Alternative Climate Policies and Intertemporal Emissions Leakage

Carolyn Fischer and Stephen Salant

Abstract

Efforts to limit cumulative emissions over the next century may be offset by emissions leakage, not only between countries but over time. Current price-cost margins for major reserves are ample, leaving scope for significant price reductions if climate policies alter demand for fossil fuels**.** This resource owner response to maintain extraction over time has been labelled the "green paradox," which has a "strong" form that implies intertemporal leakage may reach 100%, and a "weak" form that notes policies like a faster transition to clean energy may accelerate emissions, shortening the time to adapt and increasing damages. We contribute to this literature by isolating the effects of intertemporal leakage, using a model of multiple pools of different extraction costs. We compare the effects of five policy options: accelerating cost reductions in the clean backstop, taxing emissions, improving energy efficiency, a clean fuel blend mandate, and mandating carbon capture and sequestration. A stylized one-pool model identifies two types of equilibria that extend to multiple pools: full exhaustion of the last pool, and partial exhaustion of the last pool. All policies can reduce cumulative emissions, but the backstop policy accelerates extraction while conservation policies delay emissions. However, when comparing to what would happen in the absence of resource rent adjustment, we find that conservation policies have higher intertemporal leakage rates, and backstop policies can have lower leakage than an emissions tax. Leakage rates generally decline as targets become more stringent. We calibrate an extension of this model to five major categories of oil.

Key Words: green paradox, climate change, exhaustible resources

JEL Classification Numbers: Q3, Q4, Q5

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1. Introduction

Reducing emissions of the greenhouse gases (GHGs) that contribute to global climate change is the greatest collective action problem of our time. According to the Intergovernmental Panel on Climate Change (IPCC), stabilizing 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). At the same time, the current United Nations Framework Convention on Climate Change (UNFCCC), under the principle of "common but differentiated responsibilities," requires no mandatory action on the part of developing countries, including major emerging economies that are large emitters. Furthermore, in the absence of a binding successor to the Kyoto Protocol, not even developed countries are committed to emissions targets, although the Copenhagen Accord does call on countries to make individual pledges of action.

In this context of largely uncoordinated activities, several countries are taking significant steps to reduce their own GHG emissions. However, an important concern for unilateral movers is that their efforts may be partially (or completely) undermined by the actions of others.

Two channels of "carbon leakage" have been identified: spatial and intertemporal. With spatial leakage, the attempt by one government to raise the cost of fossil fuel use may drive economic activity toward unregulated, lower-cost countries. This is of greatest concern for energy-intensive, trade-exposed sectors and has prompted policy responses such as free allowance allocation, rebates, and proposals for border adjustments (see Fischer and Fox 2009). This type of leakage is likely to be small (a few percentage points) in terms of overall reductions, although it can be quite important from the point of view of reductions in particular sectors. Spatial leakage can also embody the diversion of fossil fuel consumption through energy markets; for example, as a regulating economy reduces its demand for oil, given a global supply curve, prices will fall, inducing nonregulating economies to consume more. This type of leakage has been found to be quite important in computable general equilibrium (CGE) models

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simulating climate policy responses with global trade, as the results are highly sensitive to the parameterization of global energy supplies (Burniaux and Martins 2000).

The other channel—and the focus of our paper—is the offsetting *intertemporal* responses of oil suppliers to a government's attempts to curb fossil fuel usage. Current price-cost margins for some of the world's largest reserves are ample, so there is scope for significant price reductions if clean substitutes eventually become cheap enough to threaten to lure consumers away from fossil fuels.[1] Moreover since such fuels are in finite supply, current extraction decisions depend not only on current prices but also on future prices. If climate policies make selling fossil fuels in the distant future less attractive, suppliers may prefer instead to sell more in the present. Some formulations predict that intertemporal leakage will reach 100%.

In a recent *Foreign Policy* article, the journal asked Bjorn Lomborg, "How can we stop climate change?" He answered, "By being smart and investing in research to make green energy cheap instead of trying to make oil unaffordable" (Foreign Policy 2010). This response may reflect concerns about spatial leakage, problems in coordinating GHG regulations, and political difficulties in raising consumer energy costs. But is his argument undermined by intertemporal leakage?

Sinn (2008) discusses this "green paradox" noting that, under some conditions, many climate policies—particularly alternative energy strategies—can actually accelerate rather than slow emissions over time. This can potentially not only obviate any reductions in the long run but can also increase the present discounted value of damages. His formal analysis focuses on designing extraction taxes to slow fossil fuel consumption. But he argues more generally that policies to promote energy efficiency or to expand the use of clean substitutes are destined to speed global warming, while carbon sequestration is one of the few useful options for slowing it. Hoel (2011) also focuses on the design of emissions taxes and the role of expectation formation. He shows that emissions taxes that rise too quickly can accelerate emissions. Strand (2007) makes a similar point about the indirect effects of reducing the cost of substitute technologies. Winter (2011) notes that with positive feedback effects between atmospheric carbon and the

[1] A variety of studies using a *static* computable general equilibrium (CGE) models have shown the sensitivity of leakage to fossil fuel supply elasticities (e.g., Burniaux et al. 2009, Mattoo et al. 2009). Most of these studies find leakage rates in the range of 10-30% (Babiker and Rutherford 2005), representing both changes in fossil fuel markets and the shifting of other economic activities.

release of terrestrial carbon, innovation in clean energy technology can lead to a pemanently higher temperature path. Grafton et al. (2010) find that subsidies to biofuels that are ongoing substitutes for fossil fuels may accelerate or delay extraction, depending on the relative cost parameters. Chakravorty et al. (2010) show that greater potential for learning-by-doing in the substitute technology implies lower equilibrium energy prices, in order to deter innovation, resulting in increased resource extraction and greenhouse gas emissions.

Other authors have combined the analysis of intertemporal and spatial emissions leakage. Hoel (2009) extends this analysis by assuming that countries differ in their taxation of fossil fuel use. Subsidizing development of a green substitute causes the competitive oil price to fall uniformly. Countries with sufficiently high taxes may find the green substitute more attractive than fossil fuels once it is more heavily subsidized while countries with sufficiently low taxes will continue to use fossil fuels but at a faster rate because of the reduced price. If the first effect is sufficiently strong, it may take longer to exhaust the fossil fuels and switch to the backstop than before the subsidy. Eichner and Pethig (2009) use a two-period model with separate abating, non-abating, and fossil fuel-supplying countries to explore the conditions under which tightening the emissions cap in the abating country accelerates global emissions.

In all of these models, the nonrenewable resource is ultimately exhausted and so the cumulative emission of carbon is constant—an effect that may be termed the "strong green paradox." How this constant amount of emissions is distributed over time depends on the policy analyzed. Cumulative extraction is invariant in these models because of the assumptions made about the extraction technology. In none of them are extraction costs assumed to rise as the stock of fossil fuel is depleted.

In reality, as fossil fuels become increasingly scarce, extraction costs will rise. In principle, this may be modeled either by including cumulative extraction as an argument in the cost function or by assuming that different pools of oil have different per-unit costs. Gerlagh (2009) adopts the first approach and assumes that extraction costs are linear in cumulative extraction. He finds that lowering the backstop cost still increases initial emissions—an effect he terms a "weak green paradox"— but decreases cumulative emissions. He also considers a scenario in which the backstop technology is an imperfect substitute, and it has decreasing rather than constant returns to scale; in this case, reducing the cost of the substitute lowers fossil demand and lowers rents over the entire time horizon. This both decreases and delays emissions. Van der Ploeg and Withagen (2010) also assume that extraction costs increase with depletion and posit a range of costs for backstop technologies; they find that the green paradox still holds with

cost reductions in expensive backstop technologies, but it need not arise with cost reductions in relatively cheap backstops.

The concerns raised by the green paradox are underscored when comparing the emissions associated with available fossil fuel reserves to the available carbon budgets for avoiding major climate change. According to the *IPCC 4th Assessment Report*, to reach a stabilization target of 450ppm would require cumulative emissions over the 21st century to be in the range of 1370 to 2200 GtCO2 (or 375 to 600 GtC; IPCC 2007). Kharecha & Hansen (2008) review estimates for reserves of different fossil fuels, finding ranges of 70-140 GtC for natural gas, 120-250 GtC for conventional oil, 500-1,000 GtC for coal, and 150-1,000 GtC for unconventional oil. Especially if the upper range of reserve estimates hold, complete exhaustion of all proven resource pools would mean that targets for GHG concentration are flagrantly disregarded.

Our model also allows extraction costs to increase over time, by assuming that oil pools differ in their per-unit cost of extraction. For example, oil shale is roughly four times as expensive to extract as conventional oil from the Middle East (EIA 2010); furthermore, the higher cost sources also tend to be more emissions intensive, and we incorporate this feature as well. In the absence of any policy intervention, we assume all of these resources are exhausted and scarcity rents are positive. Thus, to reduce emissions, the scarcity rents must be sufficiently eroded such that the higher-cost (and higher-emitting) resources are left in the ground. We thus find two types of equilibria ("regions") for when each of n pools becomes the last pool to be exploited; one in which scarcity rents are declining but the last pool is fully exhausted, and another in which the last pool is incompletely exhausted and has no scarcity rent.

We investigate the effects of five distinct climate policies:

- accelerating the decline in costs of a carbon-free backstop technology,
- taxing emissions,
- improving energy efficiency,
- mandating a blend or portfolio ratio with the backstop technology; and
- mandating a certain rate of carbon capture and sequestration.

Using a calibrated model, we compare the effects of each policy on (1) cumulative emissions of carbon generated by extracting and using oil[2] and on (2) the time interval before green technology replaces fossil fuels. However, we find previous analyses of the "weak green paradox" conflate the problem of intertemporal leakage—which results from the supply responses to changing future expectations—with how the policies function by nature. To gauge the magnitude of intertemporal leakage, we compare the equilibrium effects under each policy to what would happen if scarcity rents did not adjust. Understanding the actual extent of intertemporal leakage is important, since most climate policy models do not incorporate the dynamic responses of fossil fuel resource owners to changes in future demand.

We show that all of the policies can induce comparable amounts of cumulative extraction (or emissions) and we compare their effects. Accelerating cost reductions in the backstop may result in less greenhouse gas emitted but will speed up the rate of emissions and lower the price path for fossil fuels. A carbon tax (or a CCS share mandate that raises costs by the same amount) raises the retail price path and slows extraction. The CCS mandate has the added benefit of sequestering a share of the carbon that would otherwise contribute to global warming. Energy efficiency improvements slow extraction, while lowering the price path. A blend mandate also slows extraction, but it raises prices, particularly early on while the backstop is more expensive.

Since the cost of implementing some of the policies is unknown, we cannot conduct a meaningful welfare analysis. Instead, we show that, for any specified level of cumulative emissions, there is a unique policy which gives society the most time to adapt. The conservation policies (energy efficiency and blend mandates) delay extraction the longest, followed by CCS, emissions tax, and lastly the backstop policy. However, these rankings would also hold in the absence of rent adjustments. If we instead compare the rates of intertemporal leakage associated with a given level of cumulative emissions, we find different results. All policies have leakage rates that start out at or near 100 percent, but they all fall toward zero as the policies become more stringent (albeit in a zig-zag pattern). Overall, the conservation policies now have the highest leakage rates, and the backstop policy can actually outperform the emissions tax. On the other hand, if the goal is to limit the present discounted value of emissions (i.e., there is a value to delaying emissions), conservation policies do display less intertemporal leakage than other policies.

[2] The policies may also affect cumulative emissions from other sources (e.g. coal). We confine attention here to the effect each policy has on cumulative emissions from the extraction and use of oil.

The paper proceeds as follows. In Section 2, we describe the stylized two-pool model. In Section 3, we characterize the effects of the five policies, each of which has been widely discussed as a way to reduce greenhouse gas emissions. In Section 4, we compare the consequences of these policies. In Section 5, we extend our analysis using a calibrated model with growing demand and five grades of fossil fuels. Section 6 concludes the paper.

2. Single Pool Model

Consider the case of a single pool of oil of stock size (S) with a per-unit extraction cost (c), sold in a competitive market. A carbon-free backstop technology is available in unlimited capacity at constant marginal cost but it is initially too expensive to warrant consideration by consumers. Because of technological improvements, the (constant) marginal cost of this backstop, $B(t;z)$, is assumed to decline exogenously over time toward a long-run cost $B_{LR}(=\lim_{t\to\infty} B(t;z) < c)$. In simulations, we will use the following functional form: is $B(t;z) = B_{LR} + \left(B_0 - B_{LR}\right)e^{-zt}$. We assume that the parameter z can be increased by government policy. In the baseline scenario $(z = z_0 > 0)$, we assume that this per-unit cost declines slowly enough that the two pools of oil are completely exhausted before the backstop is utilized.

