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Brown Backstops Versus the Green Paradox

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Abstract

Anticipated climate policies are ineffective when fossil fuel owners respond by shifting supply intertemporally (the green paradox). This mechanism relies crucially on the exhaustibility of fossil fuels. We analyze the effect of anticipated climate policies on emissions in a simple model with two fossil fuels: one scarce and dirty (e.g. oil), the other abundant and dirtier (e.g. coal). We derive conditions for a 'green orthodox': anticipated climate policies may reduce current emissions. Calibrations suggest that intertemporal carbon leakage (from -22% to 13%) is a relatively minor concern.

Keywords: carbon tax, green paradox, exhaustible resource, backstop, climate change

1 Introduction

Well-intended climate policies may have perverse effects. Climate policies typically become stricter over time. Fossil fuel owners, deciding when to sell their scarce resources, may respond by speeding up extraction. This side effect can occur when fossil fuel reserves are limited and cheap to exploit: a reasonable characterization for conventional oil and natural gas, but much less for other important energy sources such as coal and unconventional oil.

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In this paper we ask whether climate policy has unintended consequences when there are two types of fossil fuels: one dirty and scarce, the other even dirtier and abundant.

Policies that reduce future dependence on fossil fuels might encourage suppliers, anticipating a future drop in demand, to bring forward the extraction of their resources. When present emissions are more harmful than future emissions, gradually increasing carbon taxes can be counterproductive: a green paradox (Sinn, 2008a). Developing a carbon-free substitute for fossil fuels can cause a similar effect (Strand, 2007; Hoel, 2011). Cost reductions for the substitute decrease the scarcity value of fossil fuels, and thereby increase fossil fuel supply in all periods before exhaustion.[1]

The crucial feature that drives the above mechanism is the exhaustibility of the resource. This causes the tradeoff between current and future supply, and thus the effect of (expected) future policies on current supply and emissions. If the resource is fully abundant, resource owners supply the myopically optimal quantity in each period and the link between current and future markets is severed. Exhaustibility is a fair assumption for conventional oil and natural gas, which will be depleted in 50 to 70 years at current consumption rates.[2] Coal and unconventional oil are much more abundant however. Coal reserves are sufficient to last another 250 years, and tar sand deposits in Alberta are estimated at 1800 bln barrels.[3] The supply of these resources is primarily driven by costs rather than scarcity rents. Anticipated carbon taxes cause coal mines to shut down in the future, but do not increase near-term supply.

Coal and unconventional oil are significant from an economic and a climate change point of view. Coal satisfies a third of global energy demand and accounts for almost half of energy-related CO2 emissions,[4] outranking petroleum in emission intensity by 30-40%. The IEA expects coal supply to increase by 60% in 2035 under business-as-usual policies;[5] twice as much

[1]The green paradox may vanish when the substitute has an upward-sloping supply curve (Gerlagh, 2011). Van der Ploeg and Withagen (2012a) find that the green paradox occurs for clean but expensive backstops (such as solar or wind), but not when the backstop is sufficiently cheap relative to emissions damages, as it is then attractive to leave part of the oil in the ground.

[2]BP (2010, p. 6, p. 12)

[3]Alberta's Energy Reserves 2010 and Supply/Demand Outlook 2011-2020, p.5

[4]International Energy Statistics, Energy Information Administration

[5]IEA (2010b, p. 201)

as the projected increase in oil supply. Supply of unconventional oil, which is 20% more emission-intensive than petroleum (Charpentier et al., 2009), may increase fivefold to 11 mln barrels per day in 2035. These numbers suggest that in order to keep climate change within tolerable limits, it is imperative that coal and uncoventional oil reserves remain largely unexploited (Gerlagh, 2011). A comprehensive assessment of the effectiveness of climate policies should take into account these dirty substitutes and their unique characteristics.[6]

In this paper, we develop a simple model with two time periods. We do not derive optimal policies, but present a descriptive analysis of the effect of future climate policies on emissions. We generalize assumptions in previous research along two important dimensions. Firstly, the model contains three energy types: a dirty exhaustible resource (e.g. oil), an even dirtier substitute (coal) and a clean substitute (solar). Secondly, we assume types to be imperfect substitutes for one another. Previous theoretical studies often assume perfect substitution, which is unrealistic. We model climate policy as a carbon tax or a decrease in the cost of the clean substitute. We calculate intertemporal carbon leakage as the increase in present emissions over the decrease in future emissions.

By virtue of the abundance of their resource, coal owners do not trade off present and future extraction. When faced with a demand reduction in the future, they will therefore not increase supply today. Oil emissions may leak away to the present, but the increase in current oil supply reduces demand for dirtier coal. Carbon taxes can cause negative leakage when the substitutability between oil and coal differs between periods. We may call this a 'strong green orthodox' (Grafton et al., 2012). Moreover, since carbon taxes decrease the price of oil relative to coal, a future tax delays rather than accelerates oil extraction when oil and coal are good substitutes in the future. Reducing the future cost of solar decreases present emissions when oil and coal are good substitutes or if the emission intensity of coal is high.

Our contribution is twofold. Firstly, we offer a general theoretical framework that can make more accurate predictions than models that include only one or two energy types or assume perfect substitutability. The presence of an abundant dirty substitute reduces intertemporal leakage directly and indirectly, and may even cause negative leakage rates. By making more specific

[6] Van der Ploeg and Withagen (2012b) show that rising carbon taxes may not cause a green paradox when coal, rather than renewables, is the primary alternative for oil.

assumptions, we can obtain similar findings as in other papers on the green paradox. Secondly, our model is well suited for empirical calibration. For carbon taxes, intertemporal leakage rates are negative or less than 5%. For reductions in the future cost of renewables, leakage is between 2-13% for biofuels and 0-2% for solar or wind electricity. Biofuels are a close substitute for oil, the most emission-intensive scarce fossil fuel, and hence more prone to intertemporal leakage than renewable electricity, which primarily competes with coal.

Though we focus on intertemporal leakage, our framework can also be used to analyze spatial carbon leakage, by relabeling the two time periods as two countries and setting the interest rate to zero. Calibrating a spatial version of the model, we find leakage rates ranging from negative to 40%, comparable to estimates from computable general equilibrium models (Di Maria and van der Werf, 2012). These findings suggest that the green paradox is a small concern relative to spatial carbon leakage.

The rest of this paper is organized as follows. Section 2 outlines the model. Section 3 analyzes intertemporal and spatial leakage when carbon emissions are taxed in the future. Section 4 studies the impact of reductions in the future cost of a clean substitute. We calibrate the models in section 5. Section 6 discusses implications of the model for spatial carbon leakage, and calibrates a spatial version of the model. Section 7 concludes. All proofs are relegated to the Appendix.

2 Model

Consider a model with three types of energy: an exhaustible resource, a dirty backstop and a clean backstop. The backstops are inexhaustible, supplied competitively and have constant marginal costs.[7] Though the word 'backstop' is sometimes used to denote a perfect substitute for an exhaustible resource, we explicitly allow for imperfect substitutability. The exhaustible resource is supplied competitively by a group of energy exporters and costless to extract. For the energy exporters, it is always optimal to fully exhaust the fossil resource stock S. An energy-importing country derives utility from consuming energy. Denote the exhaustible resource, the dirty and the clean backstop with superscripts R, D and C respectively. Demand functions are

[7] An upward-sloping supply curve for the clean backstop reduces intertemporal carbon leakage (Gerlagh, 2011).

given by

$$d^i(p^i, p^{-i}),\ i \in \{R, D, C\} \tag{1}$$

where p^i is the consumer price of resource i. Throughout the paper, we write shorthand d^i for (1). Partial derivatives of d^i are indicated by a subscript of the corresponding type. We make the following assumptions about energy demand

$$d^i_i < 0,\ d^i_j \geq 0 \tag{A1}$$

$$\left|d^i_i\right| > \left|d^i_j\right|,\ i \neq j \tag{A2}$$

$$d^i_j = d^j_i \tag{A3}$$

Energy types are imperfect substitutes for one another: demand for each type is non-decreasing in the price of other types (A1) and own-price effects are larger than cross-price effects (A2). Cross-price effects are symmetric (A3). Assumption (A3) is not necessary for many of our results; we explicate any invocation of (A3) in the proposition texts. The assumptions hold if the relative budget shares of the three energy types do not depend on available income.

Consumption of the exhaustible resource and the dirty backstop generates a constant amount of emissions. The dirty backstop is more emission intensive than the exhaustible resource

$$e = \zeta^R d^R + \zeta^D d^D, 0 < \zeta^R < \zeta^D$$

The model consists of two periods. All variables corresponding to the second period are denoted by capitals. We allow for emissions in the first period to be more harmful than emissions in the second period. Total emission damages are

$$\Sigma = e + \beta E,\ \beta \leq 1 \tag{3}$$

When only cumulative emissions matter, β is equal to one. When society and ecology can adapt more easily to slow rather than rapid temperature increases (Hoel and Kverndokk, 1996; Gerlagh, 2011), near-term emissions have a higher weight ($\beta < 1$). The green paradox entails a positive relation between the stringency of future climate policy and emissions (Sinn, 2008b). Following Gerlagh (2011), we differentiate between a weak green paradox (future climate policy increases present emissions) and a strong green paradox (emission damages increase).

Definition 1. *Denote the stringency of second-period climate policy by* Θ*. The weak green paradox occurs if*

$$\frac{\mathrm{d}e}{\mathrm{d}\Theta} > 0$$

The strong green paradox occurs if

$$\frac{\mathrm{d}\Sigma}{\mathrm{d}\Theta} > 0$$

Analogous to the literature on (spatial) carbon leakage, we define the intertemporal carbon leakage of a future climate policy as the share of period 2 emission reductions that 'leaks' away to the first period.

Definition 2. *The leakage* λ *of an increase in the stringency of second-period policy* Θ *is the increase in period 1 emissions over the decrease in period 2 emissions.*

$$\lambda \equiv -\frac{\mathrm{d}e}{\mathrm{d}\Theta} \Big/ \frac{\mathrm{d}E}{\mathrm{d}\Theta}$$

Both green paradoxes are related to the intertemporal leakage rate λ in a straightforward way. As intertemporal leakage is positive if and only if the future climate policy increases present emissions, the weak green paradox is equivalent to $\lambda > 0$. The strong green paradox occurs if the leakage rate exceeds the emission discount factor ($\lambda > \beta$).

