after the unregulated consumers had switched to the high-cost oil. In an absence of a change in the Hotelling rent on the low-cost pool, a tax increase would further delay the time when the regulated consumers switched to the high-cost pool and their cumulative demand for low-cost oil would increase. Since the size of the low-cost reserve is unchanged, the rent on it would therefore have to rise.

Figure 2: Unqual Emissions Factors and (LHB, LHB)

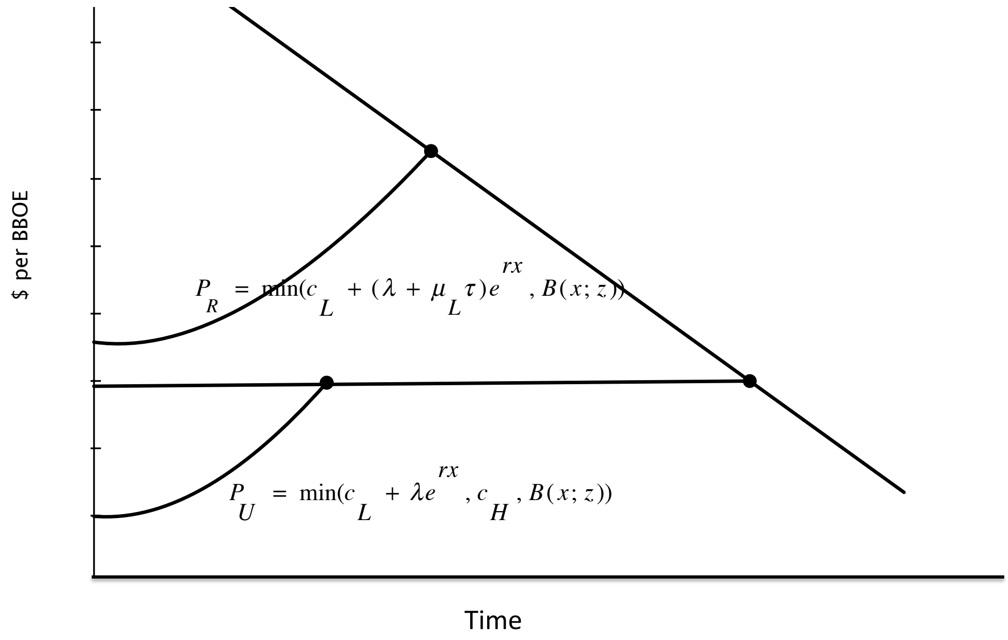


is high enough, their emissions will increase. Regulated consumers extract more of the low-cost oil but at a slower rate, switching later to the high-cost oil and then earlier to the backstop; they necessarily reduce their emissions. Cumulative consumption of the low-cost oil is unaffected, but now cumulative consumption of the high-cost pool is ambiguous. We are investigating whether cumulative emissions can ever increase in response to an increase in the emissions tax.

In the (LHB, LB) case, an increase in the emissions tax can no longer raise the rent on the low-cost reserve. For, if it did, both types of consumers would utilize the low-cost reserve less intensively and would abandon it sooner, meaning cumulative demand for the low-cost reserve would no longer equal the unchanged stock. Similarly, the rent on the low-cost reserve cannot fall so much that it outweighs the increase in the tax per barrel ($\tau\mu_L$); for a reduction in $\lambda_L + \tau\mu_L$ would raise cumulative demand above the unchanged stock.

Hence, after the increase in the emissions tax, the Hotelling rent must fall, but the reduction must not outweigh the increase in the tax per barrel. In response, the unregulated consumers deplete the resource at a more rapid rate and switch to the high-cost resource at a later date. Since the timing of their switch to the backstop is unchanged, they consume less of the high-intensity resource. Meanwhile, because the price paid by regulated consumers

Figure 3: Unqual Emissions Factors and (LHB, LB)



for the low-cost oil is uniformly higher than before the tax increase, the regulated consumers switch to the backstop sooner.

Since the low-cost resource is exhausted but less of the high-cost resource is utilized, aggregate carbon emissions fall. It is possible, however, that the unregulated users *themselves* reduce their cumulative emissions. To see that this is possible, note that $\mu_H > \mu_L$ and can be scaled up to any extent without altering either group's consumption behavior since in the (LHB, LB) case, the regulated consumers use no high-cost oil. The tax increase causes the unregulated sector to increase its cumulative depletion of the low-cost oil but to reduce its depletion of the high-cost oil. The emissions factor of the high-cost oil can be so large that the unregulated users reduce their cumulative emissions from the high-cost pool by more than they increase their emissions from the low-cost pool.

Whenever that occurs, the response of the unregulated consumers *reinforces*— rather than undermines—the attempts of the regulated region to reduce aggregate carbon emissions, another example of negative leakage.

3.2.2 An Increase in the Speed of Technological Change in the Backstop

When the regulated consumers use some of the high-cost resource (LHB, LHB), speeding up cost-reducing technical change does not affect the rents on the low-cost pool (λ_L). Every consumer in each group switches to the backstop sooner and consumes less of the high-cost reserve. Since cumulative emissions from the low-cost pool are unchanged, total emissions fall. Once again there is negative leakage from the unregulated consumers, which may be enhanced because of the unequal emissions factors.