Let x_B denote the date when the backstop replaces oil. Denote the price consumers pay at time t as $p(t)$; quantity demanded is $D(p(t))$.[3] The discount rate is assumed exogenous and denoted as r. 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 that pool's emissions factor μ: $M(t) = \mu q(t)$. We denote cumulative emissions as E. Therefore, $E = \int_0^{x_B} M(t)dt$. For the purposes of considering the weak paradox effects, we will also define the present discounted value of emissions as $PVE = \int_0^{x_B} M(t)e^{-rt}\,dt$.

Denote the present value of a barrel oil in the ground as λ. In a competitive equilibrium, the following conditions must hold. While the resource owner is extracting, the present discounted value of profit per unit is constant: or $p(t) = c + \lambda e^{rt}$ for $q(t) > 0$. If the backstop is in use and $q_B(t) > 0$, then $p(t) = B(t;z)$. Thus, the equilibrium price path is simply

[3] For clarity of exposition, in these sections we ignore any time trend in the demand function. However, in the parameterized numerical simulations, we will allow for demand growth.

$p(t) = \min(c + \lambda e^{rt}, B(t; z))$. Supply must equal demand at all points in time, so $q(t) = D(p(t))$ for $0 \le t \le x_B$, and $q_B(t) = D(p(t))$ for $t \ge x_B$. Furthermore, price is continuous across switchover points.

We then have two potential regimes. In region **(a)**, the "above ground" scenario, the pool of oil is fully exhausted. In this case, the per-unit value of oil in the ground is strictly positive $(\lambda > 0)$, and cumulative demand must equal the resource stock in each pool. Thus, we have two equations defining the two endogenous variables (λ, x_B):

$$\int_{t=0}^{x_B} D(p(t))dt = S \tag{1}$$

$$B(x_B; z) = c + \lambda e^{rx_B}. \tag{2}$$

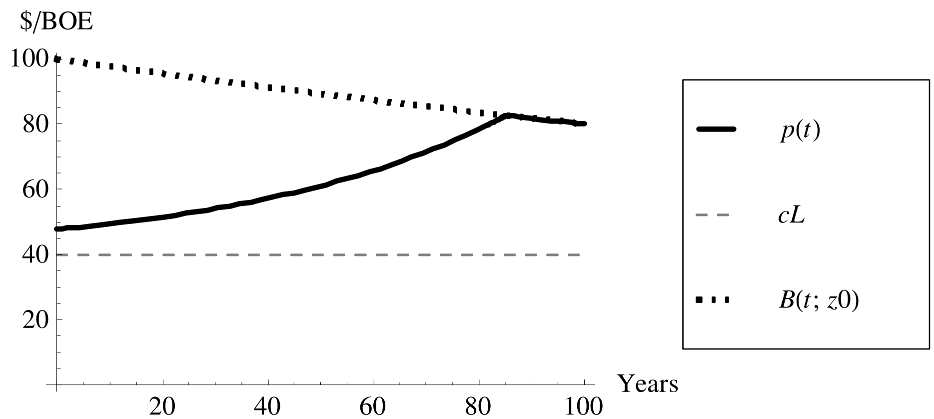
In region **(b)**, the "below ground" scenario, the pool of oil is incompletely extracted. In this case, the shadow value of oil must be zero $(\lambda = 0)$, and the share extracted θ is determined by cumulative demand up to the switchover point. The following two equations define the two endogenous variables (θ, x_B):

$$\int_{t=0}^{x_B} D(p(t))dt = \theta S \tag{3}$$

$$B(x_B; z) = c. \tag{4}$$

Figure 1 illustrates the price path in the absence of a policy intervention ("no policy," abbreviated "NP"), where $z = z_0$ and all other taxes or mandates are zero. All costs are expressed in terms of $ per barrel of oil equivalent (BOE).

Figure 1: Price Path with No Policy



3. Policies Intended to Reduce Greenhouse Gas Emissions

We compare five policies:

1. accelerating cost reductions in the backstop technology;
2. taxing fossil fuels;
3. improving energy efficiency;
4. mandating a blend or portfolio ratio with the backstop technology; and
5. mandating carbon capture and sequestration (CCS).

To simplify, we assume that each policy is exogenously imposed.[4]

We first use the single-pool model to explore the market responses and emissions outcomes of the different interventions. We then discuss extending the results in a model with n pools.

Accelerating Backstop Cost Reductions

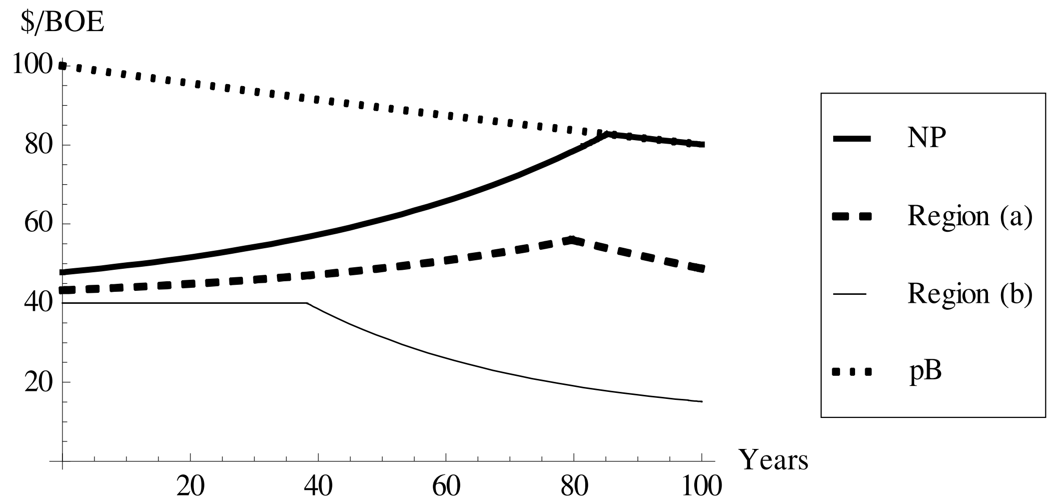
We begin with a policy that accelerates cost reductions in backstop technologies. By increasing z, the policy lowers the backstop marginal cost after the first instant. That is, $B(0;z)$ is constant regardless of z, but $\partial B(t;z)/\partial z < 0$ for $t > 0$.

In the absence of the policy, we assume that the green technology would be developed so slowly that the resource pool would eventually be exhausted (region **(a)**) before consumers switched to the green alternative. Consider now an increase in $z > z_0$ that is still modest enough that the pool would still be exhausted. An increase in z will cause the backstop marginal cost to decline faster. If the price path did not change, the transition to the clean technology would occur sooner and at a lower price. But then the oil would not be exhausted, a disequilibrium. Once rents adjust in the new equilibrium, the entire price path must fall, as Figure 2 depicts. Strengthening the policy thus lowers the rents on each resource and results in an earlier transition (x_B falls). In this region the green paradox arises: faster reductions in the unit cost of the green technology do not reduce cumulative emissions (100% leakage) but the policy does raise the average rate of emissions by shortening the time until fossil fuels are exhausted.

[4]That is, we ignore the possibility that energy prices may themselves induce changes in energy efficiency or backstop R&D, or that CCS would be induced by the tax.

Eventually, the innovation rate is large enough that the rents are driven to zero, and we enter region **(b)**. Oil would then sell at marginal cost, and that would serve as a ceiling on the price of the low-cost resource. Faster innovation will not alter the initial price, but it does hasten the transition to the green technology (smaller x_B) and therefore increases the stock of high-cost reserves that remain in the ground rather than being transformed into greenhouse gases. Note that within this region, increasing z does not alter the rate of extraction, so both the weak and strong versions of the green paradox *disappear* in the region (**b**).

Figure 2: Price Paths of the Two Regions with Backstop Policy



Emissions Tax

An emissions tax levies a cost (τ) per unit of emissions. For concreteness, we assume extractors pay the tax; however, the incidence would be the same if instead we had assumed that buyers pay the tax. For this single-pool model, since the emissions rate is invariant, the emissions tax is equivalent to an extraction tax.[5]

[5] Technically, we assume that the tax rate is fixed relative to demand. In the five-pool section, we index the tax rate to demand growth, which ensures the tax effects are comparable over time. In the single-pool model without demand growth, the tax is fixed. We recognize that the form and path of taxes on fossil fuels influence market responses over time (e.g., Sinn 2008, Hoel 2011). An optimal emissions tax path would need to account for dynamics, damages, discounting, and the possibility of a time-inconsistency problem.

Let $p(t)$ denote the price consumers pay. Hence, extractors retain $p(t)-\tau\mu$ after paying the tax. In a competitive equilibrium, then, we have $p(t)=\min(c+\tau\mu+\lambda e^{rt}, B(t;z))$. While the cumulative extraction equations ((1) and (3)) remain the same (with the new expression for the price), a modification enters the equations defining the switchover points for regions (a) and (b), respectively:

$$B(x_B; z_0) = c + \tau\mu + \lambda e^{rx_B} \tag{2'}$$

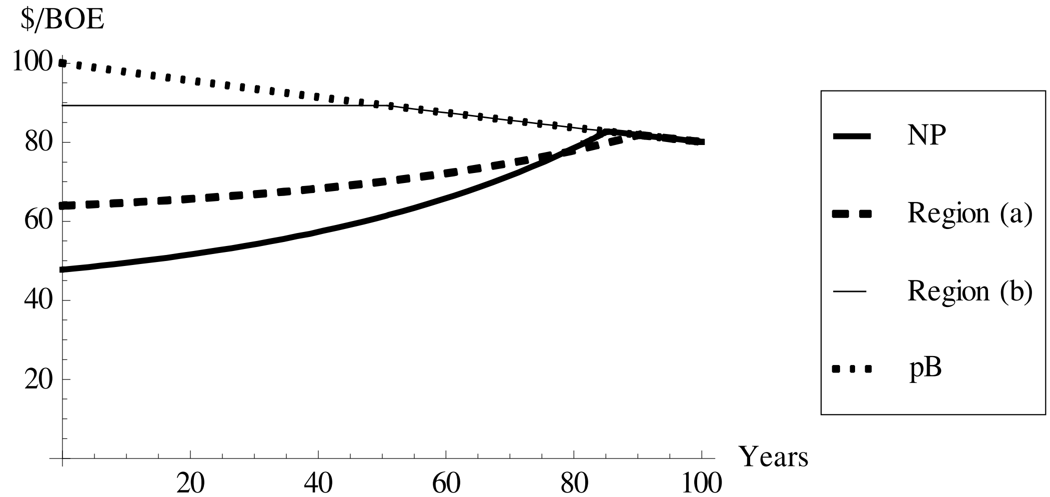
$$B(x_B; z_0) = c + \tau\mu \tag{4'}$$

Figure 3 displays price paths within the different regions.

If the emissions tax is sufficiently small, it will cause the price path to change but will still lead to complete exhaustion of each pool (region **(a)**). The new equilibrium price path must cross the old path. For, if the new price paid by consumers over time were either uniformly strictly higher or strictly lower, cumulative extraction would no longer match the stock; nor can the two paths coincide throughout, since the imposition of the tax on extraction would then induce extractors to postpone extraction, causing unsatisfied demand in the early periods. It follows that the new equilibrium price path faced by consumers must cross the old one, resulting in higher initial consumer prices and a delay in the switch to the backstop (larger x_B).

If the tax is just large enough to drive the Hotelling rent to zero, the entire pool would still be exhausted $(\theta_H = 1)$ and the boundary of region **(b)** has been reached. The price consumers pay remains $c+\tau\mu$ until consumers find the backstop cheaper. The higher the tax, the higher the price consumers pay for oil, the sooner they switch to the green backstop (smaller x_B), and the smaller is utilization of the pool (smaller θ).