Exhaustible resource owners discount future revenues at rate r. In equilibrium, they are indifferent between extracting now and in the future. Letting Π^R be the second-period producer price of the exhaustible resource, the Hotelling condition reads

$$p^R = \frac{1}{1+r}\Pi^R\left(P^R, \Theta\right) \tag{4}$$

We discuss carbon taxes (section 3) and investment in green technologies (section 4) in turn.

3 Emission Taxes

Regulators who want to reduce carbon emissions may not be able to do so immediately. Swift implementation of climate policies is often impeded by political and technological considerations. Announcing carbon taxes or caps in advance reduces compliance costs: it gives firms the opportunity to purchase abatement equipment and adjust their production processes, and allows consumers to make informed decisions about durable good purchases (Di Maria et al., 2008). The European Commission notes that "a sufficient carbon price and long-term predictibility are necessary"[8] in order to meet the 80-95% EU emission reduction target in 2050.[9]

Carbon emissions are taxed at a constant rate T in the second period. The tax may also be interpreted as a willingness to pay to reduce emissions (Hoel, 2010). Exhaustible resource owners discount future receipts net of the tax at the interest rate:

$$p^R = \frac{1}{1+r}\left(P^R - T\zeta^R\right)$$

A second-period carbon tax only affects first-period variables through the exhaustible resource price. The change in first-period emissions is

$$\frac{\mathrm{d}e}{\mathrm{d}T} = \frac{\partial e}{\partial p^R}\frac{\mathrm{d}p^R}{\mathrm{d}T} \tag{5}$$

We discuss the two components of the right-hand side in turn. The carbon tax increases the period 2 producer price of the exhaustible resource and, by (4), the period 1 price if and only if the tax increases period 2 exhaustible resource demand at the initial producer price.

$$\frac{\mathrm{d}p^R}{\mathrm{d}T} = \frac{1}{1+r}\frac{\mathrm{d}\Pi^R}{\mathrm{d}T} \gtreqless 0 \Leftrightarrow \frac{\partial D^R}{\partial T} \gtreqless 0 \tag{6}$$

Holding the producer price constant, the carbon tax directly reduces exhaustible resource demand in the second period by $-\zeta^R D^R_R$. The tax has an even stronger effect on the future price of the dirty backstop by virtue of its higher emission intensity however. This induces substitution from the dirty backstop to the exhaustible resource, increasing future exhaustible resource demand by $\zeta^D D^R_D$. The period 1 exhaustible resource price goes up if the net effect of the tax on period 2 exhaustible resource demand

$$\frac{\partial D^R}{\partial T} = \zeta^R D^R_R + \zeta^D D^R_D \tag{7}$$

[8] A Roadmap for moving to a competitive low carbon economy in 2050, p.7, European Commission COM(2011) 112

[9] Announcements should of course be credible. For discussions on credibility issues in climate policy, see Helm et al. (2003); Golombek et al. (2010).

is positive, i.e. if the substitutability between the dirty backstop and the exhaustible resource is high in period 2 and if the emission intensity of the dirty backstop is high. Conversely, a period 2 carbon tax decreases exhaustible resource prices if the dirty backstop and the exhaustible resource are poor substiutes in period 2 and if the dirty backstop has a low emission-intensity.

The effect of exhaustible resource prices on period 1 emissions is similar. An increase in the period 1 exhaustible resource price directly reduces emissions by $-\zeta^R d_R^R$. Higher exhaustible resource prices also encourage substitution towards the dirty backstop, increasing emissions by $\zeta^D d_R^D$. The net change in emissions

$$\frac{\partial e}{\partial p^R} = \zeta^R d_R^R + \zeta^D d_R^D \tag{8}$$

is positive if the dirty backstop and the exhaustible resource are good substitutes in the first period and if the emission intensity of the dirty backstop is high. On the other hand, higher exhaustible resource prices decrease first-period emissions when the substitutability between the exhaustible resource and the dirty backstop is low in the first period and when the dirty backstop is not very emission intensive. Proposition 1 gives the condition for positive leakage.

Proposition 1 (weak green paradox)**.** *Following a carbon tax increase in period 2,* $\lambda \gtreqless 0$ *iff*

$$\left(\zeta^R d_R^R + \zeta^D d_R^D\right)\left(\zeta^R D_R^R + \zeta^D D_D^R\right) \gtreqless 0 \tag{9}$$

A weak green paradox is less likely if the substitutability between the exhaustible resource and the dirty backstop is different in the two periods. Table 1 summarizes whether the weak green paradox occurs for different values of d_R^D and D_D^R and how these cases relate to previous research.

When the exaustible resource and the dirty backstop are poor substitutes in both periods (d_R^D and D_D^R are both low), the future tax reduces exhaustible resource prices and increases emissions in the first period. This is the classic green paradox result when exhaustible resource owners anticipate a future carbon tax (Hoel, 2010). When substitutability between the exhaustible resource and the dirty backstop is low in the first period but high in the second (d_R^D is low, while D_D^R is high), the tax increases exhaustible resource prices and reduces emissions in both periods. Exhaustible resource owners delay extraction in response to the tax, as the tax puts them at a comparative

Table 1: Occurrence of the weak green paradox for different values of d_R^D and D_D^R

d_R^D	D_R^D	$\frac{\mathrm{d}p^R}{\mathrm{d}T}$	$\frac{\partial e}{\partial p^R}$	weak GP?	Related articles
low	low	-	-	yes	Sinn (2008a); Hoel (2010)
low	high	+	-	no	Persson et al. (2007)
high	low	-	+	no	
high	high	+	+	yes	Smulders and van der Werf (2008) Di Maria et al. (2008)

advantage vis a vis the dirty backstop in the future. Since the dirty backstop is a poor substitute for the exhaustible resource in the short term, the decline in period 1 exhaustible resource supply does not cause a surge in dirty backstop demand. Our model provides a theoretical framework for the numerical findings of Persson et al. (2007). They show that OPEC countries may benefit rather than lose from strict climate policies, because the price of synthetic substitutes for petroleum-based fuels (e.g. diesel from coal) goes up faster than the price of oil.

When substitutability is high in the first period but low in the second (d_R^D is high, but D_D^R is low), the second-period tax reduces exhaustible resource prices and emissions go down in both periods. As the substitutability between the exhaustible resource and the dirty backstop is low in the second period, exhaustible resource prices decrease. This makes the exhaustible resource an attractive alternative to the dirty backstop in the first period. Lastly, suppose that exhaustible resource and the dirty backstop are good substitutes in both periods (d_R^D and D_D^R are both high). The tax then increases exhaustible resource prices and increases emissions in the first period, as the dirty backstop is used more intensively early on. This result connects to work of Smulders and van der Werf (2008) and Di Maria et al. (2008), who analyze how an anticipated cap on the flow of emissions affects the order of extraction when there is a high- and a low-carbon fuel. The cap makes the low-carbon fuel more valuable and increases the use of the high-carbon fuel in the period before the constraint becomes active.

Proposition 2 describes the effects of a period 2 tax on period 2 emissions and emission damages.

Proposition 2 (strong green paradox)**.** *Following a carbon tax increase in*

period 2
(i) D^D *decreases*
(ii) under (A3), E *decreases*
(iii) under (A3), $\lambda \leq 1$
(iv) $\lambda > \beta$ *iff*

$$-\frac{\zeta^R D_R^R + \zeta^D D_D^R}{d_R^R + (1+r) D_R^R} \Xi + \beta \zeta^D \left(\zeta^R D_R^D + \zeta^D D_D^D\right) > 0, \text{ where}$$
$$\Xi = (1-\beta) \zeta^R d_R^R + \zeta^D \left(d_R^D + \beta (1+r) D_R^D\right) \tag{10}$$

(v) λ *decreases in* $|D_D^D|$

A higher own-price effect of the dirty backstop causes the tax to more sharply reduce period 2 dirty backstop use, and therefore reduces leakage. The effect of the own- and cross-price effects of the exhaustible resource on the intertemporal leakage rate cannot be signed because the effect of the tax on exhaustible resource extraction is ambiguous.[10] Although the tax increases future demand for the clean backstop, clean backstop prices, quantities and elasticities do not appear in the conditions for $\lambda > 0$ and $\lambda > \beta$. The clean backstop does not generate emissions, so d^C does not enter into either e or Σ. Furthermore, the tax does not affect the price of the clean backstop, so $\frac{\mathrm{d}e}{\mathrm{d}T}$ and $\frac{\mathrm{d}\Sigma}{\mathrm{d}T}$ do not contain any derivatives with respect to p^C. The impact of the clean backstop on intertemporal leakage is implicit in the demand functions for the exhaustible resource and the dirty backstop.

Interpreting (10) is not straightforward, but we can calibrate λ as estimates of all parameters in (10) are available. Own- and cross-price effects can be rewritten as $d_j^i = \eta_j^i d^i / p^j$, where η_j^i is the elasticity of demand for type i with respect to the price of type j. We estimate the magnitude of intertemporal carbon leakage in section 5.

4 A Cheaper Clean Backstop

In addition to implementing a carbon tax, climate-conscious policymakers may opt to reduce emissions by stimulating the development of clean alternatives to fossil fuels. To model such a policy, we analyze the effect of a

[10] Albeit through a different mechanism (intertemporal substitution in consumption rather than substitution between energy types), Eichner and Pethig (2011) also find that a future emission constraint need not cause a green paradox.

reduction in the period 2 price of the clean backstop P^C on emissions. The development of alternative energy sources requires resources to be committed well before the new technologies can be put to use, so exhaustible resource owners anticipate the lower period 2 clean backstop prices when deciding on the intertemporal extraction pattern. A lower P^C reduces exhaustible resource demand in period 2, and thus decreases the right hand side of (4). For exhaustible resource owners to remain indifferent between extracting in either period, period 1 extraction d^R must go up. This is the classic green paradox result (Strand, 2007; Hoel, 2011). The improved technology also reduces emissions from the dirty backstop however. In the next Propositions, we show how the occurrence of the weak and the strong green paradox depend on the emission intensities and the substitutability between energy types.