When the regulated consumers switch from the low-cost pool directly to the backstop (LHB, LB), speeding up technical change would, in the absence of a change in the Hotelling rent, decrease cumulative demand for the low-cost resource. The Hotelling rent must therefore fall, and this causes unregulated consumers to deplete the low-cost pool at a more rapid rate and to switch later to the high-cost resource. Since they use more of the low-cost oil, the regulated consumers must use less of it. Regulated consumers accomplish this by using low-cost oil for a shorter interval, albeit at a faster rate. Emissions reductions from the regulated consumers are exactly offset by the regulated consumers' increase in emissions from the low-cost pool. Since, however, the unregulated consumers reduce their emissions from the high-cost pool, total emissions fall. If the emissions factor of the high-cost pool is sufficiently large, another case of negative leakage would occur.

3.2.3 An Increase in the Coalition Share

When regulated sector consumes part of the high-cost reserve (LHB, LHB), they deplete the low-cost resource at a (weakly) slower pace but for a longer time. Expanding the coalition of those subject to the emissions tax, therefore, may raise the cumulative demand for the low-cost resource just as in the case of the emissions tax.[15] Whenever that occurs, expanding the size of this group will drive up the Hotelling rent (λ_L). Consumers in both the regulated and the unregulated regions will deplete the low-cost pool at slower rates and for shorter intervals before switching (albeit at different times) to the high cost resource. Hence, the *per person* cumulative consumption of low-cost oil falls in *both* regions. However, since more consumers are now in the region with the higher cumulative demand, cumulative demand for the low-cost oil continues to match the unchanged stock, and emissions from the low-cost pool remain $\mu_L S_L$. Meanwhile, each consumer who was previously taxed increases his emissions from the high-cost pool as does every person who remains untaxed. This does not mean, however, that cumulative emissions necessarily increase, since consumers who are now taxed but who were not previously will (nonmarginally) cut their emissions from the high-cost pool. (In the numerical examples we have explored, this last effect always dominates and cumulative emissions fall. We conjecture that this is true in general and are in the process of investigating.)

Now consider the case when regulated consumers switch from the low-cost pool to the

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[15] To see that this is possible, suppose again that only the high-cost resource is dirty ($\mu_H > \mu_L = 0$). In that case, regulated consumers use the low-cost resource at the same rate as the unregulated consumers but switch later to the high-cost resource and hence have a larger cumulative demand for the low-cost resource.

green backstop without ever utilizing the high-cost reserves (LHB, LB). Increasing the coalition share has different competing effects. On the one hand, since prices are higher, regulated users consume the low-cost resource at a lower rate than their unregulated counterparts On the other hand, regulated users may abandon the low-cost pool (for the backstop) sooner or later than the unregulated users abandon it (for the high-cost pool). As a result, expanding the coalition may increase or decrease cumulative demand for the low-intensity resource.

The effect on unregulated emissions depends on the net effect on the Hotelling rent (λ_L) and the relative emissions intensities. If this rent decreases, the unregulated consumers will use the low-cost resource at a more rapid rate, but will switch to the high-cost resource at a later date. If the emissions factor on the high-cost pool is sufficiently large, negative leakage will occur.[16] On the other hand, if λ_L increases, the unregulated consumers use less of the low-cost resource and will switch to the high-cost resource sooner. Positive leakage results if the emissions factor on the high-cost pool is sufficiently large. We are investigating whether increasing the share of consumers subject to regulation can ever raise emisions becuase the increase in the consumption of the high-cost pool by the unregulated consumers who remain may outweigh the reduction in consumption of consumers who switch to the regulated coalition.

3.2.4 Comparison of Policy Effects

In summary, when emissions intensities differ, we observe the possibility of negative leakage with all policy options. We have not yet been able to rule out the theoretical possibility that greater policy stringency (when it causes rents on the low-cost oil to rise) may increase total emissions.

4 Limits on Regulating Carbon Emissions in the Two-Pool Model

Given any coalition size (α) and speed of technological change in the backstop (z), there is a limit to the carbon reductions that can be achieved by imposing an emissions tax. For, any tax sufficiently high to induce regulated consumers to utilize the clean backstop from the outset will generate the *same* equilibrium.[17] Increasing the tax further does not alter the equilibrium since no one pays the tax: those subject to it do not pollute; and those polluting are not subject to it. Hence, for taxes above some threshold, cumulative emissions remain constant.

To achieve any given emissions target in our model, set the tax high enough that regulated consumers use the backstop from the outset (LHB, B) and find the smallest size of the