Figure 3: Price Paths of the Regions with Tax Policy



Energy Efficiency Improvements

An alternative to taxing emissions or promoting green substitutes is to reduce the demand for oil by increasing the efficiency with which it is utilized. Examples include building retrofit programs, higher energy efficiency standards for appliances or higher fuel economy standards for motor vehicles. Efficiency at each point in time (denoted φ) is measured in energy services per barrel of oil (or substitute). As shown below, an improvement in this efficiency of utilization (an increase in φ) has two countervailing effects: (1) it reduces the number of barrels required to obtain any level of energy services; but (2) it increases the level of energy services demanded by lowering their effective price. In practice, the latter so-called "rebound effect" only partially offsets the demand-reduction effect. Consequently, improvements in efficiency result in an inward shift in the demand for oil.

Formally, we distinguish between demand for energy services (denoted v) and the demand for oil (denoted q). Let $\varphi \equiv v / q$ denote services per barrel, assumed to be constant over time and subject to the influence of the policymaker. A consumer who values energy services maximizes $U(v) - \frac{p}{\varphi} v$ and purchases v units of services, where v implicitly solves $U'(v) = \frac{p}{\varphi}$.

If the oil price (p) remains constant but efficiency improves, then the effective price of services $\left(p/\varphi \right)$ falls and more of them will be consumed---the so-called "rebound effect." However, whether or not this results in an increase in the demand for oil depends on the effective price elasticity (η) of the demand for services. Suppose, for example, that the increased

efficiency raised services per barrel by 10%, but the decline in the effective price happened also to raise the demand for services by 10%. Then there would be no change in barrels of oil demanded; if, however, the improved efficiency resulted in a smaller (respectively, larger) increase in the demand for services, the demand for oil would shift inwards (respectively, shift outward).

It is straightforward to compute the derived demand for oil. Inverting the first-order condition, we obtain: $v = U'^{-1}(p/\varphi)$, or $q = D(p/\varphi)/\varphi$, where $D(x) = U'^{-1}(x)$ is the demand for energy services (so for other policies that do not change energy efficiency, we simply have *D*(*p*)). Differentiating, we conclude that $\partial D(p;\varphi)/\partial\varphi = d(p/\varphi)[\eta(p/\varphi)-1]/\varphi^2$, where $\eta(x) \equiv -D'(x)x/D(x)$ is the elasticity of demand for energy services. It follows that an increase in efficiency cuts the demand for oil if and only if the magnitude of the elasticity of demand for services is smaller than 1. In that case, the rebound effect is dominated. Given that the rebound effect is estimated to be smaller than 10%, we assume that $\eta < 1$.[6] Therefore improved efficiency causes the demand for oil to shift inward at any price.

With this framework, we modify Equations (1) and (3) representing cumulative extraction, while (2) and (4) still govern the backstop switchover conditions for regions (a) and (b), respectively (with $z = z_0$).

$$\int_{t=0}^{x_B} \frac{1}{\varphi} D\left(\frac{c+\lambda e^{rt}}{\varphi}\right) dt = S \tag{1'}$$

$$\int_{t=0}^{x_B} \frac{1}{\varphi} D\left(\frac{c}{\varphi}\right) dt = \theta S \tag{3'}$$

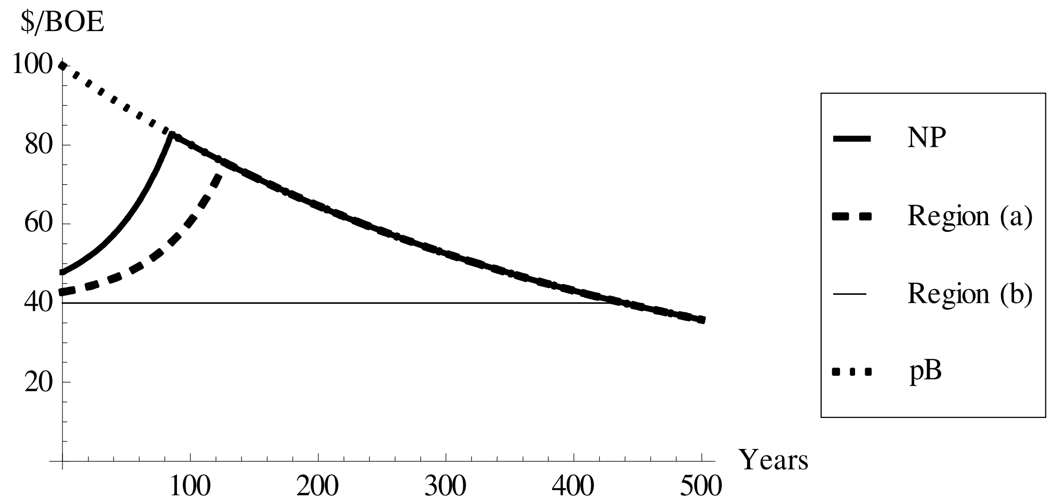
Figure 6 displays price paths for each of the regions.

Within region **(a)**, improvements in EE decrease demand for oil and result in a price path that is uniformly lower—if it did not fall, the cumulative demand up until the switchover point would be less than the stock. Thus, to continue to exhaust the resource pool, the Hotelling rent falls and the transition to the backstop occurs later. Emissions are postponed, but exhaustion still occurs.

[6] Killian and Murphy 2010, Espey, 1996, Goodwin et al (2004), Hughes et al (2008), and Small and van Dender (2007).

If improvements in EE are sufficiently large, we reach the boundary with region **(b)**, where the Hotelling rent is just driven to zero, but nonetheless the entire high-cost pool is exhausted. However, further ratcheting of EE policy has effects distinct from those of the previous policies. First, since the transition to the backstop occurs when the backstop price falls to the marginal cost of extraction, x_B is unaffected by improvements in EE. Since improvements in EE reduce the rate of utilization of fuel without altering the date when it is replaced, they result in less cumulative usage of the oil stock (reduced θ).

Figure 4: Price Paths of the Two Regions with Energy Efficiency Policy



Blend Mandate

A blend mandate would require that a certain percentage (β) of energy needs be met with the backstop technology, much as with a renewable fuel standard or renewable portfolio standard. The policy combines some of the effects of the extraction tax—paid in the form of a cost premium for the mandated share of the backstop energy source—and some of the effects of the energy efficiency policy, since fossil fuels are being displaced in a given level of energy services with the backstop.

To sell its product, an extractor must blend one barrel of fossil fuel with $\beta/(1-\beta)$ barrels of the backstop, and then sell the resulting $1/(1-\beta)$ barrels of the blended product at price p_t per barrel of blend to obtain $p_t/(1-\beta)$ per unit extracted. The extractor chooses the number of barrels to extract and blend each period to maximize:

$$\int_{t=0}^{x_B}\left(\frac{p_t}{1-\beta}-c_i-\frac{\beta}{1-\beta}B(t;z_0)\right)q_t e^{-rt}dt-\lambda_i\left(\int_{t=0}^{x_B}q_t dt-S_i\right).$$

So while the extractor is operating, the price must itself equal a blend of the two energy source costs: $p_t = (1-\beta)(c+\lambda e^{rt}) + \beta B(t;z_0)$. Meanwhile, at any given price, only a fraction of the demand for barrels of blend is fulfilled by the fossil energy source: $q_t = (1-\beta)D(p_t)$; the other $\beta D(p_t)$ units are provided by the backstop component of the blend.

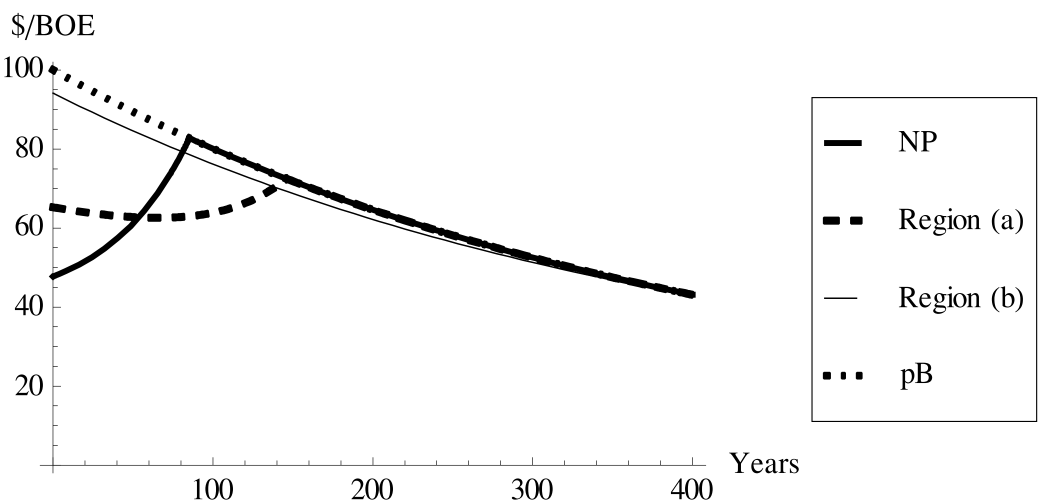
With this framework, we modify Equations (1) and (3) representing cumulative extraction, while the original equations (2) and (4) govern the backstop switchover conditions for regions (a) and (b), respectively (with $z = z_0$).

$$\int_{t=0}^{x_B} (1-\beta)D\Big((1-\beta)(c+\lambda e^{rt}) + \beta B(t;z_0)\Big)dt = S \qquad (1'')$$

$$\int_{t=0}^{x_B} (1-\beta)D\big((1-\beta)c + \beta B(t;z_0)\big)dt = \theta S \qquad (3'')$$

Figure 5 displays the price paths of the two regions with the blend mandate. The mandate functions in part like a tax, raising costs and tilting the price path flatter as it becomes more stringent. However, as the backstop price declines over time, so does the implicit tax, resulting in a declining price path in the more stringent policy regimes.

Figure 5: Consumer Price Paths of the Regions with the Blend Mandate



Larger blend requirements decrease demand for oil both by displacing oil and by raising prices—at least initially. Within region **(a)**, however, the price path cannot stay uniformly higher, else cumulative extraction would be less than the stock. Hence, the new price path must cross the no policy (or less stringent policy) path. Consequently, the switch to the backstop must occur later. As with the EE policy, emissions are postponed, but exhaustion still occurs.

With a sufficiently large blend mandate, we reach the boundary with region **(b)**, where the Hotelling rent is just driven to zero, but nonetheless the entire high-cost pool is exhausted. From here, as with the EE policy, further ratcheting of the blend mandate has no effect on the timing of the full transition to the backstop, which is determined by (4). However, ratcheting does further displace oil and encourage conservation, resulting in fewer cumulative emissions (reduced θ).

Carbon Capture and Sequestration

We model carbon capture and sequestration (CCS) as a mandate that a share ρ of emissions from fuels be captured and stored. We would not necessarily expect that the actual emissions from fuel combustion be captured and sequestered, which is particularly unrealistic for transportation fuels. Rather, we assume the mandate merely requires an equivalent amount of emissions to be sequestered, and compliance could be achieved either directly (as with the capture of emissions from oil sands upgrading, for example) or indirectly by purchasing offsets or CCS credits (such as from the capture of emissions from coal-fired or gas-fired electricity generation or even aforestation credits).

Let us assume that CCS costs κ per unit, so per-unit fuel costs are then $c+(\kappa\rho)\mu+\lambda e^{rt}$. The mandate thus has the same effect on the extraction path and price path as a carbon tax of level $\tau=\kappa\rho$. Hence, a price path in Figure 4 induced by emissions tax τ would also arise if the policy were instead to mandate that the share $\rho=\tau/\kappa$ of emissions from fossil fuels be sequestered. The two policies would not generate the same cumulative emissions, however. Indeed, the CCS policy would generate $1-\rho$ times the cumulative emissions.

4. A Comparison of the Policies

Table 1 summarizes these results.

Table 1:Summary of Policy Ratcheting Effects by Region

	Backstop arrival		*Consumer Prices*		*Cumulative Emissions*	
Region	**a**	**b**	**a**	**b**	**a**	**b**
Backstop subsidy	sooner	sooner	strictly lower	strictly lower	same	lower
Emissions Tax	later	sooner	higher initially	strictly higher	same	lower
Energy Efficiency	later	no change	strictly lower	strictly lower	same	lower
Blend Mandate	later	no change	higher initially	higher initially	same	lower
CCS mandate	later	sooner	higher initially	strictly higher	lower	lower

With only one pool, reaching any cumulative emissions target below the baseline means operating in region (b)—with the exception of the CCS policy in certain circumstances. If we then focus on region (b), it is easy to use the equilibrium conditions to rank many of the policies in terms of the switchover time and consumer surplus associated with a given level of cumulative emissions. This analysis also gives intuition in comparing policies in the *n* pool case. We also note the distinction here between the policy effects on the backstop switchover time, which has been used as an indicator of the weak green paradox, and the actual extent of intertemporal leakage, which arises through the adjustment of scarcity rents.