Proposition 3 (weak green paradox)**.** *Assume* $D_C^R > 0$*. When the clean backstop becomes cheaper in period 2,* $\lambda \gtreqless 0$ *iff*

$$\zeta^R d_R^R + \zeta^D d_R^D \lesseqgtr 0 \tag{11}$$

As opposed to the case of a future carbon tax, exhaustible resource owners always bring forward extraction when clean alternatives become cheaper in the future. The lower exhaustible resource prices also causes a drop in period 1 demand for the dirty backstop. The occurrence of the weak green paradox hinges on whether the increase in exhaustible resource-related emissions outweighs the decrease in dirty backstop-related emissions (11). This is more likely if the relative emission intensity of the exhaustible resource is high and if the substitutability between the exhaustible resource and the dirty backstop is low. All first-period effects are proportional to the change in the period 1 exhaustible resource price $\frac{\mathrm{d}p^R}{\mathrm{d}P^C}$. Because period 2 parameters only affect period 1 emissions through this term, the condition for the weak green paradox consists solely of period 1 parameters.

Proposition 4 (strong green paradox)**.** *When the clean backstop becomes cheaper in period 2,*
(i) $\lambda \leq 1$
(ii) $\lambda > \beta$ *iff*

$$\frac{D_C^R}{-d_R^R - (1+r)\, D_R^R}\left[(1-\beta)\,\zeta^R d_R^R + \zeta^D \left(d_R^D + \beta\,(1+r)\, D_R^D\right)\right] + \beta \zeta^D D_C^D < 0 \tag{12}$$

(iii) λ *increases in* D^R_C *and* $|d^R_R|$
(iv) λ *decreases in* d^D_R, D^D_R, D^D_C *and* $|D^R_R|$

As substitute types become cheaper in both periods, demand for the dirty backstop goes down in both periods. The strong green paradox arises if the damage from bringing forward exhaustible resource emissions $(1-\beta)\,\zeta^R d^R_R$ exceeds the benefits of reduced dirty backstop consumption in both periods. This is more likely when D^R_C is high, as a decrease in P^C then poses a larger threat to exhaustible resource demand in period 2. An increase in $|d^R_R|$ increases leakage by making it more attractive to shift exhaustible resource supply to period 1 (the reverse applies to $|D^R_R|$). Lastly, λ decreases in d^D_R, D^D_R and D^D_C, as high values of these parameters induce more substitution away from the dirty backstop.

By making stronger assumptions on the substitutability structure, we can obtain more powerful results about the occurrence of the green paradox and compare our findings with previous research. We analyze three special cases in which two of the energy types are perfect substitutes. When we calibrate Proposition 4 in section 5, we look at three scenarios that relate to these special cases.

4.1 Perfect substitutability between R and C

We are interested in this case as a reference point: the assumption that clean backstops are perfect substitutes for the exhaustible resource is common in green paradox models. It leads to the most powerful green paradox results in the literature. When the exhaustible resource and the green backstop are imperfect substitutes, exhaustible resource owners are ensured of future demand for their commodity and the green paradox may vanish (Gerlagh, 2011).

Corollary 1. *With perfect substitution between the exhaustible resource and the clean backstop*
(i) if $P^C > P^R$*, a decrease in* P^C *has no effect*
(ii) if $P^C = P^R$*, then* $\lambda > \beta$ *if*

$$(1-\beta)\,\zeta^R d^R_R + \zeta^D\left(d^D_R + \beta\,(1+r)\,D^D_R\right) < 0 \tag{13}$$

When P^C is sufficiently low, it fully determines exhaustible resource prices in both periods and the last term in (12) vanishes. In accordance with the literature, the condition for the strong green paradox is weaker than in the general case. Corollary 1 shows that if we take into consideration the availability of dirty backstops, the substitutability structure that is most conducive to the green paradox no longer suffices for its occurrence. Even when the exhaustible resource and the clean backstop are perfect substitutes, both near-term emissions and emission damages may go down as a result of lower clean backstop prices.

4.2 Perfect substitutability between D and C

Corollary 2. *With perfect substitution between the clean and the dirty backstop*
(i) if $P^C > P^D$*, a decrease in* P^C *has no effect*
(ii) if $P^C = P^D$*, the strong green paradox does not occur*
(iii) if $p^C > p^D,\ P^C < P^D$*, then* $\lambda > \beta$ *iff*

$$(1-\beta)\,\zeta^R d_R^R + \zeta^D d_R^D < 0 \tag{14}$$

(iv) if $p^C < p^D$ *and* $P^C < P^D$*, then* $\lambda = 1$

When the clean backstop is more expensive than the dirty backstop in both periods, the former is used in neither period and a small cost reduction has no effect. In the knife-edge case when the period 2 prices of the clean and the dirty backstop are equal, a reduction in the price of the clean backstop eliminates all demand for the dirty backstop, so there is no strong green paradox. When the clean backstop is already cheaper than the dirty backstop in the second period, further cost reductions only reduce dirty backstop use in period 1, at the cost of accelerated exhaustible-resource extraction. A green paradox then becomes more likely. When the clean backstop is cheaper than the dirty backstop in both periods, the latter is never used. The model reduces to a classic green paradox model and both the weak and the strong green paradox occur.

The analysis in Corollary 2 is complementary to Fischer and Salant (2010) and van der Ploeg and Withagen (2012b). Fischer and Salant (2010) analyze the effect of cheaper backstops in the presence of high- and low-cost oil. They find that moderate cost reductions for the backstop will cause some high-cost oil to remain unexploited and thus improve the environment.

Table 2: Occurrence of the strong green paradox for cost reductions for the clean backstop

Substitutability between	Likelihood of strong GP	Related articles
R, C	+	Strand (2007); Hoel (2011); Gerlagh (20
D, C	-	van der Ploeg and Withagen (2012a) Fischer and Salant (2010)
R, D	-	

Beyond the point at which all high-cost oil remains in situ, further investments bring forward extraction of the low-cost oil and cause a 'renewed' green paradox. Van der Ploeg and Withagen (2012b) assume perfect substitutability between a clean and a dirty backstop and note that subsidizing renewables to the cost of the dirty backstop always reduces climate damages.

4.3 Perfect substitutability between R and D

Corollary 3. *With perfect substitution between the exhaustible resource and the dirty backstop*
(i) if $p^R < p^D$ *and* $P^R < P^D$, $\lambda = 1$
(ii) if $p^R < p^D$ *and* $P^R = P^D$, $\lambda = 0$

If the economy is in regime (ii), cost reductions benefit the environment by reducing the use of the dirty backstop in period 2, without affecting exhaustible resource extraction. When the clean backstop is sufficiently cheap, demand for the dirty backstop in period 2 goes to zero. The economy then moves into regime (i), in which additional investment only brings forward the extraction of the exhaustible resource and the green paradox returns.

Table 2 consolidates the discussion from the subsections.

5 Empirical Calibration and Special Cases

In this section, we explore the magnitude of intertemporal carbon leakage by calibrating Propositions 2 and 4. When calibrating Proposition 4, we vary the substitutability between energy types and illustrate how the leakage rates change under different assumptions.

At the economy-wide level, conventional oil and coal are currently the biggest contributors to the climate change problem. We therefore approximate the effect of a future carbon tax on the time path of aggregate emissions by looking at its effect on oil and coal use. The substitution possibilies between oil and coal are not equally relevant in all sectors however. In electricity generation, coal primarily competes with conventional natural gas, the other scarce fossil fuel. We take a more detailed look at the electricity sector and calibrate the effect of a future tax on natural gas and coal emissions from electricity generation.

We observe current energy demand and prices, and the IEA forecasts future demand and prices. The upper panel of Table 3 presents an overview of these statistics. We use empirical estimates of interfuel own- and cross-price elasticities from previous work, though the values differ substantially across studies and may not adequately reflect long-term substitution possibilies (Stern, 2012).

In the first calibration exercise, we take oil as the exhaustible resource and coal as the dirty backstop. From the upper pannel of Table 3, oil and coal demand are both expected to increase in 2035, though the relative increase is larger for coal. The oil price more than doubles during the next 26 years; we assume the coal price to remain constant. The literature on interfuel substitution typically distinguishes between coal and electricity as energy inputs. Since most coal is used for electricity generation, we take the elasticities for electricity as those for the dirty backstop.[11] We assume the elasticities to be equal across time periods.

We calculate the intertemporal leakage of a small global carbon tax in 2035. The first four columns in Table 4 contain the estimated economy-wide own- and cross-price elasticities for oil and electricity from five studies. Using the parameters from Table 3, for each set of estimates we determine the change in oil extraction and emissions and the intertemporal carbon leakage λ as a result of a small tax increase.

The intertemporal leakage rate is negative for three elasticity estimates, and the rates are small in absolute value. Except for Perkins' estimates, the effects of the future tax on second-period coal use through the own-price effect outweigh the substitution effects and the changes in the intertemporal

[11] We multiply the elasticity of oil demand with respect to electricity prices by the global share of coal-based electricity generation in total electricity generation, which was 0.47 in 2009 (IEA, 2011, p. 544).

Table 3: Current and future energy demand and prices

	2009	2035
Aggregate oil demand	29165	36765
Aggregate coal demand	24096	38631
Oil price	60.4	135
Coal price	20.84	20.84
Natural gas demand for electricity generation	7337	12640
Coal demand for electricity generation	15683	26612
Natural gas price	40.14	78.12
Coal price	20.84	20.84

[a] Quantities in mln boe, prices in 2009$ per boe. Emission intensities in t/boe: 0.3644 for oil; 0.5169 for coal; 0.3101 for natural gas. Values for 2035 are from the 'Current Policies' scenario of the World Energy Outlook 2010. A full list of definitions and sources is provided in Table H.1.

Table 4: Estimates of economy-wide demand elasticities and intertemporal leakage predictions

Study	η_R^R	η_D^R	η_R^D	η_D^D	$\frac{\mathrm{d}d^R}{\mathrm{d}T}$	$\frac{\mathrm{d}e}{\mathrm{d}T}$	$\frac{\mathrm{d}E}{\mathrm{d}T}$	λ
Perkins (1994)	-0.25	0.07	0.11	-0.07	-18.93	-3.49	-15.56	-0.22
Cho et al. (2004)	-0.97	-0.01	-0.10	-0.79	48.67	19.93	-412.60	0.05
Ma et al. (2008)	-0.27	0.01	0.07	-0.68	9.07	2.27	-337.95	0.01
Serletis et al. (2009)[b]	-0.04	0.00	0.05	-0.07	0.63	-0.14	-30.88	-0.00
Serletis et al. (2010)	-0.12	0.04	0.07	-0.13	-10.23	-1.02	-50.46	-0.02

[a] Equations for $\frac{\mathrm{d}d^R}{\mathrm{d}T}$, $\frac{\mathrm{d}e}{\mathrm{d}T}$ and $\frac{\mathrm{d}E}{\mathrm{d}T}$ are given by (H.1), (H.2) and (H.3), respectively. λ is defined in Definition 2. [b] Median estimates over all countries included in the study.