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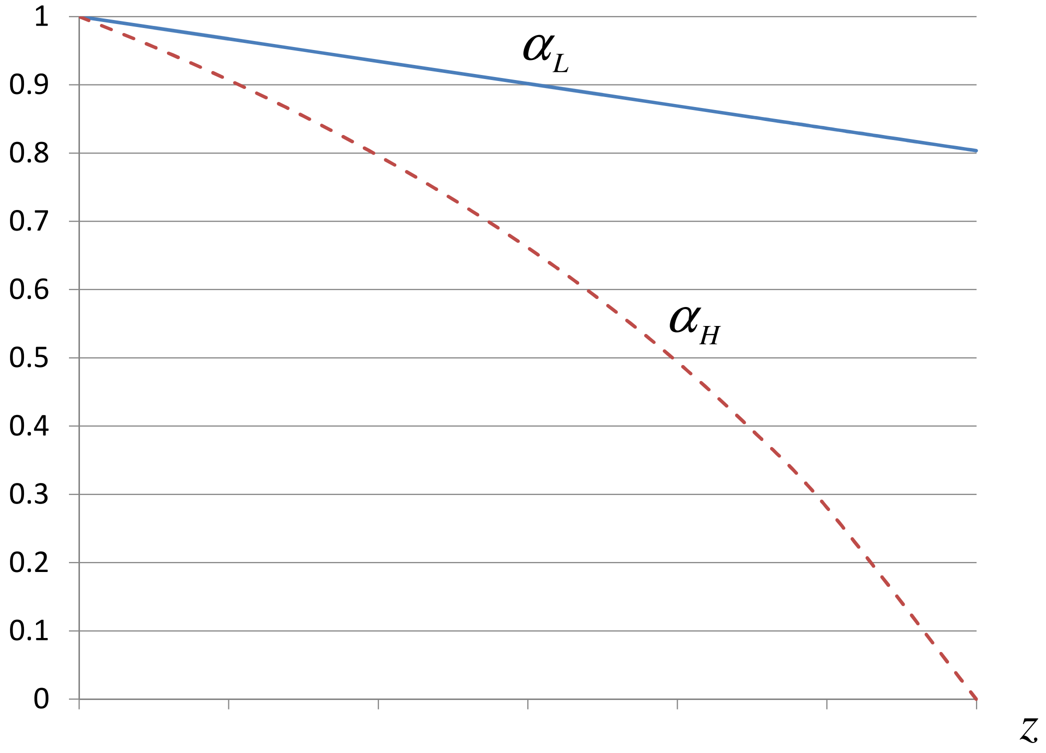
[16] Recall that when emissions intensities are equal this scenario leads to higher emissions among the unregulated consumers.

[17] Any tax that makes using a barrel of the lowest cost fossil fuel more expensive for regulated consumers than paying $B(0;z)$ to use a barrel equivalent of the clean backstop (e.g. $\tau \geq c_L/\mu_L$) is clearly "sufficiently high;" therefore, existence of such a tax is never an issue.

Figure 4: Minimum Share of World Demand Needed for Regulated Region to Cut Emissions from a Given Pool



regulated coalition sufficient to achieve the desired cumulative emissions target. Even a target $E = 0$ can be achieved by assigning everyone ($\alpha = 1$) to the regulated region. The required α will depend on the speed of backstop cost reductions. Hence, the minimum coalition size needed to achieve any emissions target E^* given z can be expressed as $\alpha(z; E^*)$. Since policies are substitutes, one can achieve the same target with a smaller size coalition and faster backstop cost reduction. That is, the function is strictly decreasing in its first argument; since a more stringent target would require more consumers to be subject to the tax, the function is also strictly decreasing in its second argument.

In this section, we pick the cumulative emissions target E^* to be the smallest cumulative emissions that leave the marginal pool with zero rent ($\lambda_H = 0, \theta_H = 1$). The following four equations implicitly define the four variables $(\lambda_L, \alpha_H, x_H^U, x_B^U)$:

$$(1 - \alpha_H) \int_{t=0}^{x_H^U} D(c_L + \lambda_L e^{rt}) dt \quad = \quad S_L \tag{10}$$

$$\begin{aligned}(1-\alpha_H)\int_{t=x_H^U}^{x_B^U} D(c_H)dt &= S_H & (11)\\ c_H &= c_L + \lambda_L e^{rx_H^U} & (12)\\ B(x_B^U;z) &= c_H. & (13)\end{aligned}$$

Let α_H be the minimum share of the regulating coalition (given z, S_L, S_H) for which some cumulative emissions reduction is possible (i.e. $E \leq \mu_L S_L + \mu_H S_H$).

Recall that if $z = 0$, then $B(t;0) > c_H$ for all t, and the unregulated region will always exhaust both pools; therefore, as long as there is any demand from the unregulated region, (any $\alpha < 1$) cumulative carbon emissions cannot be reduced at all by imposing emissions taxes in the regulated region.

Equations (**??**) to (**??**) can be solved for $\alpha_H(z)$ to obtain:

$$\alpha_H(z) = 1 - \frac{S_H}{D(c_H)(x_B^U(z) - x_H^U(z, S_L))}.$$

$\alpha_H(z)$ is a strictly decreasing boundary (depicted as the lower curve in Figure **??**). For any z, a coalition smaller than $\alpha_H(z)$ will be unable to reduce global carbon emissions *at all* no matter what emissions taxes it imposes since, even if that region uses no fossil fuels, the unregulated region would exhaust both stocks.

Even if the regulated region comprises a large enough proportion of the total demand that carbon emissions can be reduced somewhat by emissions taxes, emissions can never be reduced below $\mu_L S_L$ if the regulated region is smaller than some higher threshold $\alpha_L(z)(> \alpha_H(z))$. To derive this higher threshold (depicted as the upper boundary in Figure **??**), note that $(1 - \alpha_L)x_B^U D(c_L) = S_L$ or

$$\alpha_L(z) = 1 - \frac{S_L}{D(c_L)x_B^U(z)}.$$

Since x_B^U is implicitly defined by $B(x_B^U; z) = c_L$, $x_B^U(z)$ is a strictly decreasing function. Therefore, the minimum coalition size needed to be able to reduce cumulative emissions is decreasing in the resource stock size ($\partial\alpha_L/\partial S_L < 0$) and also decreasing in the rate of technological change in the backstop: $\partial\alpha_L/\partial z = (1 - \alpha_L)x_B^{U\prime}(z)/x_B^U(z) < 0$. Thus, although Hoel (2011), Fischer and Salant (2012) and others show that lowering backstop costs tends to accelerate emissions when exhaustion is complete, here technology policy creates an opening for climate regulation to have a beneficial impact on cumulative emissions. Figure **??** depicts the two boundaries.