Backstop Timing

First, consider the effects of each policy on the backstop switchover time associated with a given level of cumulative emissions. For simplicity, we assume demand is time invariant, which allows for easy expressions of the stock equations (3).

For example, with the backstop policy, z must be such that ${x_B}^{BS} = \theta S / D(c)$.

With a tax, then, we have ${x_B}^{tax} = \theta S / D(c + \tau\mu) > {x_B}^{BS}$, since $\tau > 0$.

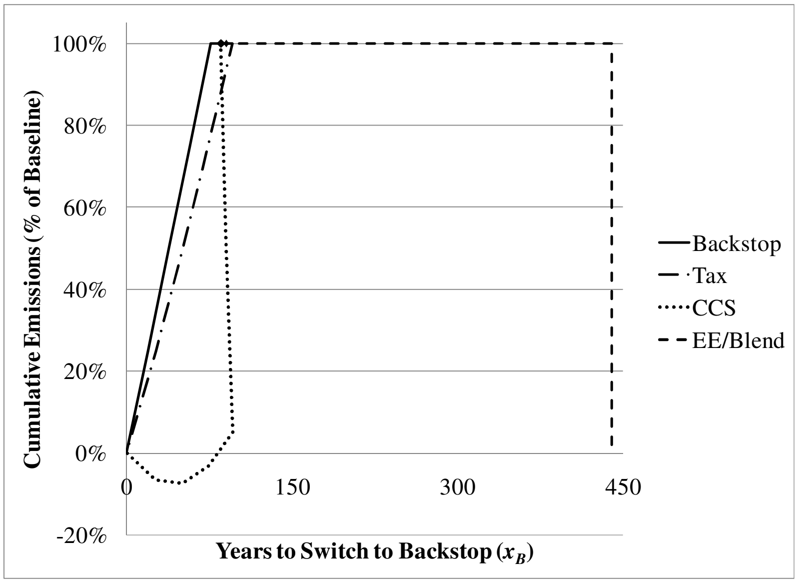
Since the blend mandate and the EE policy have identical switchover conditions, they must have identical transition points in region (b). Using that condition, we show that $B({x_B}^{EE}; z_0) = c < c + \tau\mu = B({x_B}^{tax}; z_0)$, implying that ${x_B}^{blend} = {x_B}^{EE} > {x_B}^{tax} > {x_B}^{BS}$.

The CCS policy is less easy to compare. With CCS, the effects on extraction are identical to those of an emissions tax equal to the cost of the mandate; i.e., $\rho\kappa = \tau$. Consequently, at a given amount of extraction, the CCS policies would have the same x_B as the tax. But sequestration means a given amount of extraction is associated with fewer emissions, so meeting the same cumulative target, we have $\rho\kappa < \tau$ (else emissions would be lower) and more extraction than with the tax. *If* the target is such that extraction is still incomplete, and one is still within region (b), we can prove the ranking using the equilibrium condition (4): $B(x_B{}^{CS}; z_0) = c + \rho\kappa\mu < c + \tau\mu = B(x_B{}^{tax}; z_0)$ so $x_B{}^{CCS} > x_B{}^{tax}$. However, some cumulative targets met by a tax in region (b) might be met with a CCS mandate still in region (a), with full extraction. In this case, we have $B(x_B{}^{CS}; z_0) = c + \rho\kappa\mu + \lambda e^{-rx_B}$, which may or may not be less than $c + \tau\mu$. In either case, since $c < c + \kappa\rho\mu < c + \kappa\rho\mu + \lambda e^{rx_B}$, we know that $x_B{}^{blend} = x_B{}^{EE} > x_B{}^{CCS}$, regardless of the region the CCS policy is in for the given target.

Thus, we have a (nearly) complete ranking, for a given level of cumulative emissions: $x_B{}^{blend} = x_B{}^{EE} > \begin{matrix} x_B{}^{CCS} \\ x_B{}^{tax} \end{matrix} > x_B{}^{BS}$.

Figure 6 confirms this, by plotting cumulative emissions against x_B for each policy. We observe that in region (a), the backstop policy causes an earlier switch, while the tax delays it, and the EE/blend mandates delay even more. In region (b), the backstop and tax policies bring the switchover time forward monotonically, but they do not cross, while the EE and blend policies have no effect on the backstop timing. Region (a) of the CCS policy crosses region (b) of the tax, and then remains with a later switchover date, given any cumulative target.

Figure 6: Cumulative Emissions and Switchover Timing with One Pool

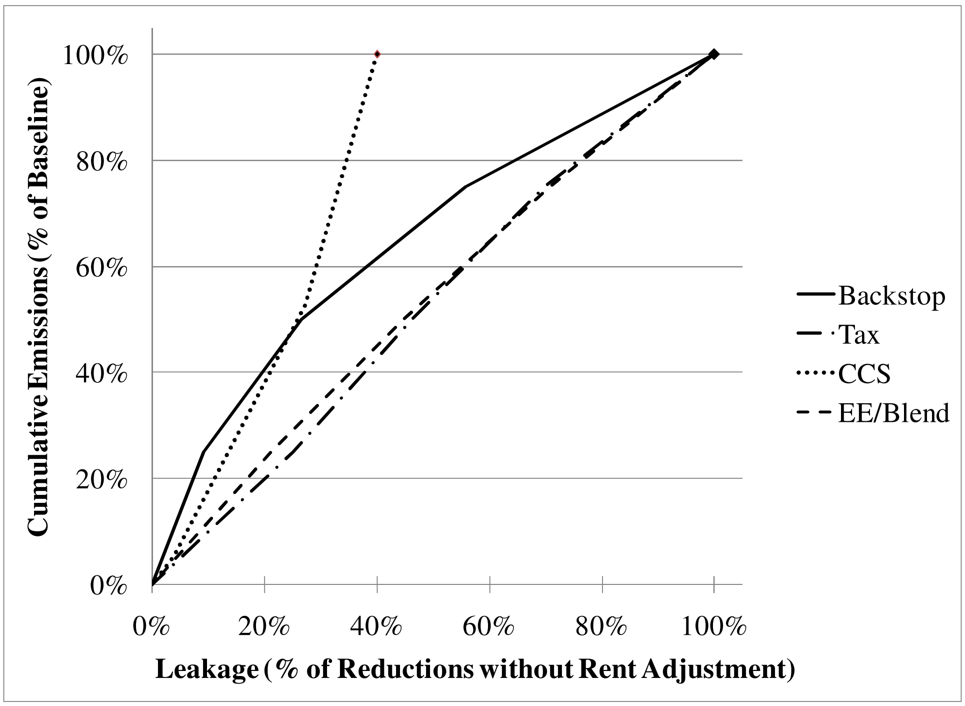


By this ranking of x_B, the conservationist policies delay more consumption, reducing average emissions, while the backstop policy leads to the highest average emissions, given a cumulative emissions target. However, are average emissions an appropriate measure of the weak green paradox? Note that these same rankings in region (b) also hold for the "no leakage" counterfactual (in which extraction costs also remain constant, but at λ_{NP}). In other words, if we eliminate the problem of intertemporal leakage, we see that these policies still induce changes in the timing of the transition to the backstop, and therefore average or present value emissions. Those effects are distinct from the real problem of intertemporal leakage, which is the acceleration of consumption that arises from falling Hotelling rents, and all policies suffer from a version of that problem.

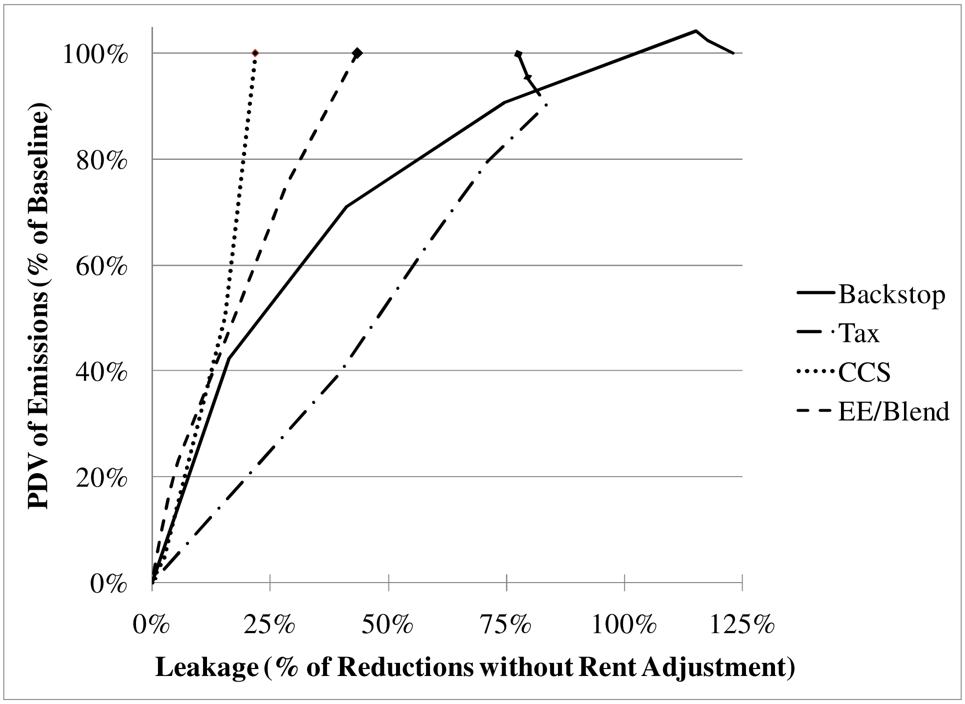
Leakage

A more appropriate measure of a policy's susceptibility to intertemporal leakage is to measure that leakage rate—the amount of additional emissions caused by the rent adjustments in comparison to the reductions that would occur in their absence. Formally, we measure for each policy *i*, $L_i = (E_i - E_i^{NL}) / E_i^{NL}$ and $PVL_i = (PVE_i - PVE_i^{NL}) / PVE_i^{NL}$, as functions of policy stringency. Since these measures are more complicated to derive analytically, we use the following parameterized example.

The next two figures plot the relationships between leakage rates and the cumulative (or PV) emissions target reached by each policy. Comparing cumulative emissions targets, we see that the backstop policy actually suffers from *less* intertemporal leakage than the tax or conservation policies. Unsurprisingly, though, the CCS policy has the least leakage problem—at least initially, since it achieves positive reductions even when cumulative extraction is unchanged.



In terms of present value emissions, however, the story changes. The backstop policy initially has a leakage rate in excess of 100%, while the other policies have less than 100% leakage on the margin. However, as emissions are reduced, the leakage rate associated with the backstop policy gradually converges toward that of the conservation and CCS policies, while the emissions tax retains the highest intertemporal leakage rate.



Consumer Effects

Next we can rank the consumer effects, as measured by the price of energy services. In region (b), with the exception of the blend mandate, the policies produce constant consumer prices until the backstop switch. In that case, for a given *z*, a lower consumer price until the switch means a higher present value of consumer surplus. We have established that $c/\varphi < c < c + k\rho\mu < c + \tau\mu$. However, the backstop policy also lowers consumer prices after the switch. Therefore, we know that $CS_{EE} > CS_{CCS} > CS_{tax}$ and $CS_{BS} > CS_{CCS} > CS_{tax}$, but it is unclear whether $CS_{EE} > CS_{BS}$.

The blend mandate is more difficult to rank, because even in region (b) the consumer price is nonstationary, declining over time with the cost of the backstop portion of the blend: recall that $p(t) = (1-\beta)c + \beta B(t, z_0)$. Since the blend mandate raises the price above *c*, we can also state clearly that $CS_{EE} > CS_{Blend}$ and $CS_{BS} > CS_{Blend}$; however, the comparison with the tax is less obvious. We know that, for a given emissions level, cumulative oil consumption is the same as with the tax, but since only $(1-\beta)$ of the energy consumed is from oil, we know that cumulative energy services consumption is higher with the blend mandate. But what we need to compare is the PDV of consumer surplus, given the policy stringencies required. We know that $x_B^{blend} > x_B^{tax}$, so consumer prices must be lower with the blend for $t \geq x_B^{tax}$ up to x_B^{blend}, since

during that time consumers are still relying in part on the lower cost oil. If initial prices are also lower, then they must be lower throughout and the blend mandate would necessarily have a smaller impact on consumers. For $(1-\beta)c+\beta B_0 < c+\tau\mu$ to hold requires $\beta(B_0-c)<\tau\mu$. This might hold for certain parameter and target combinations, but it is not a general result.