Table 5: Estimates of demand elasticities in electricity generation and intertemporal leakage predictions

Study	η^R_R	η^R_D	η^D_R	η^D_D	$\frac{\mathrm{d}d^R}{\mathrm{d}T}$	$\frac{\mathrm{d}e}{\mathrm{d}T}$	$\frac{\mathrm{d}E}{\mathrm{d}T}$	λ
Söderholm (2000)[b]	-0.82	0.03	0.04	-0.20	11.66	2.99	-70.75	0.04
Söderholm (2001)[b]	-0.38	0.03	0.09	-0.13	3.46	0.21	-42.26	0.00
Ko and Dahl (2001)	-1.46	1.54	0.28	-0.57	-150.45	-14.77	-78.47	-0.19
Serletis et al. (2010)	-0.14	0.14	0.06	-0.12	-13.85	2.91	-21.97	0.13

[a] Equations for $\frac{\mathrm{d}d^R}{\mathrm{d}T}$, $\frac{\mathrm{d}e}{\mathrm{d}T}$ and $\frac{\mathrm{d}E}{\mathrm{d}T}$ are given by (H.1), (H.2) and (H.3), respectively. λ is defined in Definition 2. [b] Median estimates over all countries included in the study.

pattern of oil extraction. For two sets of estimates in which η^R_D is high compared to $|\eta^R_R|$, the tax benefits oil exporters and increases second-period oil extraction, as in Persson et al. (2007): the tax-induced increase in future oil demand through substitution from coal to oil is larger than the decrease through higher own prices. The intertemporal leakage rate is negative for these two estimates: since oil is relatively cheap in the first period, the own-price effect of oil $\eta^R_R d^R/p^R$ is strong in the first period. When the oil price increases in the first period, the reduction in oil-related emissions exceeds the increase in coal-related emissions. Overall, the sum of period 1 and 2 emission reductions is almost linear in η^D_D, suggesting that the most important effect of carbon taxes is the direct reduction in coal use. The estimated emission reductions may be biased downwards, since we conservatively assumed that oil reserves are fully exhausted.

In the second calibration exercise, we look at the effects of a small future carbon tax on emissions in electricity generation, taking natural gas as the exhaustible resource. The lower panel of Table 3 shows current and future natural gas and coal demand for electricity generation. Demand for both energy types increases by 70% in 2035, though the relative price of natural gas goes up significantly.

Table 5 contains the leakage estimates using own- and cross-price elasticities for natural gas and coal in electricity generation. Natural gas demand is more elastic than coal demand, as gas-fired power plants have higher marginal and lower fixed costs. Because natural gas is much cleaner than coal, a future tax increases future natural gas demand and delays natural gas extraction for two sets of elasticity estimates. When the cross-elasticities are small, as in Söderholm (2000) and Söderholm (2001), the tax accelerates natural gas extraction but the intertemporal leakage rate is low, as the direct decrease in second-period coal use dominates the effects on first-period emissions. The leakage rates have opposite signs in the bottom two rows depending on the $|\eta_R^R|/\eta_R^D$ ratio. For high values of this ratio (Ko and Dahl, 2001), higher first-period natural gas prices decrease first-period natural gas emissions by more than they increase emissions from coal. For low values of $|\eta_R^R|/\eta_R^D$ (Serletis et al., 2010), the converse applies and total first-period emissions increase.

Our calibration fixes the sum of current and future natural gas use for electricity generation. In reality, the change in cumulative natural gas use in electricity generation depends on the tax' effect on energy use in other sectors. Natural gas competes with oil, more than with coal, for heating and in industry (Stern, 2012). As oil is cleaner than coal, natural gas' comparative advantage vis-a-vis other fossil fuels as a result of a carbon tax is largest in electricity generation. By this reasoning, we may expect cumulative natural gas use in the electricity sector to increase. The resulting effect on emissions in the electricity sector depends on the elasticity of coal demand with respect to natural gas prices. A further caveat is that the difficulty to measure long-run substitution possibilities is especially relevant for electricity generation, as power plants have very long service lives. If we believe that the true own- and cross price elasticities are larger across the board, a future carbon tax will cause a larger reduction in cumulative emissions, but the leakage rate (which is a ratio of current and future emission reductions) may not be as responsive.

Finally, we calibrate Proposition 4. Energy types differ in their suitability for two main purposes: electricity generation and transport. Natural gas (R), coal (D) and wind and solar energy (C) more readily lend themselves for electricity generation, whereas oil (R), tar sands (D) and biofuels (C) are primarily used in the transportation sector. Energy types that are employed in the same submarket are closer substitutes than ones that are not. We look at three scenarios with different substitutability structures. The calibrations highlight the sensitivity of the intertemporal leakage rate to interfuel substitution possibilities, and illustrate how technology improvements for wind or solar energy and biofuels are likely to impact emissions from conventional oil, coal and unconventional oil - the three fossil fuels that present the biggest threat to the global climate.

The studies on interfuel substitution in the previous calibrations do not include renewable energy, so we follow the CGE literature on carbon leakage and assume a nested CES demand structure with two nests: electricity E and non-electricity N. We set the elasticity of substitution between nests at 1.5 and within nests at 5. In each scenario, we consider a relevant combination of energy types and group them by primary use. Appendix H contains a full description of the demand structure and parameter values per scenario.

5.1 Developing Alternative Fuels

In the first scenario, we study the effect of anticipated cost reductions for biofuels on emissions from oil (R) and coal (D). First-generation biofuels such as ethanol from sugarcane already compete with petroleum-based fuels, which currently dominate the transportation market. Second-generation fuels from biomass have the potential to be cheaper in the long run and exert less pressure on land and water supplies, but still face significant barriers to large-scale commercialization (Sims et al., 2010). By Proposition 4 and Corollary 1, the high substitutability between the clean backstop and the exhaustible resource and the low substitutability between the exhaustible resource and the dirty backstop are both associated with high leakage rates. This scenario is therefore likely to produce lavish estimates of the leakage rate.

Figure 1 shows the effect of reductions in the period 2 biofuel price on the first-period oil price (top left), the marginal intertemporal leakage rate (bottom left), first-period oil and coal demand (top right) and second-period biofuel and coal demand (bottom right). The oil stock is normalized to one, so the top-right panel also indicates the fraction of the oil stock that is used in the first period. To facilitate comparisons of the change in first- and second-period coal demand, the right axes of the rightmost figures have the same scale. The horizontal axes indicate the relative second-period biofuel cost reduction as a fraction of the original second-period price, which is equal to the first-period price.

The share of the oil stock that is extracted in the first period increases almost linearly in the period 2 cost reduction for biofuels. For large cost reductions, the oil stock is exhausted almost completely in the first period. The associated drop in first-period oil prices is not large enough to substantially affect first-period coal consumption. When the cost reduction for biofuels is small, the marginal decrease in second-period coal use is also low, and the leakage rate reaches 13%. For larger cost reductions, it becomes comparatively more attractive to substitute biofuels for coal for non-transport

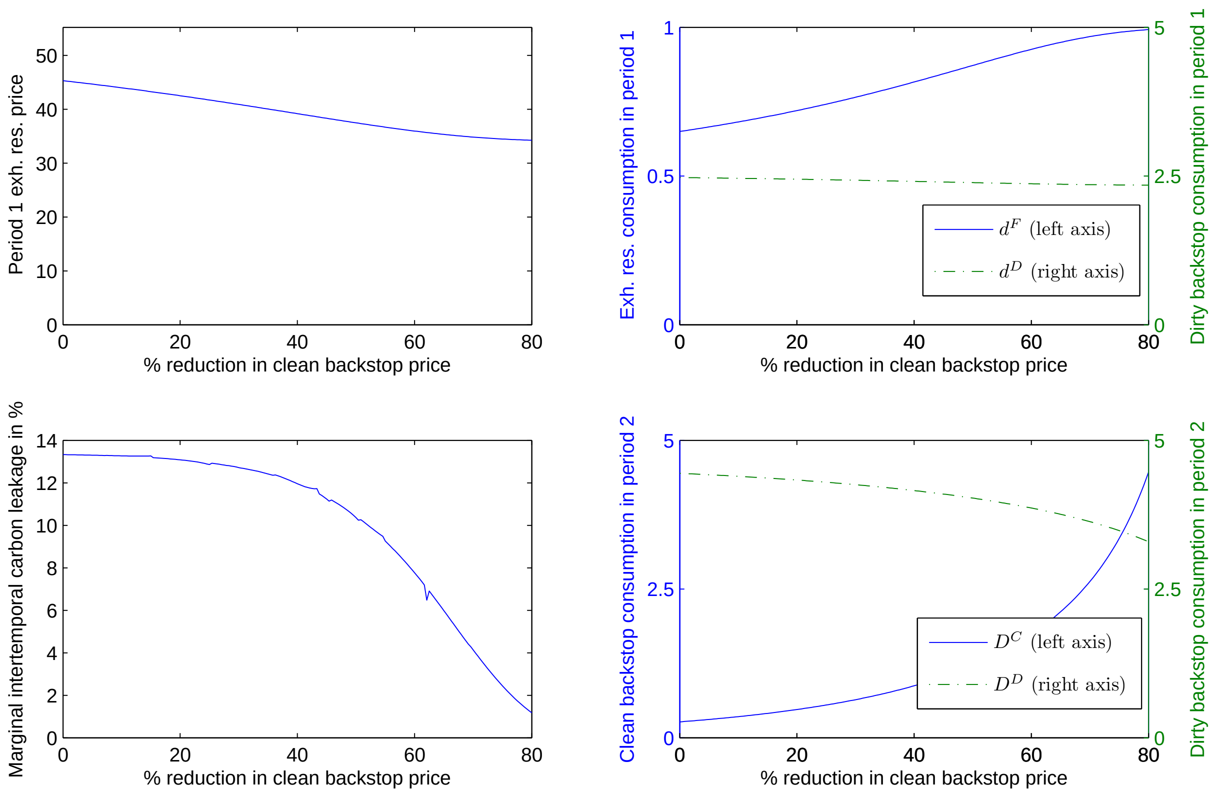

Figure 1: Effects of future cost reductions for biofuels (parametrization in Appendix H).

purposes, as evidenced by the concave shape of the dashed curve in the bottom-right panel. The leakage rate drops to below 2% when the second-period cost reduction equals 80% of the initial price.