The previous analysis has assumed an emissions tax so high that the regulated users switch immediately to the backstop. However, a similar analysis can be conducted if the emissions tax were set lower. Since raising any of the three exogenous variables (τ, α, z) reduces aggregate emissions, the three policies are substitutes. For example, suppose one could achieve a cumulative emissions target if *every* consumer in the world ($\alpha = 1$) were subject to a moderate tax without any government promotion of technological change in the backstop ($z = z_0$). Then one could achieve the *same* emissions target with a smaller number of consumers ($\alpha < 1$) subject to the same emissions tax but with increased government promotion of technological change ($z > z_0$). Given that a small fraction of world demand for fossil fuels is likely to be subject to emissions taxes or, equivalently, to cap-and-trade regulation—and that those taxes are unlikely to be sufficient to eliminate fossil fuel demand in those countries—the recognition that this deficiency can be offset by more vigorous promotion of technological change in the backstop seems important.

5 Parameterized Five-Pool Model

The foregoing analysis was qualitative. In this section, we generalize our model to take account of five types of exhaustible resources, calibrate it using available data on oil,[18] and simulate it to investigate the phenomena discussed previously. In particular, we determine the smallest coalition size capable of achieving a given emissions target as a function of the speed of cost-reducing technical change. We also show that negative leakage arises in our simulations.

5.1 Calibration

We draw on the literature to parameterize a multiple-pool model reflecting the five major types of oil: low-cost Middle East and North African (MENA) conventional oil (”*Conv.*”); other conventional oil with mid-range costs (“*Other*”); enhanced oil recovery and deep-water drilling (”*EOR*”) ; heavy oil bitumen (including oil sands) (“*Heavy*”), and oil shales (“*Shale*”). For each pool, we specify the size, per-unit cost, and emissions factor. On the demand side, we draw on empirical estimates of elasticities and projections of growth over time. We make the following assumptions (see Fischer and Salant 2012 for details).

Estimates of oil reserves and costs vary widely.[19] For our purposes, we draw rough estimates from the fall 2010 International Energy Agency (IEA) report, which gives a range of production costs and available reserves by oil type. Our specific reserves and cost assumptions are given in Table 1. To convert to CO_2 emissions (right column), we assume (as suggested by the U.S. Environmental Protection Agency) that a barrel of oil contributes 0.43 tons[20] of CO_2 and adjust for the fact that different unconventional sources have larger

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[18] We focus on emissions from the extraction and use of oil because this fuel arguably has the greatest potential for the rent adjustments that lead to intertemporal leakage. GHG emissions from coal are potentially much larger, but the resource is also considered much less (or non-) scarce.

[19] The Energy Information Administration (EIA) currently estimates global proven reserves to be about 1,200 billion barrels (including conventional and some unconventional, like Canadian oil sands). Kharecha and Hansen (2008) report reserves estimates in GtC, which if converted to billion barrels of oil equivalent (BBOE) range from 1,000 to 2,100 BBOE of conventional oil and 1,300 to 8,500 BBOE of unconventional oil. Aguilera et al. (2009) include projections of future reerve growth, leading to estimates of conventional oil reserves of 6,000 to 7,000 billion barrels available at prices as low as $5 a barrel, heavy oil reserves of 4,000 billion barrels at $15 per BOE, oil sands reserves of 5,000 billion barrels at $25 per BOE, and up to 14,000 billion barrels of oil shale that could be tapped at $35 per BOE.

[20] http://www.epa.gov/grnpower/pubs/calcmeth.htm.

emissions factors relative to conventional oil.[21]

We note that proved reserves from global fossil fuel resources contain approximately four times enough carbon to drive global temperatures up by 2 degrees centigrade; by themselves, these oil reserves exceed the carbon budget for meeting IPCC targets (Fischer and Salant 2012). Hence, in the absence of geoengineering or carbon sequestration, the only way to moderate temperature increases is to remove from use the highest-cost types of fossil fuels. and to limit ourselves to exhausting only the lowest-cost resources.

Table 3: Reserves and Cost Assumptions

Oil reserve source	**BBOE**	**Extrn cost**	**Emssns factor**	**CO_2(GtC)**
MENA conventional	900	\$17	1	387
Other conventional	940	\$25	1	404
EOR, deep water	740	\$50	1.105	352
Heavy oil, oil sands	1,780	\$60	1.27	972
Oil shale	880	\$70	2	757
Biofuels, backstop technology	Unlimited	\$100	0	0

The assumed initial backstop marginal cost is drawn from a range of common estimates of advanced biofuels, in line with the IEA estimates; although conventional biofuels like sugarcane ethanol are currently cheaper, the second-generation fuels like cellulosic ethanol and biodiesel—which have greater potential for the larger-scale supplies needed to function as backstop technologies—have higher costs.[22] Although we draw on biofuels in making these cost estimates, we recognize that future backstops could include other options, like hydrogen or clean electricity for plug-in vehicles.[23] For this exercise, we assume that backstop costs are initially \$100 and will ultimately asymptote to \$10 (i.e., be lower than conventional oil in the far future): $B(t;z) = 10 + (100 - 10)e^{-zt}$. The difference between the marginal cost of the backstop at time t and in the long run declines at rate z, and that rate helps determine the ultimate date of exhaustion. The combination of these cost assumptions ensures that, with a relatively modest rate of cost-reducing technical change in the backstop ($z = .0025$), all oil resources will be fully exhausted by the end of the century. We further assume that the backstop fuels are non-emitting.[24]

For demand, we parameterize a linear function. According to EIA, global annual oil consumption has been roughly 86 million barrels per day in recent years, or an annual consumption of 31.4 billion barrels.[25] We assume an effective price elasticity of -0.25. This

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[21] See Table 3-2 of the California technical analysis of the low-carbon fuel standard, $http : //www.energy.ca.gov/low\_carbon\_fuel\_standard/UC\_LCFS\_study\_Part\_1 - FINAL.pdf$.