Finally, although the EE and backstop policies have the smallest impacts on consumer surplus (actually benefiting consumers), they also have costs that are not accounted for in these metrics. Namely, the cost of R&D, technological deployment, and policy inducements needed to reach the given targets is difficult to quantify and may well outweigh the consumer benefits.

5. Extension to Multiple Pools

This pattern generalizes if there are $n > 1$ pools. If the per-unit costs of extraction differ among these pools, they will be extracted in order of their extraction costs (Herfindahl, 1967) . Moreover, in the equilibrium a pool with a lower extraction cost will have a higher Hotelling rent. Let x_k denote the date of transition from pool $k-1$ to the pool k.

Suppose we gradually tighten one of the policies considered previously. Then the equilibrium will fall successively into each of $2n$ qualitative regions $R_{1a}, R_{1b}, \dots R_{na}, R_{nb}$. In (a) regions, every pool that is utilized will ultimately be exhausted and the associated Hotelling rents will each be strictly positive. Strengthing the policy within an odd-numbered region causes the rents to decline until the lowest rent reaches zero. Further strengthening of the policy moves the equilibrium into a (b) region. In such regions, the last pool utilized has a zero Hotelling rent and will (except for the boundary case) be only partially exhausted. Further strengthening of the policy within a (b) region has no effect on the strictly positive Hotelling rents. When the resource pool with the zero rent ceases to be utilized at all $(\theta_i = 0)$, the equilibrium falls into the next (a) region, etc…

The set of equations defining these endogenous variables is described in Section A1 of the Appendix.

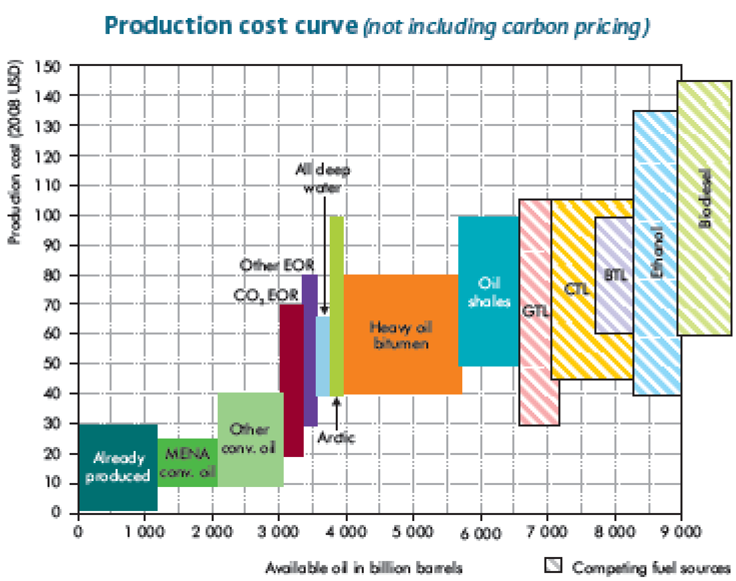
Simulation Model

To assess the potential consequences of these different policies, we simulate each of them using a model calibrated to reflect real-world data. In particular, we take account of demand elasticity and demand growth over time as well as the size, per-unit cost, and emissions factor for each of five types of pools of oil: Middle East and North African (MENA) conventional oil,

other conventional oil, enhanced oil recovery (EOR) and deep-water drilling, heavy oil bitumen (including oil sands), and oil shales.

Estimates of oil reserves and costs vary widely. EIA currently estimates global proven reserves to be about 1200 billion barrels (including conventional and some unconventional like Canadian oil sands). Kharecha and Hansen (2008) report reserves estimates in GtC, but converting to billion barrels of oil equivalent (BBOE), they find a range of 1000-2100 BBOE of conventional oil and 1300-8500 BBOE of unconventional oil. Aguilera et al. (2009) include projections of future reserve growth, leading to estimates of conventional oil reserves of 6000-7000 billion barrels available at prices as low as \$5/barrel, heavy oil reserves of 4000 billion barrels at \$15/BOE, oil sands reserves of 5000 billion barrels at \$25/BOE, and up to 14,000 billion barrels of oil shale that could be tapped at \$35/BOE. 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 (Figure 7).

Figure 7: (Source: IEA 2010)



Our specific reserves and cost assumptions are given in Table 2. To convert to CO2 emissions (right column), we assume (as suggested by U.S. EPA) that a barrel of oil contributes

0.43 tons[7] of CO_2 and adjust for the fact that different unconventional sources have larger emissions factors relative to conventional oil.[8]

Table 2: Reserves and Cost Assumptions

Oil reserve source	*Available Reserves (BBOE)*	*Production cost*	*Relative Emissions Factor*	*CO2 (Gt)*
Middle East/N. Africa conventional	900	$17	1	387
Other conventional	940	$25	1	404
EOR and deep water	740	$50	1.105	352
Heavy Oil/Oil Sands	1780	$60	1.27	972
Oil Shale	880	$70	2	757
Biofuels / backstop technology	Unlimited	$100	0	0

The assumed initial backstop price is drawn from a range of common estimates of 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 larger scale supplies needed to function as backstop technologies—have higher costs.[9] Thus, starting from a backstop price of $100, we assume that costs will ultimately asymptote to $10 (i.e., be lower than conventional oil in the far future), following a modest no-intervention cost reduction rate of 0.25% per year of the excess over the long-run cost ($z = 0.0025$). The combination of these cost assumptions ensures that all oil resources would be fully exhausted in the absence of policy interventions. We do assume that the backstop fuels are non-emitting, while acknowledging their actual emissions factors, particularly those associated with land use changes, are a subject of great controversy. While we draw on biofuels for these cost assumptions, future backstops could also include other options like hydrogen or clean electricity for plug-in vehicles.

CCS cost estimates vary widely, according to the source of the carbon stream being captured (coal-fired power plants being cheaper than industrial sources), the transportation costs, and the sink being used (geological sequestration being cheaper than ocean sequestration or mineral carbonization), as well as monitoring and verification costs (IPCC 2010).[10] CCS from oil

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

[8] 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

[9] In 2007, USDA estimated cellulosic ethanol production costs at $2.65 per gallon, compared with $1.65 for corn-based ethanol.

[10] http://www.ipcc.ch/pdf/special-reports/srccs/srccs_technicalsummary.pdf

sands upgrading is likely to be on the costlier end; furthermore, it is limited to the energy used for upgrading, so a mandate of any larger magnitude would require purchasing sequestration credits from other sources. For our purposes, we assume a constant and fixed cost of $100 per ton sequestered, which falls within the admittedly large range of estimates.

For the demand side of the simulation model, we parameterize a linear demand function. According to the Energy Information Administration (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.[11] EIA's International Energy Outlook 2010 projects global demand to increase 49% from 2007 to 2035, or about 1.45% per year, primarily from developing countries.[12] We incorporate demand growth by assuming that the intercept of the demand function rises at this rate.

We assume an effective elasticity of -0.25. This value roughly corresponds to the median estimate of a global oil demand elasticity from Killian and Murphy (2010). Earlier estimates of the price elasticity of demand for gasoline (primarily in the U.S.) find short-term demand elasticities of about -0.25 and long-run elasticities of about -0.6 (Espey (EJ, 200?) and Goodwin et al. 2004). On the other hand, Cooper (2003) and Dargay and Gately (2010) find much lower price elasticities of demand (-0.15 and smaller) when considering a broader array of countries, particularly non-OECD countries, and more recent time periods. However, Killian and Murphy (2010) warn that most studies of such elasticities using dynamic models have been econometrically flawed by not accounting for price endogeneity.

Initial demand is parameterized so that the slope at the quantity of 31.4 BBOE corresponds to our assumed demand elasticity at the equilibrium price for t=0 in the model. The implied initial choke price of our demand curve is $205, rising over time at 1.45% per year; so that the emissions tax policy has a comparable effect over time, we assume the tax rate rises at the demand growth rate.[13] We assume a discount rate of r = 2% per year.

Of course, our simple Hotelling model does not explain the simultaneous exploitation of high-cost resources alongside low-cost ones and predicts an initial price of $41/barrel instead of

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

[12] http://www.eia.doe.gov/oiaf/ieo/highlights.html

[13] As Sinn (2008) and Hoel (2011) point out, the time path of emissions fees or extraction taxes matters for the present discounted value of emissions, given a cumulative emissions outcome.

$75 per barrel.[14] However, it does add a great deal more realism to a model that still allows for the kinds of green paradoxes explored in the literature. We find these modest additions lead to a significant weakening of intertemporal leakage concerns.

Simulation Results

Figure 8 displays the no-policy price path indicated by the five-pool model. We see that differentiating among more pools leads to a smoother price path. Demand growth outpaces price growth, so corresponding consumption rises smoothly over time, and fossil fuels are exhausted after 81 years.

Figure 8: No Policy Price Path with Five Pools

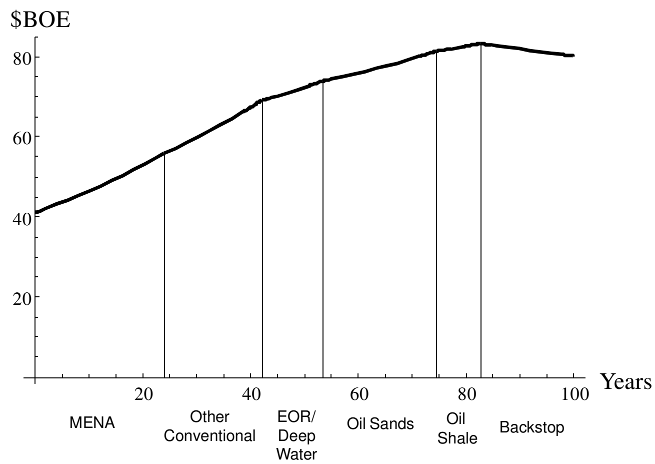


Figure 9 has ten panels. The five panels on the left indicate how strengthening the five respective policies affects cumulative emissions; the five panels on the right indicate how strengthening these policies affects the present discounted value of emissions. The solid lines show the predictions of the five-pool model after rents re-equilibrate, while the dashed lines

[14] Gaudet, Moreaux, and Salant (2001) show how to generalize the Hotelling model to the case where the location of demanders (as well as reserve deposits) is exogenously distributed. In such a model, resources pools are sometimes accessed simultaneously by spatially distributed users even though the pools differ in extraction costs (a high-cost pool might be located near one consumer and a lower-cost pool might be located near another consumer, with the two pools far apart from each other). Despite its greater realism, we declined to use this spatial Hotelling model in our preliminary investigation. We decided to use the nonspatial Hotelling model instead since that model has been used by all of the other contributors to the Green Paradox literature. Our goal here is to clarify how the introduction of heterogeneity in the extraction costs and emissions factors of the different pools of fossil fuels alters conclusions others have drawn about the magnitude of intertemporal emisisons leakage.

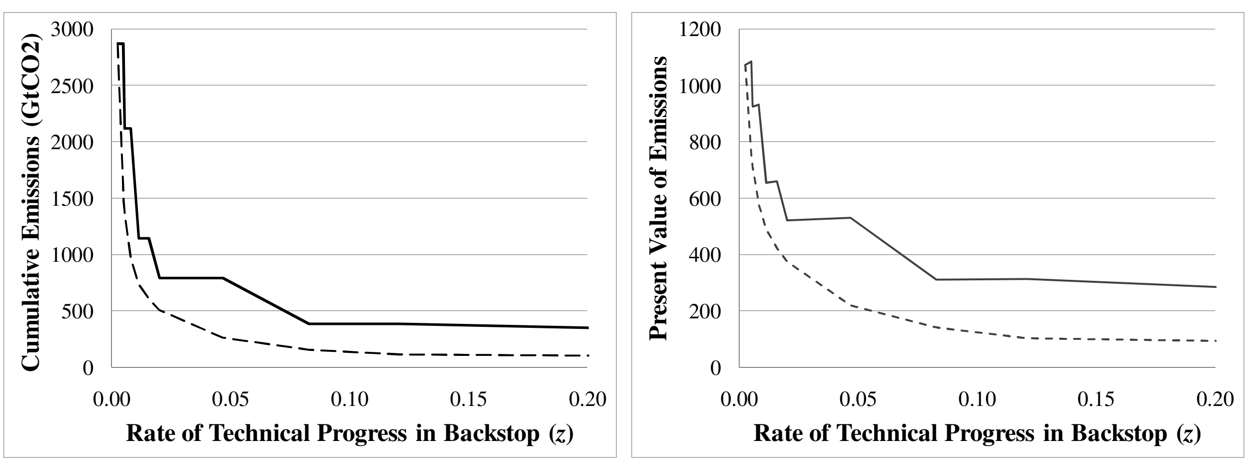
indicate the consequences of the policies if rents remained fixed at the no policy level (no intertemporal leakage).