Of the renewable energy types, biofuels are the closest substitute to oil - the most emission intensive scarce fossil fuel. Investments in biofuel technologies are therefore more likely to lead to a green paradox than investments in wind or solar power. Still, the above calibration illustrates that biofuels' potential to reduce emissions from coal can reduce intertemporal leakage rates to levels significantly below the 100% that would obtain in models with one fossil fuel that is always fully exhausted. In a more comprehensive model that also includes unconventional oil, the leakage rate would be even lower, because unconventional oil is more abundant and more emission-intensive than conventional oil and a closer substitute for biofuels than coal is. On the other hand, we abstract from emissions from land use changes, which may lead to a downard bias in the leakage rate.

5.2 Renewable Energy for Electricity

In the second scenario, we consider oil (R) in the non-electricity nest and coal (D) and solar energy (C) in the electricity nest. The opportunities to employ renewable energy are highest in the electricity sector. Coal and renewable energy sources are main inputs for electricity generation, with worldwide market shares of 42% and 19% in 2008 respectively (IEA, 2010b). Investing in hydro-, wind- and solar power may reduce coal use without causing as strong an increase in short-term oil extraction.

Figure 2 depicts the effects of future cost reductions for solar energy. The oil price is unresponsive for small cost reductions, owing to the limited substitutability between oil and electricity. Only when solar energy becomes very cheap, it emerges as a credible substitute for oil and the oil price reacts more strongly. The pattern of intertemporal carbon leakage is similar. When the cost reduction is not too large, it mainly induces substitution from coal- to solar-based electricity in the second period. The decrease in second-period coal use dwarfs the change in oil extraction, giving rise to intertemporal leakage rates under 1%. The leakage rate goes up only when solar energy becomes very cheap in the future: coal is then hardly used anymore, and subsequent cost reductions increasingly serve to bring forward oil extraction. Extending the analysis to include natural gas may increase the leakage rate, though not by much as it is relatively emission extensive compared to coal.

This calibration complements the intuition behind Corollary 2, in which the clean and dirty backstop are perfect substitutes. From an environmental point of view, investment in renewable energy sources is primarily attractive insofar as it reduces the use of dirty backstops. When this goal has been achieved, intertemporal carbon leakage becomes a stronger concern. Compared to the first scenario, the high substitutability between the clean and the dirty backstop is favourable in terms of the leakage rate. The estimates from the second scenario suggest that improvements in renewable electricity technologies are especially suitable for reducing cumulative emissions, without bringing forward emissions from scarce fossil fuels.

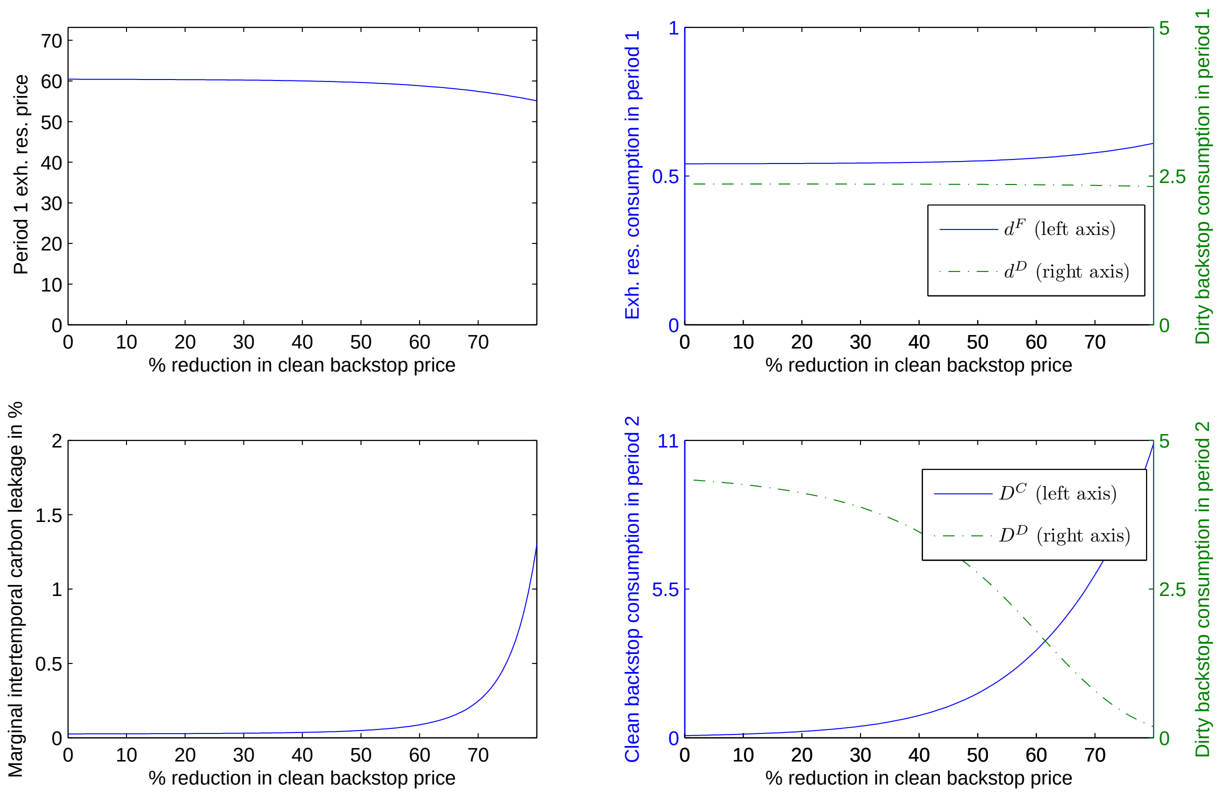

Figure 2: Effects of future cost reductions for solar-based electricity (parametrization in Appendix H).

5.3 Conventional and Unconventional Oil

In the last scenario, we illustrate how cost reductions for solar-based electricity (C) affect emissions from conventional (R) and unconventional (D) oil in the non-electricity nest.

Cost reductions for solar energy do not cause a big decrease in total second-period fossil fuel use, but the decrease is larger for uncoventional oil: the slope of the dashed line in the bottom-right panel is larger than that of the solid line in the top-right panel. This is not surprising as unconventional oil is the dominant fuel in the second period, as stipulated by the Herfindahl rule. First-period emissions increase as first-period unconventional oil use is

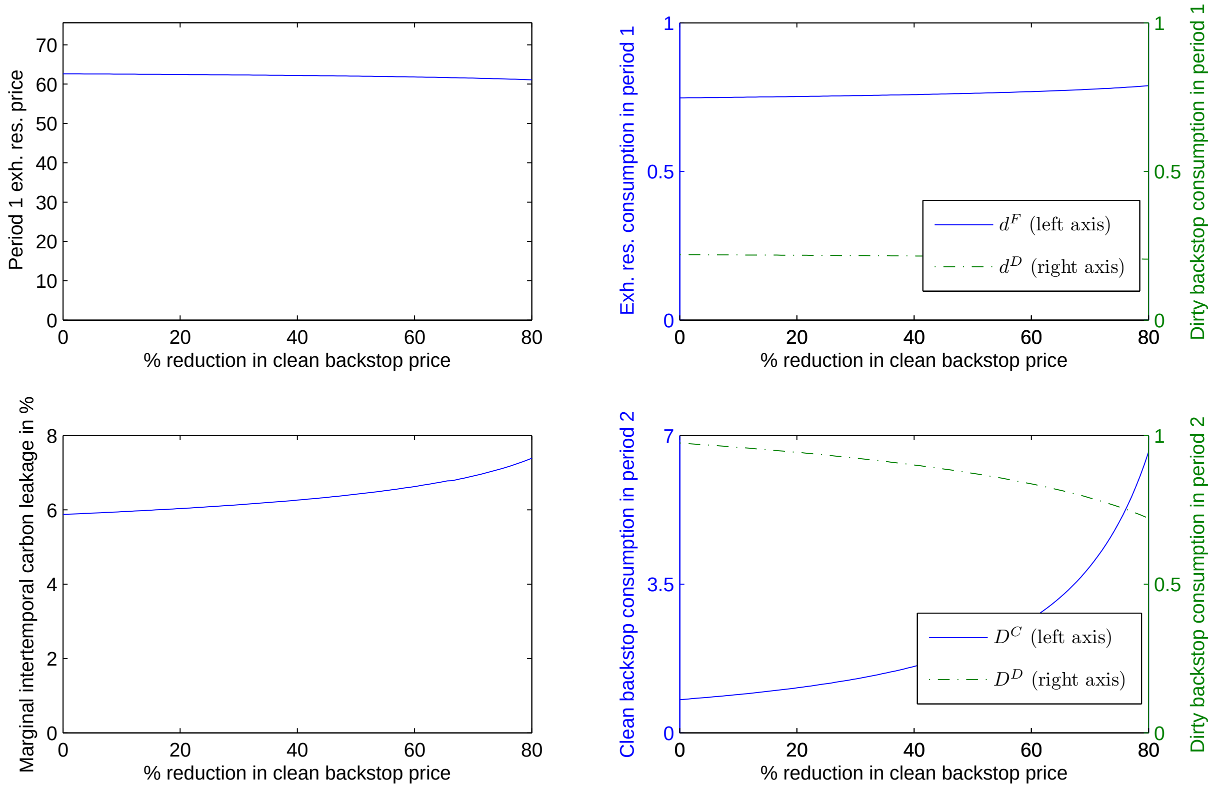

Figure 3: Effects of future cost reductions for solar-based electricity (parametrization in Appendix H).

almost unaffected, but the leakage rates do not exceed 6-8%. These estimates accord with the prediction from Corollary 3 that reductions in future clean backstop prices primarily go at the expense of dirty backstop demand if the exhaustible resource and the dirty backstop are good substitutes.