[22] In 2007, the U.S. Department of Agriculture estimated cellulosic ethanol production costs at \$2.65 per gallon, compared with \$1.65 for corn-based ethanol.

[23] Of course, synthetic fuels derived from coal or natural gas could also be substitutes, but we assume fuel-based backstops are precluded.

[24] We acknowledge that the actual emissions factors for biofuels, particularly those associated with land-use changes, are controversial.

[25] $http : //tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid = 5\&pid = 54\&aid = 2$.

value roughly corresponds to the median estimate of global oil demand elasticity from Kilian and Murphy (2010).[26] We assume an interest rate of $r = 0.02$.

EIA (2010) projects global demand to increase 49 percent from 2007 to 2035, or about 1.45 percent per year, primarily from developing countries. We incorporate demand growth by assuming that the linear demand curve shifts out at this rate without changing slope. In the simulations, we assume that at time the inverse demand curve is: $D(p(t), t) = 205e^{.0145t} - .1914P(t)$. Using this demand curve, (1) the initial price in the equilibrium induces a quantity demanded of 31.4 BBOE when backstop technical change is modest ($z = .0025$) and (2) has a point elasticity at that quantity of $-.25$ at that quantity.

5.2 Comparative Statics: Five Pool Model

In this section we conduct simulations with the 5-pool model. To understand the tradeoffs across the policies, we focus on equilibria where some oil shale is left in the ground and therefore shale has zero rents, while oil sands (the pool with the next lowest cost) is completely exhausted and has positive rents.[27] Note that oil shale has a much higher emissions intensity (2 times that of conventional oil) than oil sands (1.27 times conventional oil). Shale is the counterpart of the high-cost pool (H) in Section 3 and oil sands (along with the preceding pools) is the counterpart of the low-cost pool (L).

We set a common point with the three policies so that the regulated region switches from oil sands to the backstop but, at the moment of the switch, the high-cost pool is the same price as the backstop.[28] Under a less stringent policy, the regulated consumers would switch from oil sands to shale before switching to the backstop; under a more stringent policy they would find the high-cost pool strictly more expensive when switching to the backstop. That is, equilibria of the (LHB, LHB) type lie on the less stringent side and equilibria of the (LHB, LB) type lie on the more stringent side of this point. Under the least stringent policy we consider, all the shale is extracted although the rent remains zero (the counterpart to $\lambda_H = 0$ but $\theta_H = 1$.)[29] Under the most stringent policy, none of the shale is extracted (the counterpart to $\lambda_H = 0$ but $\theta_H = 0$.)[30]

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[26] Earlier estimates of the price elasticity of demand for gasoline (primarily in the United States) find short-term demand elasticities of about -.25 and long-run elasticities of about -0.6 (Espey 1996; Goodwin et al. 2004). On the other hand, Cooper (2003) and Dargay and Gately (2010) find much lower price elasticities of demand (-.15 and smaller) when considering a broader array of countries, particularly non-OECD countries, and more recent time periods. However, Kilian and Murphy (2010) warn that most studies of such elasticities using dynamic models are econometrically flawed since they do not account for price endogeniety.

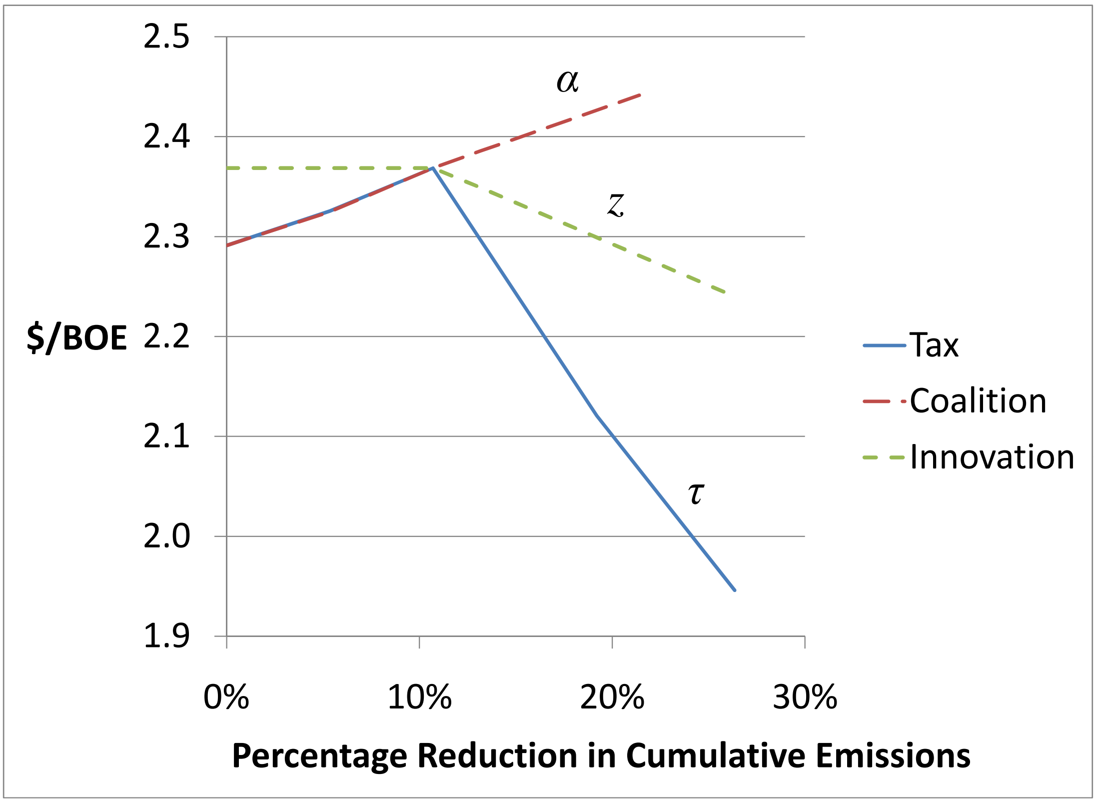
[27] Every pool extractable at a cost lower than oil sands is, of course, also completely exhausted. Had there been any pools more costly to extract than shale, they would have been too expensive to touch.