For the backstop policy, we see that with five pools, the results with rent adjustment are closer to the no-leakage results than in the simplified two-pool model, and this holds for the emissions tax and CCS policy as well (particularly the latter). We also see for these policies that the response of emissions in present value terms is similar to that of cumulative emissions. Both decline steeply after short intervals of rent reductions in the odd-numbered regions, and the three highest cost pools are left unexploited with relatively modest policy levels. While technically the backstop policy increases and the emissions tax decreases the present value of emissions during periods of rent dissipation, both effects are quite small.

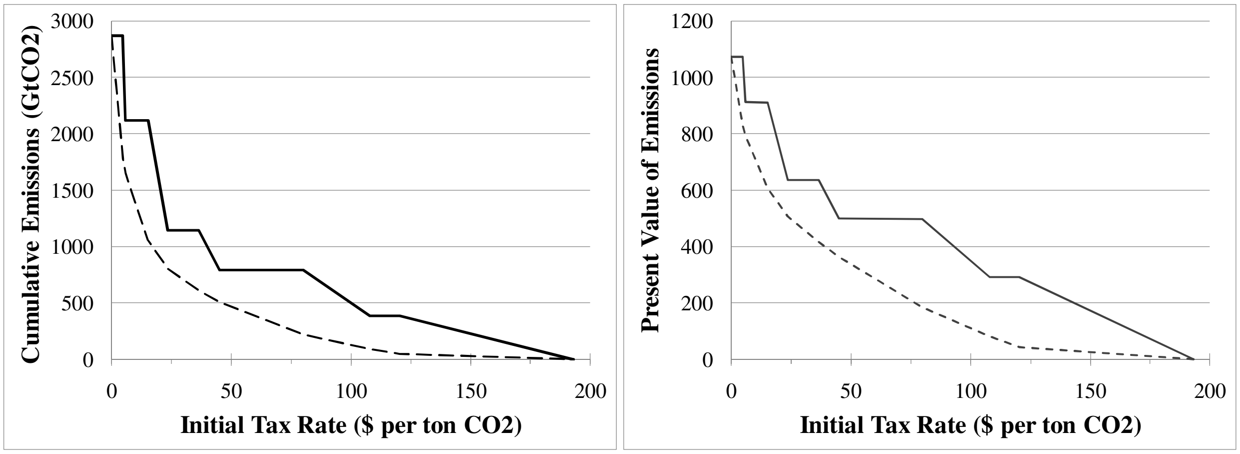
The energy efficiency improvement and blend mandate policies are difficult to distinguish from one another but quite different from the other policies. Indeed, extremely high rates of the policy values are needed just to displace the highest cost pool, and leakage in terms of cumulative emissions is 100 percent up to that point. On the other hand, these policies do cause the present value of emissions to decline monotonically, with much smaller leakage rates in comparison to the no-rent-adjustment case.

Figure 9: Cumulative Emissions and Present Value Emissions as a Function of Policy Stringency with Five Pools with (Solid Line) and without (Dashed Line) Rent Adjustment

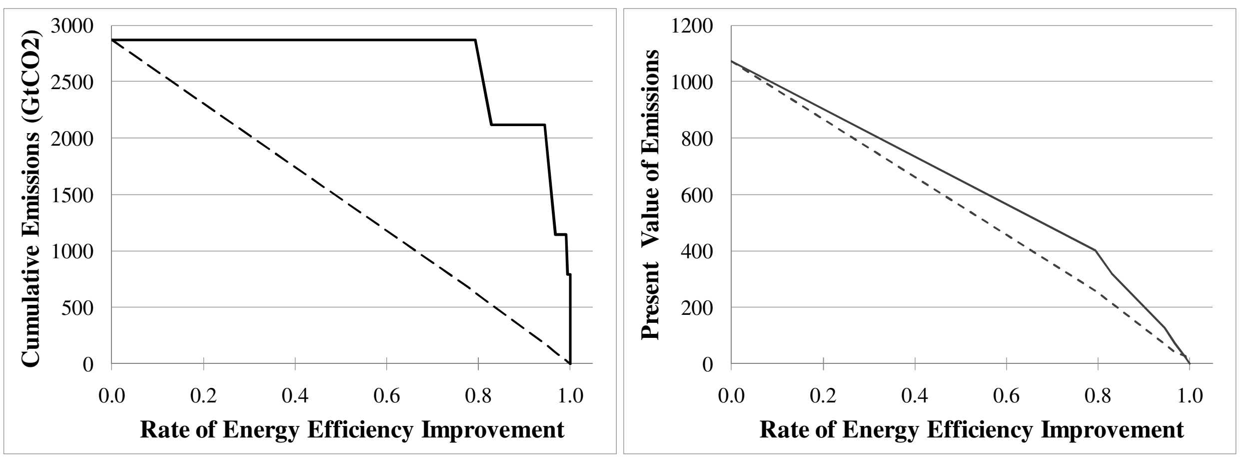
a. Backstop Policy



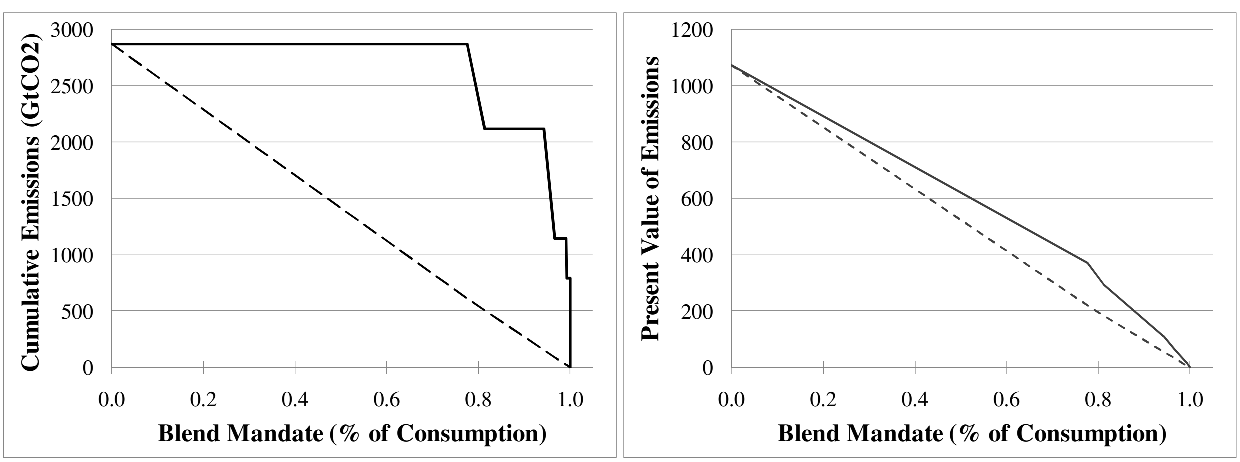
b. Emissions Tax



c. Energy Efficiency Improvement



d. Blend Mandate



e. CCS Mandate

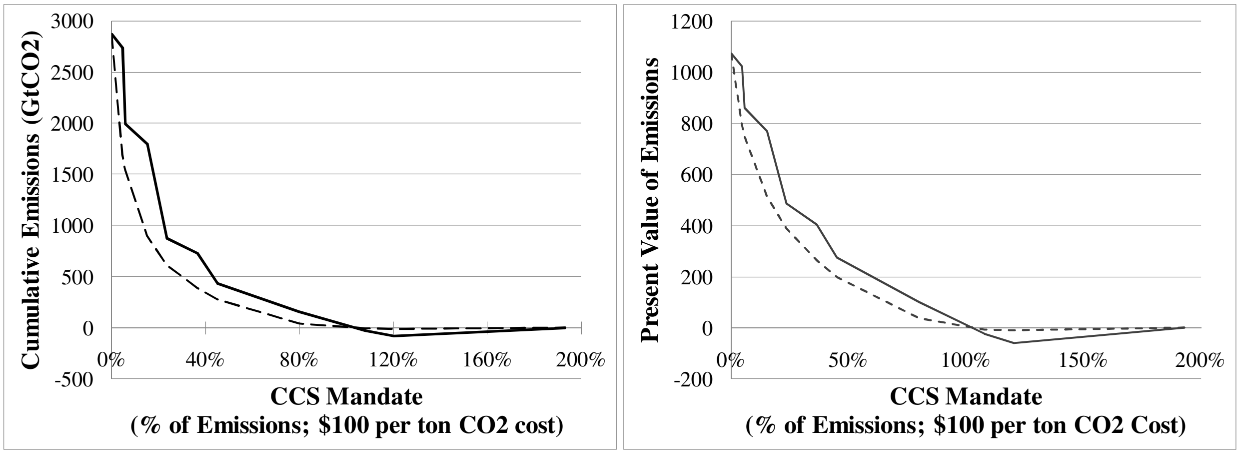
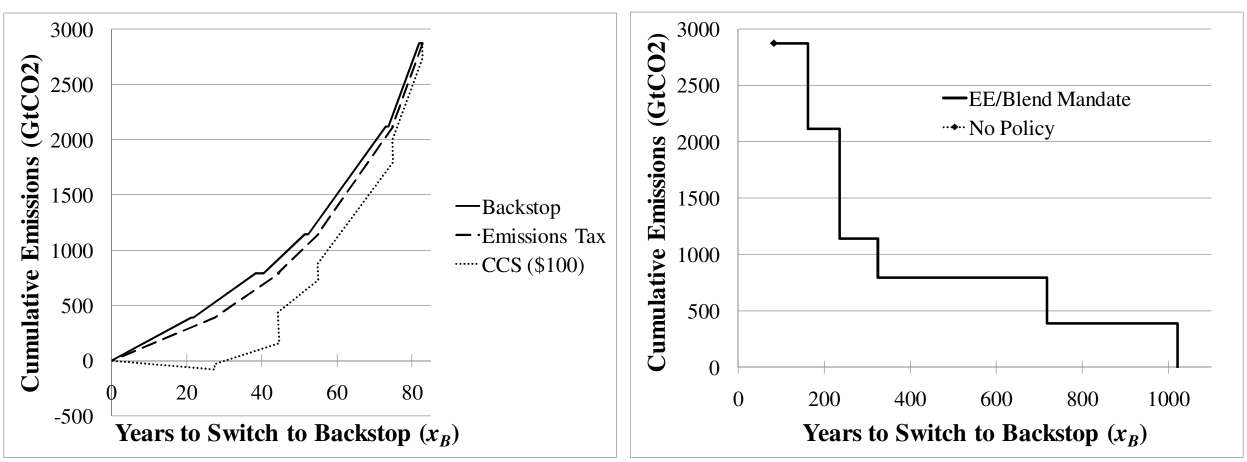


Figure 10 displays the relationship between cumulative emissions and the length of time to switch to the backstop for the five-pool model. With the greater number of pools and more cost differentiation, we notice that the regions in which the last pool is fully extracted are less pronounced than in the two-pool model, leading to a smoother relationship between the switchover timing and cumulative emissions. The difference between the backstop and emissions tax policy is also smaller, meaning average emissions are more similar. The energy efficiency and blend mandates still have the effect of greatly delaying the arrival of the backstop.

Figure 10: Cumulative Emissions and Timing of Switch to Backstop with Five Pools



The policies also differ substantially in their effects on consumers. Figure 11 compares the relationship between cumulative emissions and the initial consumption of energy services at t=0. This metric is simple to calculate, and the results are closely related to the overall effects on

discounted consumer surplus. We see that, for eliminating the emissions from the three highest cost pools, the emissions tax (and CCS mandate) reduces consumption modestly, while the backstop policy raises it modestly. These policies diverge more strongly as the lower cost pools are left in the ground. In contrast, the blend mandate reduces initial consumption significantly before the rents of oil shale are dissipated, while the energy efficiency mandate causes the consumption of energy *services* to grow significantly, due to the rebound effect.