6 Spatial carbon leakage

Climate policies may also have unintended side-effects in a spatial setting. When a group of countries reduces emissions unilaterally, pollution might move to other countries. This spatial carbon leakage occurs through two main channels (Felder and Rutherford, 1993). Firstly, dirty industries relocate to countries with laxer regulation. Secondly, a stringent environmental policy in environmentally conscious countries causes the world market price of fossil fuels to fall, increasing their use in lax countries. Estimated leakage rates range from a modest 2-5% to over 100%, the latter implying that unilateral carbon reduction policies increase global emissions (Burniaux and Oliveira Martins, 2012; Paltsev, 2001; Babiker, 2005).[12]

Our model can be used to analyze spatial rather than intertemporal carbon leakage by relabeling 'period 2' as a climate-conscious country, 'period 1' as a non-abating country and setting the interest rate to zero. The model does not explicitly incorporate industry relocation effects, but shows how unilateral carbon taxes affect world market fossil fuel prices and thereby emissions in non-abating countries. Paltsev (2001); Fischer and Fox (2009); Kuik and Hofkes (2010) argue that changes in energy prices are the most important determinant of carbon leakage.

Proposition 2 shows that spatial carbon leakage rates are below 100%. Reductions in dirty backstop use in abating countries are not offset by emission increases in non-abating countries. If unilateral climate policies decrease exhaustible resource prices, as policy makers sometimes fear, non-abating countries substitute away from dirty backstops, mitigating spatial carbon leakage. Leakage may even be negative if interfuel substitution possibilities differ between countries (as in Table 1). The assumption that total exhaustible-resource supply is fixed is less plausible than in the intertemporal model, but leads to conservative leakage estimates.

We calibrate a spatial version of the model to illustrate the magnitude of spatial leakage relative to intertemporal leakage. We disregard the time dimension and evaluate the leakage to the rest of the world (ROW) if the EU Emissions Trading Scheme (ETS) carbon price increases above its 2009 level of €15 per tonne. We restrict ourselves to the effects on aggregate oil and coal demand; we present a calibration for the electricity sector in the Appendix. Table 6 describes demand and prices in EU and ROW. The EU accounts for 14% of global oil demand and 8% of global coal demand. The EU ETS price adds about 50% to the price of coal.

Table 7 shows the effects of a carbon tax increase in the EU. The spatial

[12]Studies on international environmental agreements find a related effect. Because environmental standards are strategic substitutes, non-signatories will increase emissions (Barrett, 1994; Hoel, 1994).

Table 6: Aggregate demand and prices for spatial model

	ROW	EU
Aggregate oil demand	24959	4206
Aggregate coal demand	22143	1953
Oil price	60.40	68.00
Coal price	20.84	31.62

[a] Quantities in mln boe, prices in 2009$ per boe. Emission intensities in t/boe: 0.3644 for oil; 0.5169 for coal. A full list of definitions and sources is provided in Table H.1.

Table 7: Estimates of economy-wide demand elasticities and spatial leakage predictions

Study	η_R^R	η_D^R	η_R^D	η_D^D	$\frac{\mathrm{d}d^R}{\mathrm{d}T}$	$\frac{\mathrm{d}e}{\mathrm{d}T}$	$\frac{\mathrm{d}E}{\mathrm{d}T}$	λ
Perkins (1994)	-0.25	0.07	0.11	-0.07	0.52	0.09	-0.74	0.12
Cho et al. (2004)	-0.97	-0.01	-0.10	-0.79	19.98	8.25	-20.85	0.40
Ma et al. (2008)	-0.27	0.01	0.07	-0.68	4.87	1.18	-12.66	0.09
Serletis et al. (2009)[b]	-0.04	0.00	0.05	-0.07	0.57	-0.15	-1.06	-0.14
Serletis et al. (2010)	-0.12	0.04	0.07	-0.13	0.00	0.00	-1.69	0.00

[a] Equations for $\frac{\mathrm{d}d^R}{\mathrm{d}T}$, $\frac{\mathrm{d}e}{\mathrm{d}T}$ and $\frac{\mathrm{d}E}{\mathrm{d}T}$ are given by (H.1), (H.2) and (H.3), respectively. λ is defined in Definition 2. [b] Median estimates over all countries included in the study.

leakage rates are mostly positive, unlike most intertemporal rates in Table 4. The EU consumes more oil compared to coal than the world at large, so the tax-induced reduction in EU oil demand is larger than the increase through substitution from coal to oil. A carbon tax increase in the EU therefore decreases world oil prices. Energy demand in ROW is similar to global energy demand. Like in the intertemporal calibration, a decrease in oil prices triggers an increase in emissions in ROW for four out of five estimates.

The spatial leakage rates tend to be larger than the intertemporal rates in absolute value, due to two reasons. Firstly, a tax increase has a modest effect on coal consumption in the EU, as coal demand in the EU is already low to begin with. This means that the denominator of the leakage rate - the total emission reduction in the EU - is low. Secondly, the future tax in the previous calibration is subject to a discount rate, whereas the unilateral tax is not. This exacerbates the reaction of oil suppliers in the three middle rows in Table 7, also increasing the absolute value of the leakage rate. For the estimates from Serletis et al. (2010), the direct and indirect effects of the EU tax on oil demand in the EU net out. Oil prices and hence ROW emissions remain unchanged, so the leakage rate is zero.

Our spatial leakage rates are similar to estimates from the computable general equilibrium literature on carbon leakage, albeit in the lower part of the spectrum (Di Maria and van der Werf, 2012). Comparing the intertemporal and spatial leakage rates, intertemporal leakage seems to be a small concern relative to spatial leakage.

Appendix I presents an extended model with two periods *and* two countries, in which one country implements a unilateral carbon tax in the second period. A future unilateral tax reduces second-period emissions in the adopting country. Future emissions in the non-abating country may increase or decrease, but any increase in emissions is lower than the reduction in the abating country. The effect of the future unilateral tax on first-period emissions is governed by a modified version of (9) which includes the first-period demand response in the non-abating country. The unweighted sum of current and future emissions in both countries always decreases as a result of a future unilateral tax. Emission damages can therefore only go up when total first-period emissions increase and the emission discount factor is sufficiently low.

7 Conclusion

We employ a general model to analyze intertemporal carbon leakage in the presence of an abundant dirty backstop such as coal or unconventional oil. The green paradox literature overstates the adverse consequences of imperfect climate policies by not taking into account their potential to reduce emissions from coal and unconventional oil. It is important to consider these fuels as they already account for 50% of energy-related emissions, and will become even more important in the future.

A carbon tax increases the price of oil, but the price of coal goes up even more. The effect of an anticipated carbon tax on future oil demand depends on the relative strength of a direct own-price and an indirect substitution effect. When improved technology (e.g. diesel from coal) makes coal a better substitute for oil in the future than it is today, intertemporal leakage may become negative. Anticipated carbon taxes cause significant substitution from coal to oil in the future and thereby induce oil owners to delay extraction. The reduction in present oil supply does not trigger a large increase in coal demand, as coal is a poor substitute for oil today. Future availability of cheap renewables lowers coal emissions directly (through substitution from coal to renewables) and indirectly (cost reductions for renewables decrease oil prices, reducing coal demand).

Calibrations of the model suggest that the effects of anticipated climate policies on present emissions are small compared to future emission reductions. Interestingly, some of the intertemporal leakage estimates are negative, implying that a future carbon tax reduces present emissions. Investments in renewable electricity technologies lead to very small leakage rates, because they are a good substitute for coal but have only a small impact on oil extraction.

The aim of climate policy is to decrease cumulative extraction, i.e. ensuring that some fossil fuels remain in the ground. The 'marginal resources' are not conventional oil and natural gas, which are so cheap to exploit that carbon taxes will only affect the distribution of rents and the timing of extraction. Climate policy should rather aim at reducing emissions from costly, emission-intensive and abundant resources such as coal and unconventional oil. The results from this paper imply that these efforts may be effective, even if it is not possible to instate all-encompassing carbon constraints.

A Proof of Proposition 1

The weak green paradox occurs when (5) is positive. Using (6), the condition becomes

$$\frac{\partial e}{\partial p^R}\frac{\partial D^R}{\partial T} > 0 \tag{A.1}$$

The result follows by substituting (7) and (8).

B Proof of Proposition 2

We first show that the tax increases the consumer price of the exhaustible resource by less than that of the dirty backstop.

Lemma 1. $\frac{dP^R}{dT} < \frac{dP^D}{dT}$

Proof. Assume not. Then, because own-price effects are stronger than cross-price effects (A2), exhaustible resource demand in period 2 decreases. The tax increases the period 2 producer price $P^R - T\zeta^R$ as $\frac{\mathrm{d}P^D}{\mathrm{d}T} = \zeta^D$ and $\zeta^R < \zeta^D$. By the Hotelling condition (4), p^R increases and demand for the exhaustible resource goes down in period 1. This violates the requirement that the stock is fully exhausted. □

Lemma 1 and (A2) entail $\frac{\mathrm{d}D^D}{\mathrm{d}T} < 0$, establishing (i). Totally differentiate with respect to T the stock constraint

$$\frac{\mathrm{d}d^R}{\mathrm{d}T} + \frac{\mathrm{d}D^R}{\mathrm{d}T} = d^R_R\frac{\mathrm{d}p^R}{\mathrm{d}T} + D^R_R\frac{\mathrm{d}P^R}{\mathrm{d}T} + D^R_D\zeta^Z = 0 \tag{B.1}$$

and the Hotelling condition (4)

$$\frac{\mathrm{d}p^R}{\mathrm{d}T} = \frac{1}{1+r}\left(\frac{\mathrm{d}P^R}{\mathrm{d}T} - \zeta^R\right) \tag{B.2}$$

Solving these two equations for $\frac{\mathrm{d}p^R}{\mathrm{d}T}$ and $\frac{\mathrm{d}P^R}{\mathrm{d}T}$ yields

$$\frac{\mathrm{d}p^R}{\mathrm{d}T} = -\frac{\zeta^R D^R_R + \zeta^D D^R_D}{d^R_R + (1+r)\,D^R_R} \tag{B.3}$$

$$\frac{\mathrm{d}P^R}{\mathrm{d}T} = \frac{\zeta^R d^R_R - (1+r)\,\zeta^D D^R_D}{d^R_R + (1+r)\,D^R_R} \tag{B.4}$$