[28] τ =.497916 dollars per ton of CO_2, $z = .004954, \alpha = .5$

[29] Under the tax policy, this least stringent case can be achieved by maintaining $z = .004954, \alpha = .5$ but setting $\tau = 0$; under the innovation policy, it can be achieved by maintaining $\tau = .497916, \alpha = .5$ but setting z=.004751; under the coalition policy, it can be achieved by setting $\tau = .497916, z = .004954$, but $\alpha = 0$.

[30] Under the tax policy, the most stringent policy can be achieved by maintaining $z = .004954, \alpha = .5, \tau = 4.136419$; under the innovation policy, it can be achieved by maintaining $\tau = .497916, \alpha = .5$ but setting z=.004751; under the coalition policy, one would need $\alpha > 1$ to achieve these reductions, so we use

Figure 5: **Rent for Oil Sands (Penultimate Pool)**



Figures ?? and ?? illustrate the results, which follow the intuition developed in Section 3.2. On the horizontal-axis for each is the percentage reduction in cumulative emissions achieved by the given policy combination. In the "Tax" case, only τ varies to achieve those reductions; in the "Coalition" case, only α varies; and in the "Innovation" case, only z varies. In each case, larger emissions reductions correspond to a greater level of policy stringency.

Figure ?? shows the effect of increasing policy stringency on the rents of the penultimate pool, oil sands. When the regulated consumers use some of the last pool (the counterpart to (LHB, LHB)), we find that oil sands rents are increasing with the stringency of the tax and coalition policies—that is, regulated consumers increase their cumulative demand for oil sands despite higher prices overall because of the difference in the emissions factors of oil shale and oil sands. The innovation policy has no effect on the oil sands rent in this case, as it simply causes both types of consumers to switch to the backstop earlier.

Once the policies are sufficiently stringent for the equilibrium to be in the counterpart

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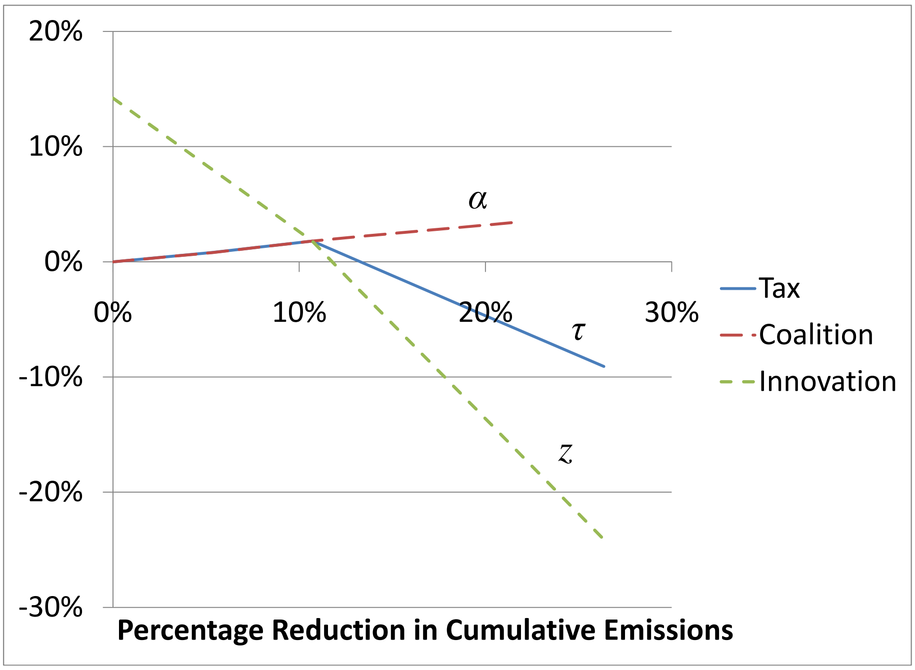
$\tau = .497916, z = .004954, \alpha = 1$ as the most stringent and calculate the remaining shale extraction.