Figure 11: Cumulative Emissions and Initial Consumption of Energy Services with Five Pools

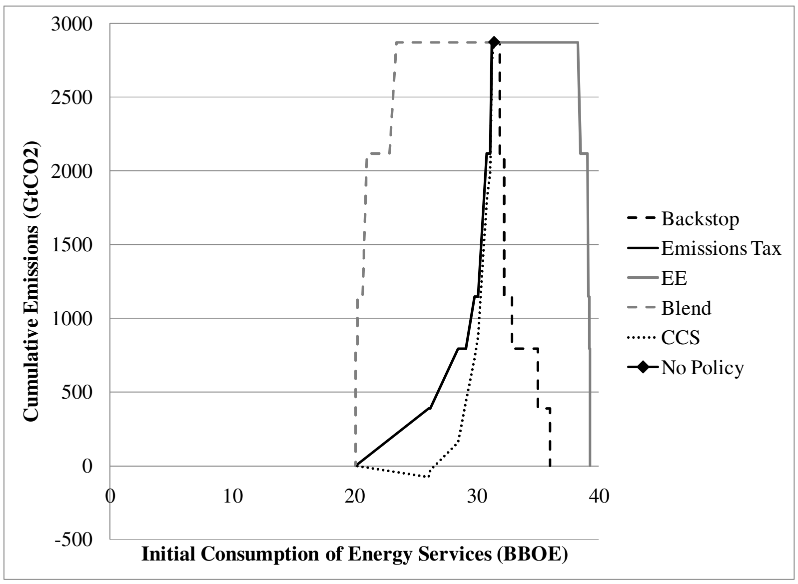
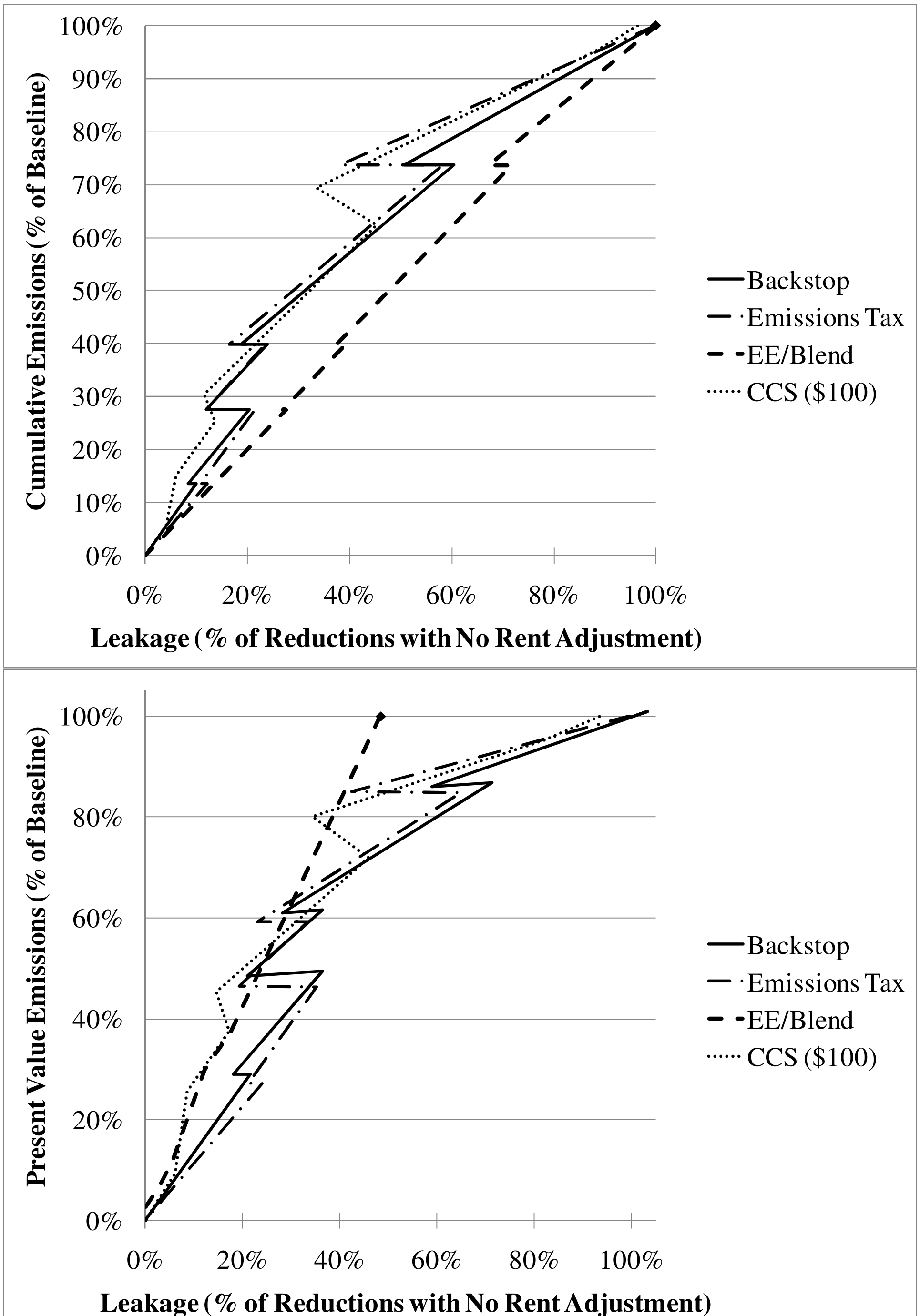


Figure 12 depicts the average intertemporal leakage rates associated with a given level of reductions in cumulative emissions (on the left) or present value of emissions (on the right). Average leakage is defined as the difference in reductions with and without rent adjustment, as a percentage of reductions that would occur with no rent adjustment. Policies to the left have less leakage, on average. We see that for all policies initially have 100 percent leakage, and that rate declines as cumulative emissions fall. For given level of cumulative emissions, the energy efficiency and blend mandates consistently have the highest leakage rates. The emissions tax has less leakage than the backstop policy initially, but for more dramatic reductions its leakage rate is slightly higher. Recall that each policy is being compared against itself, without rent adjustment, so the CCS leakage rate crosses the emissions tax and backstop policies.

In terms of the present value of emissions, however, the results are different. Here, the energy efficiency and blend mandates have the smallest leakage rates.

Figure 12: Comparing Leakage across Policies (difference in reductions as a percentage of reductions that would occur with no rent adjustment)



Of course, while these figures give an indication of the extent of weak or strong leakage that might occur with the different policies, they do not indicate the relative cost-effectiveness. To do this requires cost information that we do not have in reliable form, particularly the cost of

accelerating cost reductions in alternative fuels, and the cost of permanent improvements in energy efficiency. However, Table 3 compares the levels of policy stringency required to achieve given levels of extraction in the simulation model. For example, to avoid the emissions of the oil sands and shale reserves requires a $23/ton CO2 tax (lower than EU ETS prices and expectations of U.S. legislative proposals for a cap-and-trade program 2020), or an increase in the rate of cost reductions in cellulosic biofuels by nearly 1% per year, or a 97% improvement in energy efficiency, a 97% blend requirement, or a 23% CCS mandate (at $100 per ton sequestered, although a lesser mandate of about 21% would get similar cumulative emissions reductions).

Table 3: Levels of Policy Stringency Required

Region	*Backstop Reduction Rate*	*CO2 Tax ($/ton)*	*Energy Efficiency Gains*	*Blend Share*	*CCS Share ($100)*
No Policy	0.003	0	0.000	0.000	0.00
No Shale Rents, Full Extraction	0.005	5	0.794	0.776	0.05
No Shale Rents or Extraction	0.006	6	0.829	0.813	0.06
No Oil Sands Rents, Full Extraction	0.008	15	0.945	0.942	0.15
No Oil Sands Rents or Extraction	0.011	23	0.967	0.966	0.23
No Deepwater Rents, Full Extraction	0.016	36	0.991	0.991	0.36
No Deepwater Rents or Extraction	0.020	45	0.994	0.994	0.45
No Conventional Rents, Full Extraction	0.047	80	1.000	1.000	0.80
No Conventional Rents or Extraction	0.083	108	1.000	1.000	1.08
No MENA Rents, Full Extraction	0.121	120	1.000	1.000	1.20
No MENA Rents or Extraction	Infinite	193	1.000	1.000	1.93

6. Concluson

Climate change is a long-term problem, and since GHGs decay quite slowly, stabilizing their atmostpheric concentrations requires something akin to a limit on cumulative emissions over the next century. Concern over the green paradox takes two main forms. One is that efforts to reduce GHG emissions may be undone in part or in whole by emissions leakage, not only across countries but over time, given that the major sources of GHGs are exhaustible resources. A more subtle form of the green paradox is that, not only may emissions leak over time, but some efforts to spur a transition to clean energy may accelerate emissions in such a way that the present value of the damages of climate change may actually increase.

Our study reinforces earlier findings that accelerating cost reductions in a clean backstop technology tends also to accelerate extraction of nonrenewable resources; however, earlier transition to a backstop can reduce cumulative emissions when exhaustion will not be complete. An emissions tax, on the other hand, slows emissions; however, it also may either slow or accelerate arrival of the backstop, depending on whether cumulative extraction is unaffected or reduced. Meanwhile, energy efficiency improvements, as we have represented them here, delay emissions and the adoption of the backstop technology (at least, they never accelerate that adoption). While all policies considered can reduce cumulative emissions under the right circumstances, the CCS mandate was the only policy that did it in all circumstances.

However, many of these effects are features of the policies themselves and not a product of the fact that exhaustible resource owners will re-optimize intertemporally. Even if scarcity rents did not adjust, the backstop policy will necessarily accelerate the switchover. If we instead compare the rates of intertemporal leakage associated with a given level of cumulative emissions, we find that the conservation policies have the highest leakage rates, while the backstop policy can outperform the emissions tax. Leakage rates are highest (and the green paradox strongest) when policies are weak, but as reduction targets become more stringent, leakage rates tend to fall.

We note some important simplifications in our analysis. For one, our fixed emissions tax would not reflect an optimal tax path, unless the present value of marginal damages were also fixed.[15] If the goal were to cap cumulative emissions by a certain date, the emissions tax would rise at the rate of discount, which implies a reduction in rents to the resource owner that still exhausts, but not a tilting of the path: $p - c_i = (\tau + \lambda_i)e^{rt}$. If EE improvements were increasing over time, those expectations might have different effects on the time path of emissions. One could also consider a time path of increasing CCS requirements. Such alternatives would need to be considered if one were to address optimal policies.

Even with the given policies, additional assumptions would be needed to address questions of relative cost effectiveness. We have not explicitly represented the costs of EE improvements, backstop technology policy, or CCS. For example, while EE may look attractive in terms of its ability to delay emissions, ultimately it will also depend on the costs of achieving

[15] Van der Ploeg and Withagen (2010) find that, within their framework of increasing extraction costs, the optimal tax path rises and then falls.

EE improvements at those scales; indeed, in our simple simulation model, to achieve more than modest reductions requires massive reductions in energy demand. An emissions tax would be an efficient policy in the absence of market failures, but a fair evaluation of its costs and benefits relative to the other policies requires taking those market failures and barriers into account (see, e.g., Fischer and Newell 2008). Nor in our parsing of the policy effects did we allow for emissions prices or energy price changes to induce investments in backstop or energy efficiency improvements or in CCS. In reality, climate policy will be a portfolio of options and responses. The research on intertemporal leakage indicates that this portfolio may need to be somewhat more ambitious than otherwise thought to reach emissions goals, but the efforts are not likely to be undone to the extent indicated by earlier studies.