The effect of T on E is

$$
\begin{aligned}
\frac{\mathrm{d}E}{\mathrm{d}T} &= \zeta^D \frac{\mathrm{d}D^D}{\partial T} + \zeta^R \frac{\mathrm{d}D^R}{\mathrm{d}T} \\
&= \zeta^D \left(D_D^D \zeta^D + D_R^D \frac{\mathrm{d}P^R}{\mathrm{d}T} \right) + \zeta^R \left(D_R^R \frac{\mathrm{d}P^R}{\mathrm{d}T} + D_D^R \zeta^D \right) \\
&= \zeta^D \left(D_D^D \zeta^D + D_R^D \frac{\zeta^R d_R^R - (1+r)\,\zeta^D D_D^R}{d_R^R + (1+r)\, D_R^R} \right) + \zeta^R \left(D_R^R \frac{\zeta^R d_R^R - (1+r)\,\zeta^D D_D^R}{d_R^R + (1+r)\, D_R^R} + D_D^R \zeta^D \right) \\
&= \frac{1}{d_R^R + (1+r)\, D_R^R} \Big[(1+r) \left(\zeta^D\right)^2 \left(D_D^D D_R^R - D_R^D D_D^R \right) \\
&+ d_R^R \Big(\left(\zeta^D\right)^2 D_D^D + \zeta^D \zeta^R \left(D_R^D + D_D^R \right) + \left(\zeta^R\right)^2 D_R^R \Big) \Big] \qquad \text{(B.5)}
\end{aligned}
$$

The fraction outside the square brackets is negative. The first term inside the square brackets is positive by (A2). The second term is also positive since $d_R^R < 0$ and

$$
\begin{aligned}
&\left(\zeta^D\right)^2 D_D^D + \zeta^D \zeta^R D_D^R + \zeta^D \zeta^R D_R^D + \left(\zeta^R\right)^2 D_R^R < \\
&- \left(\zeta^D\right)^2 D_R^D + \zeta^D \zeta^R D_D^R + \zeta^D \zeta^R D_R^D - \left(\zeta^R\right)^2 D_D^R = \\
&- \left(\zeta^D D_R^D - \zeta^R D_D^R\right)^2 < 0
\end{aligned}
$$

The first inequality follows from (A2); the last equality from (A3). Therefore, $\frac{\mathrm{d}E}{\mathrm{d}T} < 0$, completing the proof of (ii). To prove (iii), we show that the sum of period 1 and 2 dirty backstop demand goes down.

$$
\begin{aligned}
\frac{\mathrm{d}\left[d^D + D^D\right]}{\mathrm{d}T} &= d_R^D \frac{\mathrm{d}p^R}{\mathrm{d}T} + D_R^D \frac{\mathrm{d}P^R}{\mathrm{d}T} + \zeta^D D_D^D \\
&= d_R^D \frac{\mathrm{d}p^R}{\mathrm{d}T} + D_R^D \left((1+r) \frac{\mathrm{d}p^R}{\mathrm{d}T} + \zeta^R \right) + \zeta^D D_D^D \\
&= \frac{\mathrm{d}p^R}{\mathrm{d}T} \left(d_R^D + (1+r)\, D_R^D \right) + \zeta^R D_R^D + \zeta^D D_D^D \\
&= \underbrace{-\frac{d_R^D + (1+r)\, D_R^D}{d_R^R + (1+r)\, D_R^R}}_{<1} \underbrace{\left(\zeta^R D_R^R + \zeta^D D_D^R \right)}_{I} + \zeta^R D_R^D + \zeta^D D_D^D \\
&\overset{I>0}{<} \zeta^R \left(D_R^R + D_R^D \right) + \zeta^D \left(D_D^R + D_D^D \right) < 0 \qquad \text{(B.6)}
\end{aligned}
$$

The second equality in (B.6) follows by substituting (B.2); the fourth by substituting (B.3). The fraction in (B.6) is smaller than one by (A2). The second inequality holds by (A2) and (A3). When $I < 0$, $\frac{\mathrm{d}\left[d^D + D^D\right]}{\mathrm{d}T}$ is negative by (A2), completing the proof of (iii). Lastly, calculate the effect on emission damages

$$\begin{aligned}
\frac{\mathrm{d}\Sigma}{\mathrm{d}T} &= (1-\beta)\,\zeta^R \frac{\mathrm{d}d^R}{\mathrm{d}T} + \zeta^D \left(d^D_R \frac{\mathrm{d}p^R}{\mathrm{d}T} + \beta \left(D^D_R \frac{\mathrm{d}P^R}{\mathrm{d}T} + \zeta^D D^D_D \right) \right) \\
&= (1-\beta)\,\zeta^R \frac{\mathrm{d}d^R}{\mathrm{d}T} + \zeta^D \left(\frac{\mathrm{d}p^R}{\mathrm{d}T} \left(d^D_R + \beta\,(1+r)\,D^D_R \right) + \beta \left(\zeta^R D^D_R + \zeta^D D^D_D \right) \right) \\
&= \frac{\mathrm{d}p^R}{\mathrm{d}T} \left[(1-\beta)\,\zeta^R d^R_R + \zeta^D \left(d^D_R + \beta\,(1+r)\,D^D_R \right) \right] + \beta\zeta^D \left(\zeta^R D^D_R + \zeta^D D^D_D \right) \\
&= -\frac{\zeta^R D^R_R + \zeta^D D^R_D}{d^R_R + (1+r)\,D^R_R} \left[(1-\beta)\,\zeta^R d^R_R + \zeta^D \left(d^D_R + \beta\,(1+r)\,D^D_R \right) \right] + \\
&\quad \beta\zeta^D \left(\zeta^R D^D_R + \zeta^D D^D_D \right)
\end{aligned} \tag{B.7}$$

The second equality in (B.7) follows from (B.2); the fourth by substituting (B.3).

C Proof of Proposition 3

The change in first-period emissions is

$$\frac{\mathrm{d}e}{\mathrm{d}P^C} = \zeta^R d^R_R \frac{\mathrm{d}p^R}{\mathrm{d}P^C} + \zeta^D d^D_R \frac{\mathrm{d}p^R}{\mathrm{d}P^C} = \frac{\mathrm{d}p^R}{\mathrm{d}P^C} \left(\zeta^R d^R_R + \zeta^D d^D_R \right) \tag{C.1}$$

Analogously to Appendix B, we can back out $\frac{\mathrm{d}p^R}{\mathrm{d}P^C}$. Totally differentiate the stock constraint and (4) with respect to P^C

$$d^R_R \frac{\mathrm{d}p^R}{\mathrm{d}P^C} + D^R_R \frac{\mathrm{d}P^R}{\mathrm{d}P^C} + D^R_C = 0 \tag{C.2}$$

$$\frac{\mathrm{d}p^R}{\mathrm{d}P^C} = \frac{1}{1+r} \frac{\mathrm{d}P^R}{\mathrm{d}P^C} \tag{C.3}$$

Solving for $\frac{\mathrm{d}p^R}{\mathrm{d}P^C}$, we obtain

$$\frac{\mathrm{d}p^R}{\mathrm{d}P^C} = -\frac{D^R_C}{d^R_R + (1+r)\,D^R_R} \tag{C.4}$$

The weak green paradox occurs when $\frac{\mathrm{d}e}{\mathrm{d}P^C} < 0$. As $\frac{\mathrm{d}p^R}{\mathrm{d}P^C} > 0$, $\frac{\mathrm{d}e}{\mathrm{d}P^C} < 0$ iff $\zeta^R d^R_R + \zeta^D d^D_R < 0$.

D Proof of Proposition 4

We established that $\frac{\mathrm{d}p^R}{\mathrm{d}P^C} > 0$, so by (4), exhaustible resource prices in both periods are increasing in P^C. Then d^D, D^D, $e+E$ and E are increasing in P^C. It follows that $\lambda = -\frac{\mathrm{d}e}{\mathrm{d}P^C} / \frac{\mathrm{d}E}{\mathrm{d}P^C} \leq 1$, proving (i). The change in emission damages is

$$\begin{aligned}
\frac{\mathrm{d}\Sigma}{\mathrm{d}P^C} &= (1-\beta)\,\zeta^R \frac{\mathrm{d}d^R}{\mathrm{d}P^C} + \zeta^D \left(d_R^D \frac{\mathrm{d}p^R}{\mathrm{d}P^C} + \beta \left(D_R^D \frac{\mathrm{d}P^R}{\mathrm{d}P^C} + D_C^D \right) \right) \\
&= (1-\beta)\,\zeta^R \frac{\mathrm{d}d^R}{\mathrm{d}P^C} + \zeta^D \left(d_R^D \frac{\mathrm{d}p^R}{\mathrm{d}P^C} + \beta \left(D_R^D \,(1+r)\, \frac{\mathrm{d}p^R}{\mathrm{d}P^C} + D_C^D \right) \right) \\
&= \frac{\mathrm{d}p^R}{\mathrm{d}P^C} \left[(1-\beta)\,\zeta^R d_R^R + \zeta^D \left(d_R^D + \beta\,(1+r)\, D_R^D \right) \right] + \beta \zeta^D D_C^D \\
&= \frac{D_C^R}{-d_R^R - (1+r)\, D_R^R} \left[(1-\beta)\,\zeta^R d_R^R + \zeta^D \left(d_R^D + \beta\,(1+r)\, D_R^D \right) \right] + \beta \zeta^D D_C^D
\end{aligned} \tag{D.1}$$

The second equality in (D.1) follows from (C.3); the last from (C.4). The leakage rate is

$$\begin{aligned}
\lambda &= -\frac{\frac{\mathrm{d}p^R}{\mathrm{d}P^C} \left(\zeta^R d_R^R + \zeta^D d_R^D \right)}{\zeta^R \frac{\mathrm{d}D^R}{\mathrm{d}P^C} + \zeta^D \left(D_R^D \frac{\mathrm{d}P^R}{\mathrm{d}P^C} + D_C^D \right)} \\
&= \frac{\frac{D_C^R}{d_R^R + (1+r)\, D_R^R} \left(\zeta^R d_R^R + \zeta^D d_R^D \right)}{\zeta^R \frac{d_R^R D_C^R}{d_R^R + (1+r) D_R^R} + \zeta^D \left(\frac{D_R^D}{D_R^R} \left(\frac{d_R^R D_C^R}{d_R^R + (1+r)\, D_R^R} - D_C^R \right) + D_C^D \right)} \\
&= \frac{D_C^R \left(\zeta^R d_R^R + \zeta^D d_R^D \right)}{\zeta^R d_R^R D_C^R + \zeta^D \left(-D_R^D \,(1+r)\, D_C^R + D_C^D \left(d_R^R + (1+r)\, D_R^R \right) \right)}
\end{aligned} \tag{D.2}$$

The second equality follows from $\frac{\mathrm{d}D^R}{\mathrm{d}P^C} = -\frac{\mathrm{d}d^R}{\mathrm{d}P^C}$ and (C.4). By taking derivatives of (D.2), we obtain (iii) and (iv).