Figure 6: **Percentage Change in Emissions of an Unregulated Consumer**



of the (LHB, LB) region, however, the differences in the effects of the policies become more pronounced. Further increases in the emissions tax cause the regulated consumers to switch from oil sands to the backstop sooner, and the resulting decrease in demand drives down rents sharply. Expanding the coalition, however, without increasing the emissions tax, causes a larger share of global demand to seek the less emissions-intensive pools (including oil sands) for a longer period, and the rents thus continue to rise. Meanwhile, increasing the rate of technological change causes regulated demanders to switch sooner from oil sands to the backstop, putting downward pressure on the rents.

Figure **??** depicts the effects of the three policies on cumulative emissions and on emissions originating in the unregulated sector. The percentage change in emissions of a member of the unregulated community (the percentage change in E_U) is on the vertical axis.[31] We see that leakage occurs in the Tax and Coalition policies when they drive up the oil sands rents, causing unregulated consumers to switch sooner to shale oil, which is a much more emissions-intensive resource. By contrast, the Innovation policy always induces negative leakage, by causing unregulated consumers to switch sooner to the backstop.

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[31] Thus, the change in the size of the coalition is not taken into account when computing emissions from the unregulated consumers when the coalition policy changes.

5.3 Limits on Regulating Carbon Emissions in the Five-Pool Model

Given a level of the coalition and backstop technology policies, emissions pricing can reduce emissions, but only up to a point. Once demand for fossil fuels is eliminated among regulated consumers, any additional emissions reductions must come from unregulated consumers.

For each pool i, we calculate the border $\alpha_i(z)$, that is, the minimum coalition size needed to effect any emissions reductions from the given pool, as a function of the rate of technological change. For smaller coalition sizes, the pool will be completely exhausted regardless of the emissions tax in the regulating regions.

The resulting borders are depicted in Figure **??**. We see that for the higher cost pools like oil sands and oil shale, smaller coalitions can reduce emissions from these pools for any level of cost-reducing technical change in the backstop; alternatively, a slower rate of technical change in the backstop is sufficient to reduce emissions for any given size of the regulated region. For example, for shale oil, a 0.5% annual rate of improvement in the backstop would allow a coalition of any size ($\alpha > 0$) to have an impact on emissions. At an 0.8% rate of improvement, a coalition of any size could begin to reduce emissions from heavy oil. On the other hand, that 0.8% rate of improvement would be insufficient to reduce emissions from deep-water oil unless the regulated coalition represented at least 69% of world demand since deep-water oil is much less expensive to extract.

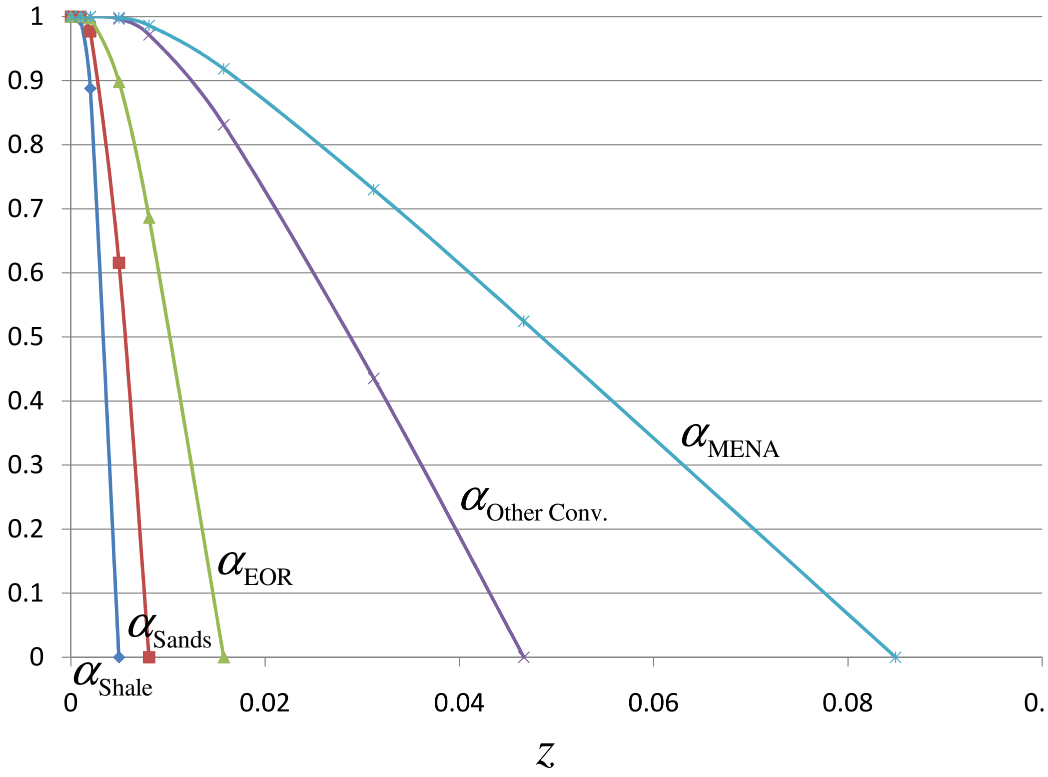
To keep any of the lower-cost pools in the ground, however, a very large coalition and/or fast pace of cost reductions in the backstop is needed. Technical change of nearly 5% annually is needed for small coalitions to cause other conventional oil to be left in the ground, and annual cost reductions of 8% or more would be needed for small coalitions to affect total extraction from MENA oil. At the 5% rate of change, at least half of demand must be regulated to affect MENA oil.