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Appendix

Formal Model with n *Pools*

A1: The Regions if Backstop Cost Reductions are Accelerated

Recall that $z \geq z_0$ denotes the investment by the government in accelerating backstop cost reductions. Depending on the setting of *z*, one of 2n equilibria will arise.

m(a): If pool $m \leq n$ is the marginal pool, all lower cost pools are exhausted and all higher cost pools remain unexploited. In region *a*, pool *m* itself is exhausted. For any exogenous policy $z \geq z_0$, the following 2*m* equations define the 2*m* endogenous variables $(\lambda_1,...,\lambda_m, x_2,...,x_m, x_B)$:

$$\int_{t=x_k}^{x_{k+1}} D(c_k + \lambda_k e^{rt})dt = S_k, \quad k = 1,...,m-1$$

$$\int_{t=x_m}^{x_B} D(c_m + \lambda_m e^{rt})dt = S_m$$

$$c_{k+1} + \lambda_{k+1} e^{rx_{k+1}} = c_k + \lambda_k e^{rx_{k+1}}, \quad k = 1,...,m-1$$

$$B(x_B; z) = c_m + \lambda_m e^{rx_B}.$$

Given the multipliers in this solution, the equilibrium price path is $p(t) = \min(c_1 + \lambda_1 e^{rt},...,c_m + \lambda_m e^{rt}, B(t;z))$.

m(b): In region *b* for pool *m*, only the fraction θ_m of the marginal pool *m* is depleted; the remainder is left below ground. For any exogenous $z \geq z_0$, the following 2*m* equations define the 2*m* endogenous variables $(\lambda_1,...,\lambda_{m-1}, \theta_m, x_2,...,x_m, x_B)$:

$$\int_{t=x_k}^{x_{k+1}} D(c_k + \lambda_k e^{rt})dt = S_k, \quad k = 1,...,m-1$$

$$\int_{t=x_m}^{x_B} D(c_m)dt = \theta_m S_m$$

$$c_{k+1} + \lambda_{k+1} e^{rx_{k+1}} = c_k + \lambda_k e^{rx_{k+1}}, \quad k = 1,...,m-1$$

$$B(x_B; z) = c_m.$$

Given the multipliers in this solution, the equilibrium price path is $p(t) = \min(c_1 + \lambda_1 e^{rt},...,c_{m-1} + \lambda_{m-1} e^{rt}, c_m, B(t;z))$

A2: The Regions if an Emissions Tax is Increased

Recall that $\tau \geq 0$ denotes the emissions tax imposed on extractors. Depending on that tax level, one of 2*n* equilibria will arise.

m(a): If pool m is the marginal pool, all lower cost pools are exhausted and all higher cost pools remain unexploited. In region *a*, pool *m* itself is exhausted. For any exogenous emissions tax $\tau \geq 0$, the following 2*m* equations define the 2*m* endogenous variables $(\lambda_1,...,\lambda_m,x_2,...,x_m,x_B)$:

$$\int_{t=x_k}^{x_{k+1}} D(c_k + \tau\mu_k + \lambda_k e^{rt})dt = S_k, \quad k = 1,...,m-1$$

$$\int_{t=x_m}^{x_B} D(c_m + \tau\mu_m + \lambda_m e^{rt})dt = S_m$$

$$c_{k+1} + \tau\mu_{k+1} + \lambda_{k+1}e^{rx_{k+1}} = c_k + \tau\mu_k + \lambda_k e^{rx_{k+1}}, \quad k = 1,...,m-1$$

$$B(x_B;z) = c_m + \tau\mu_m + \lambda_m e^{rx_B}.$$

Given the multipliers in this solution, the equilibrium price path is $p(t) = \min(c_1 + \tau\mu_1 + \lambda_1 e^{rt},...,c_m + \tau\mu_m + \lambda_m e^{rt}, B(t;z)).$

m(b): In region *b* for pool *m*, only the fraction θ_m of the marginal pool *m* is depleted; the remainder is left below ground. For any exogenous $\tau \geq 0$, the following and 2*m* equations define the *2m* endogenous variables $(\lambda_1,...,\lambda_{m-1},\theta_m,x_2,...,x_m,x_B)$:

$$\int_{t=x_k}^{x_{k+1}} D(c_k + \tau\mu_k + \lambda_k e^{rt})dt = S_k, \quad k = 1,...,m-1$$

$$\int_{t=x_m}^{x_B} D(c_m + \tau_m\mu_m)dt = \theta_m S_m$$

$$c_{k+1} + \tau\mu_{k+1} + \lambda_{k+1}e^{rx_{k+1}} = c_k + \tau\mu_k + \lambda_k e^{rx_{k+1}}, \quad k = 1,...,m-1$$

$$B(x_B;z) = c_m + \tau\mu_m.$$

Given the multipliers in this solution, the equilibrium price path is $p(t) = \min(c_1 + \tau\mu_1 + \lambda_1 e^{rt},...,c_{m-1} + \tau\mu_{m-1} + \lambda_{m-1}e^{rt},$
$c_m + \tau\mu_m, B(t;z)).$

A3: The Regions if Energy Efficiency is Improved

Recall that $\varphi > 0$ denotes energy efficiency measured in energy services per barrel of conventional oil.

m(a): If pool m is the marginal pool, all lower cost pools are exhausted and all higher cost pools remain unexploited. In region *a*, pool *m* itself is exhausted. For any exogenous policy $\varphi \geq 0$, the following 2*m* equations define the 2*m* endogenous variables $(\lambda_1,...,\lambda_m, x_2,...,x_m, x_B)$:

$$\int_{t=x_k}^{x_{k+1}} \frac{1}{\varphi} D\left((\frac{1}{\varphi})(c_k + \lambda_k e^{rt}) \right) dt = S_k \qquad \text{k=1,...,m} - 1$$

$$\int_{t=x_m}^{x_B} \frac{1}{\varphi} D\left((\frac{1}{\varphi})(c_m + \lambda_m e^{rt}) \right) dt = S_m$$

$$c_{k+1} + \lambda_{k+1} e^{rx_{k+1}} = c_k + \lambda_k e^{rx_{k+1}} \quad \text{k=1,...,}m-1$$

$$B(x_B; z_0) = c_m + \lambda_m e^{rx_B}.$$

Given the multipliers in this solution, the equilibrium price path is $p(t) = \min(c_1 + \lambda_1 e^{rt},...,c_m + \lambda_m e^{rt}, B(t;z)).$

m(b): In region *b*, , only the fraction θ_m of the marginal pool *m* is depleted; the remainder is left below ground. For any exogenous $\varphi \geq 0$, the following *2m* equations define the *2m* endogenous variables $(\lambda_1,...,\lambda_{m-1}, \theta_m, x_2,...,x_m, x_B)$::

$$\int_{t=x_k}^{x_{k+1}} \frac{1}{\varphi} D\left((\frac{1}{\varphi})(c_k + \lambda_k e^{rt}) \right) dt = S_k \quad \text{k=1,...,}m-1$$

$$\int_{t=x_m}^{x_B} \frac{1}{\varphi} D\left(\frac{c_H}{\varphi} \right) dt = \theta_m S_m$$

$$c_{k+1} + \lambda_{k+1} e^{rx_{k+1}} = c_k + \lambda_k e^{rx_{k+1}} \quad \text{k=1,...,}m-1$$

$$B(x_B; z_0) = c_m.$$

Given the multipliers in this solution, the equilibrium price path is $p(t) = \min(c_1 + \lambda_1 e^{rt},...,c_{m-1} + \lambda_{m-1} e^{rt}, c_m, B(t;z))$.

A4: The Regions under a Blend Mandate

Recall that $\beta \in [0,1)$ denotes the minimum share of energy needs that must be met by the the backstop technology (an obvious example is the ethanol blending requirement). This requirement has two effects: 1) it imposes an additional cost on fossil fuels, in the form of an implicit tax equal to the cost of backstop fuel required per unit of fossil fuel, and 2) it replaces a share of fossil fuel with the backstop in overall energy consumption.

m(a): If pool *m* is the marginal pool, all lower cost pools are exhausted and all higher cost pools remain unexploited. In region *a*, pool *m* itself is exhausted. For any exogenous policy the following *2m* equations define the 2*m* endogenous variables $(\lambda_1,...,\lambda_m,x_2,...,x_m,x_B)$:

$$\int_{t=x_k}^{x_{x+1}} (1-\beta)D((1-\beta)(c_k+\lambda_k e^{rt})+\beta B(t;z_0))dt = S_k, \quad k=1,...,m-1$$

$$\int_{t=x_m}^{x_B} (1-\beta)D((1-\beta)(c_m+\lambda_m e^{rt})+\beta B(t;z_0))dt = S_m$$

$$c_{k+1}+\lambda_{k+1}e^{rx_{k+1}} = c_k+\lambda_k e^{rx_{k+1}}, \qquad \text{k=1,...,m} - 1$$

$$B(x_B;z_0) = (c_m+\lambda_m e^{rx_B})$$

Given the multipliers in this solution, the equilibrium price path is

$$p(t) = \min[(1-\beta)(c_1+\lambda_1 e^{rt})+\beta B(t;z_0),...,(1-\beta)(c_m+\lambda_m e^{rt})+\beta B(t;z_0), B(t;z_0)].$$

m(b): In region *b*, only the fraction θ_m of the marginal pool *m* is depleted; the remainder is left below ground. For any exogenous $\beta \in [0,1)$, the following *2m* equations define the *2m* endogenous variables $(\lambda_1,...,\lambda_{m-1},\theta_m,x_2,...,x_m,x_B)$:

$$\int_{t=x_k}^{x_{k+1}} (1-\beta)D((1-\beta)(c_k+\lambda_k e^{rt})+\beta B(t;z_0))dt = S_k, \quad k=1,...,m-1$$

$$\int_{t=x_m}^{x_B} (1-\beta)D((1-\beta)(c_m)+\beta B(t;z_0))dt = \theta_m S_m$$

$$c_{k+1}+\lambda_{k+1}e^{rx_{k+1}} = c_k+\lambda_k e^{rx_k} \qquad k=1,...,m-1$$

$$B(x_B;z_0) = c_m.$$

Given the multipliers in this solution, the equilibrium price path is

$$p(t) = \min[(1-\beta)(c_1+\lambda_1 e^{rt})+\beta B(t;z_0),...,(1-\beta)(c_m+\lambda_m e^{rt})+\beta B(t;z_0), B(t;z_0)]$$

A5: The Regions under a CCS Mandate

Recall that ρ is the share of fossil fuels which must be extracted (as with oil sands upgrading) or burned (as with coal-fired generation) using carbon capture and sequestration technology, which costs *k* per unit.

m(a): In region *a*, the following *2m* equations define the *2m* endogenous variables $(\lambda_1,...,\lambda_m,x_2,...,x_m,x_B)$:

$$\int_{t=x_k}^{x_{k+1}} D(c_k+\rho\kappa\mu_k+\lambda_k e^{rt})dt = S_k, \quad k=1,...,m-1$$

$$\int_{t=x_m}^{x_B} D(c_m+\rho\kappa\mu_m+\lambda_m e^{rx_m})dt = S_m$$

$$c_{k+1}+\rho\kappa\mu_{k+1}+\lambda_{k+1}e^{rx_{k+1}} = c_k+\rho\kappa\mu_k+\lambda_k e^{rx_{k+1}}, \quad k=1,...,m-1$$

$$B(x_B;z) = c_m+\rho\kappa\mu_m+\lambda_m e^{rx_m}.$$

Given the multipliers in this solution, the equilibrium price path is $p(t)=\min(c_1+\rho\kappa\mu_1+\lambda_1 e^{rt},...,c_m+\rho\kappa\mu_m+\lambda_m e^{rt},B(t;z))$.

Total emissions are $E=(1-\rho)\sum_{k=1}^{m}\mu_k S_k$. The remaining $\rho\sum_{k=1}^{m}\mu_k S_k$ is sequestered.

m(b): In region *b*, the following 2*m* equations define the 2*m* endogenous variables $(\lambda_1,...,\lambda_{m-1},\theta_m,x_2,...,x_m,x_B)$:

$$\int_{t=x_k}^{x_{k+1}} D(c_k+\rho\kappa\mu_k+\lambda_k e^{rt})dt = S_k, \quad k=1,...,m-1$$

$$\int_{t=x_m}^{x_B} D(c_m+\rho\kappa\mu_m)dt = \theta_m S_m$$

$$c_{k+1}+\rho\kappa\mu_{k+1}+\lambda_{k+1}e^{rx_{k+1}} = c_k+\rho\kappa\mu_k+\lambda_k e^{rx_{k+1}}, \quad k=1,...,m-1$$

$$B(x_B;z) = c_m+\rho\kappa\mu_m.$$

Given the multipliers in this solution, the equilibrium price path is

$$p(t)=\min(c_1+\rho\kappa\mu_1+\lambda_1 e^{rt},...,c_{m-1}+\rho\kappa\mu_{m-1}+\lambda_{m-1}e^{rt},$$
$$c_m+\rho\kappa\mu_m,B(t;z)).$$

Total emissions are $E=(1-\rho)(\mu_m\theta_m S_m+\sum_{k=1}^{m-1}\mu_k S_k)$. The remaining $\rho(\mu_m\theta_m S_m+\sum_{k=1}^{m-1}\mu_k S_k)$. is sequestered.