To put these results in perspective, as of 2009, the Kyoto Protocol parties with targets (participating Annex I countries) represented barely 25% of global emissions from fuel combustion (IEA 2011). Meanwhile, in the Annual Energy Outlook for 2012, EIA forecasts a 1.1% annual increase in ethanol (E-85) prices from 2010-2035, as compared to a 1.6% annual increase for gasoline and diesel. However, our model predicts oil price increases of 1.3% per year, assuming no change in backstop prices, which implies a larger improvement in the relative price of renewable than in the EIA forecast. Therefore, if one believes our model, in the absence of another alternative technology becoming more rapidly cheaper in the future, the prospects of the modest Kyoto coalition being able to change cumulative oil extraction seem rather dim.

6 Conclusion

This paper contributes to recent literature on the Green Paradox and carbon leakage that distinguishes between regulated and unregulated regions in a Hotelling framework. Unlike previous models, we consider technical change in a clean energy backstop that causes costs to fall over time, ultimately allowing the new technology to outcompete conventional fuels.

Figure 7: **Minimum Coalition Size to Effect Emissions Reduction in a Given Pool in 5-Pool Simulation**



Consequently, even unregulated consumers may prefer to switch from fossil fuels to the backstop prior to complete exhaustion, which means that cumulative emissions reductions can occur in this model. Furthermore, we differentiate among grades of oil that are characterized by different costs, emission factors, and underground reserves. We link the analysis to GMS (2001), which opens the door for greater realism in future models of intertemporal emissions leakage. Finally, we complement the analysis with a calibrated simulation of global oil markets, based on available estimates of reserves, costs, and projections of global demand.

In this framework, each of our three policy levers—emissions pricing, coalition building, and innovation in the backstop—can reduce cumulative emissions. Furthermore, we identify situations in which increasing policy stringency can cause unregulated consumers to reduce their emissions—“negative leakage.” Here, the differing emissions intensities of different resource pools play a role. Notably, the technology policy always induces negative leakage (as long as cumulative emissions are being reduced). The result stands in striking contrast to the earlier Green Paradox literature, which focused on the case of complete extraction and found that technology policies were destined to accelerate global warming.

Since the most a regulating coalition can do is eliminate its own demand, the limits to limiting greenhouse gases depend on the share of world demand that is unregulated and the speed of technical change in the backstop. Hence, increasing the regulating coalition size and accelerating backstop cost reductions are policy substitutes for achieving a target emissions reduction. Given the difficulties in securing international cooperation on global warming, promoting technical change in clean energy sources may be a more effective instrument for reducing carbon emissions in the absence of a unified global effort. However, dramatic reductions in global emissions appear challenging in the absence of widespread participation in carbon regulation and rapid development of clean energy alternatives.

Appendix: Equilibria with complete extraction

If the per-unit value of each grade of oil in the ground is strictly positive ($\lambda_L > 0, \lambda_H > 0$), cumulative demand must exhaust the resource stock in each pool. Furthermore, consumer prices are continuous across switchover points.[32] Finally, supply must equal demand at all times. Thus, we have six equations defining the six endogenous variables when both pools are fully exhausted $(\lambda_L, \lambda_H, x_H^R, x_B^R, x_H^U, x_B^U)$:

$$\alpha \int_{t=0}^{\min(x_H^R, x_B^R)} D(c_L + e^{rt}[\lambda_L + \tau\mu_L])dt \quad + \quad (1-\alpha)\int_{t=0}^{x_H^U} D(c_L + \lambda_L e^{rt})dt = S_L \tag{14}$$

$$\alpha \int_{t=\min(x_H^R, x_B^R)}^{x_B^R} D(c_H + e^{rt}[\lambda_H + \tau\mu_H]) \quad + \quad (1-\alpha)\int_{t=x_H^U}^{x_B^U} D(c_H + \lambda_H e^{rt})dt = S_H \tag{15}$$

$$c_H + e^{rx_H^R}[\lambda_H + \tau\mu_H] \quad = \quad c_L + e^{rx_H^R}[\lambda_L + \tau\mu_L] \tag{16}$$

$$c_H + \lambda_H e^{rx_H^U} \quad = \quad (c_L + \lambda_L e^{rx_H^U}) \tag{17}$$

$$B(x_B^U; z) \quad = \quad c_H + \lambda_H e^{rx_B^U} \tag{18}$$

$$x_B^R \geq 0, B(x_B^R; z) - \min\{c_L + e^{rx_B^R}[\lambda_L \quad + \quad \tau\mu_L], c_H + e^{rx_B^R}[\lambda_H + \tau\mu_H]\} \leq 0, \ c.s. \tag{19}$$

When fossil fuels are consumed, the producer price in each region (and the consumer price in the unregulated region) at time t is $c_i + \lambda_i e^{rt}$ for $i = \{U, R\}$; the consumer price in the regulated region is $\mu_i \tau e^{rt}$ higher.

Equations (**??**)–(**??**) characterize the five possibilities that can give rise to complete exhaustion of both pools. Either the unregulated region uses the energy sources in the order $L \rightarrow H \rightarrow B$ while the regulated region uses pools in any one of the following three sequences: (1) $L \rightarrow H \rightarrow B$, (2) $L \rightarrow B$, or (3) B or alternatively the unregulated region uses the energy sources in the order $H \rightarrow B$ and the regulated region in the order $L \rightarrow H \rightarrow B$ or $L \rightarrow B$

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[32] This implies that producer prices jump down (and government tax revenue jumps up) if the emissions factors and hence the emissions taxes on the two pools differ.

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