E Proof of Corollary 1

We omit the proof of (i). For (ii), note that the price of the clean backstop fully determines exhaustible resource prices

$$\begin{aligned} \lim_{\left(D_R^R, D_R^C\right) \to (-\infty, +\infty)} \frac{\mathrm{d}P^R}{\mathrm{d}P^C} = \\ \lim_{\left(D_R^R, D_R^C\right) \to (-\infty, +\infty)} \left(-\frac{(1+r)\, D_C^R}{d_R^R + (1+r)\, D_R^R} \right) = 1 \end{aligned} \tag{E.1}$$

The D_C^D term in (D.1) is superfluous because of (E.1) and since dirty backstop users are indifferent between substituting to the exhaustible resource and to the clean backstop. $\frac{\mathrm{d}\Sigma}{\mathrm{d}P^C}$ then has the same sign as the term in square brackets in (D.1).

F Proof of Corollary 2

We omit the proof of (i). For (ii), D^D is infinitely elastic with respect to P^C at $P^C = P^D$. From (D.2), we see that $\lim_{D_C^D \to \infty} \lambda = 0$. For (iii), $D_C^D = D_D^R = 0$ when $P^C < P^D$. It then follows that $\frac{\mathrm{d}\Sigma}{\mathrm{d}P^C}$ has the same sign as $(1-\beta)\, \zeta^R d_R^R + \zeta^D d_R^D$. For (iv), $d_R^D = D_C^D = D_D^R = 0$ when $p^C < p^D$ and $P^C < p^D$. We then have $\frac{\mathrm{d}\Sigma}{\mathrm{d}P^C} < 0$.

G Proof of Corollary 3

The proof of (i) is analogous to the proof of (iv) in Corollary 2. For (ii), we see in (D.2) that $\lim_{\left(D_R^R, D_R^D\right) \to (-\infty, +\infty)} \lambda = 0$.

H Calibrations

In Table 4, the expressions for $\frac{\mathrm{d}d^R}{\mathrm{d}T}$, $\frac{\mathrm{de}}{\mathrm{d}T}$ and $\frac{\mathrm{d}E}{\partial T}$ are given by $d_R^R \frac{\mathrm{d}p^R}{\mathrm{d}T}$, (A.1) and (B.5) respectively.[13] Substituting elasticities for the partial derivatives of the demand function and using the assumption that the elasticities are

[13] The derivation of these equations does not depend on assumption (A3).

equal across periods, we get

$$\frac{\mathrm{d}d^R}{\mathrm{d}T} = \frac{\zeta^R \eta_R^R \dfrac{D^R}{P^R} + \zeta^D \eta_D^R \dfrac{D^R}{P^D}}{-1 - (1+r)\dfrac{D^R}{P^R}\dfrac{p^R}{d^R}} \tag{H.1}$$

$$\frac{\mathrm{d}e}{\mathrm{d}T} = \frac{\mathrm{d}d^R}{\mathrm{d}T}\left(\zeta^R + \zeta^D \frac{\eta_R^D}{\eta_R^R}\frac{d^D}{d^R}\right) \tag{H.2}$$

$$\frac{\mathrm{d}E}{\mathrm{d}T} = \left(\zeta^D\right)^2 \eta_D^D \frac{D^D}{P^D} + \zeta^D \eta_R^D \frac{D^D}{P^R}\left(\frac{-\frac{\mathrm{d}d^R}{\mathrm{d}T}}{\eta_R^R \frac{D^R}{P^R}} + \zeta^D \frac{\eta_D^R}{-\eta_R^R}\frac{P^R}{P^D}\right) - \zeta^R \frac{\mathrm{d}d^R}{\mathrm{d}T} \tag{H.3}$$

Table H.1 lists the definitions and sources of the variables used for the calibrations in Tables 4 and 7. In the calibrations for spatial leakage, P^R and P^D are inclusive of a €15 per tonne carbon tax.

Table H.2 contains information on natural gas and coal use for electricity generation in the EU and in the rest of the world (ROW). The EU relies more on natural gas for its electricity generation vis-a-vis ROW. Because natural gas is only 60% as emission intensive as coal, the relative price difference for the two resources is much smaller in the EU.

Table H.3 presents the spatial leakage calibration for the electricity sector. As in the intertemporal calibration in Table 5, a unilateral tax increase raises natural gas demand for electricity generation in the EU for the two bottom elasticity estimates. Because the EU consumes more natural gas and less coal relative to the world at large, the direct own-price effect of the tax on natural gas consumption is stronger than in the intertemporal calibration, and the substitution effect from coal to gas is weaker. For (Ko and Dahl, 2001) and (Serletis et al., 2010), the reaction of natural gas suppliers is therefore weaker than in the intertemporal calibration, bringing the leakage rates closer to zero. The spatial leakage rate for the (Söderholm, 2000) estimates is higher than the intertemporal rate in Table 5 because the tax' direct effect on coal consumption in the EU is low, owing to the low initial level of coal consumption in the EU.

For the calibrations in sections 5.1, 5.2 and 5.3, we employ the following model. Let X denote compositie energy and indicate nests by $k \in \{N, E\}$. The elasticity of substitution between and within nests is σ_X and σ_k, respectively. The value share of nest k in composite energy demand is α_k^X; the share of type i in nest k is α_i^k. Denote available income by y. Then

Table H.1: Data definitions and sources for emission tax calibrations

Variable	Definition	Source
	Table 4	
d^R, d^D	Total primary oil and coal demand in 2009, mln boe	IEA (2011, p. 544)
D^R, D^D	Total primary oil and coal demand in 2035, mln boe	IEA (2010b, p. 619)
p^R	IEA crude oil import price in 2009, \$ per barrel	IEA (2010b, p. 71)
P^R	IEA crude oil import price in 2035, \$ per barrel	IEA (2010b, p. 71)
p^D, P^D	Average EU steam coal import costs in 2009, \$ per boe[b]	IEA (2010a, p. III.44)
	Table 5	
d^R, d^D	Natural gas and coal demand for power generation in 2009, mln boe	IEA (2011, p. 544)
D^R, D^D	Natural gas and coal demand for power generation in 2035, mln boe	IEA (2010b, p. 619)
p^R	European natural gas import import price in 2009, \$ per boe	IEA (2010b, p. 71)
P^R	European natural gas import import price in 2035, \$ per boe	IEA (2010b, p. 71)
p^D, P^D	Average EU steam coal import costs in 2009, \$ per boe	IEA (2010a, p. III.44)
	Table 7	
d^R, d^D	EU total primary oil and coal demand in 2009, mln boe	IEA (2011, p. 564)
D^R, D^D	ROW total primary oil and coal demand in 2009, mln boe	IEA (2011, p. 544, p. 564)
p^R	IEA crude oil import price in 2009, \$ per boe	IEA (2010b, p. 71)
p^D	Average EU steam coal import costs in 2009, \$ per boe	IEA (2010a, p. III.44)
P^i	$p^i + €15^b \zeta^i,\ i \in \{R, D\}$	
	Table H.3	
d^R, d^D	EU natural gas and coal demand for power generation in 2009, mln boe	IEA (2011, p. 544)
D^R, D^D	ROW natural gas and coal demand for power generation in 2035, mln boe	IEA (2011, p. 544, p. 564)
p^R	European natural gas import import price in 2009, \$ per boe	IEA (2010b, p. 71)
p^D	Average EU steam coal import costs in 2009, \$ per boe	IEA (2010a, p. III.44)
P^i	$p^i + €15^b \zeta^i,\ i \in \{R, D\}$	
ζ^i	$\dfrac{\text{Total CO2 emissions from type } i \text{ in 2009, t}}{\text{Total primary energy demand for type } i \text{ in 2009, boe}}$	IEA (2011, p. 544, p. 546)

[a] All energy demand is converted from Mtoe in source data; 1 toe = 7.315 boe. Energy prices are converted from \$ per MBtu or \$ per tce in source data; 1 MBtu = 0.1843 boe; 1 tce = 4.787 boe. All 2035 values are from the 'Current Policies' scenario in IEA (2010b).
[b] Exchange rate: \$1 = €0.719

Table H.2: Demand for electricity generation and prices for spatial model

	ROW	EU
Natural gas demand for electricity generation	6320	1017
Coal demand for electricity generation	14147	1536
Natural gas price	40.14	46.63
Coal price	20.84	31.62

[a] Quantities in mln boe, prices in 2009$ per boe. Emission intensities in t/boe: 0.3101 for natural gas; 0.5169 for coal. A full list of definitions and sources is provided in Table H.1.

Table H.3: Estimates of demand elasticities in electricity generation and spatial leakage predictions

Study	η_R^R	η_D^R	η_R^D	η_D^D	$\frac{\mathrm{d}d^R}{\mathrm{d}T}$	$\frac{\mathrm{d}e}{\mathrm{d}T}$	$\frac{\mathrm{d}E}{\mathrm{d}T}$	λ
Söderholm (2000)[b]	-0.82	0.01	0.04	-0.20	4.67	1.18	-3.86	0.31
Söderholm (2001)[b]	-0.38	0.01	0.09	-0.13	2.02	0.10	-1.92	0.05
Ko and Dahl (2001)	-1.46	0.72	0.28	-0.57	-1.87	-0.16	-5.30	-0.03
Serletis et al. (2010)	-0.14	0.07	0.06	-0.12	-0.16	0.04	-1.20	0.03

[a] Equations for $\frac{\mathrm{d}d^R}{\mathrm{d}T}$, $\frac{\mathrm{d}e}{\mathrm{d}T}$ and $\frac{\mathrm{d}E}{\mathrm{d}T}$ are given by (H.1), (H.2) and (H.3), respectively. λ is defined in Definition 2. [b] Median estimates over all countries included in the study.

$$d^i = \left(\frac{y}{p^X}\right) \sum_{k\in\{N,E\}} \alpha_k^X \left(\frac{p^X}{p^k}\right)^{\sigma_X} \alpha_i^k \left(\frac{p^i}{p^k}\right)^{\sigma_k} \tag{H.4}$$

$$p^X = \left(\sum_{k\in\{N,E\}} \alpha_k^X \left(p^K\right)^{\frac{1-\sigma_X}{\sigma_X}}\right)^{\frac{\sigma_X}{1-\sigma_X}},\ p^k = \left(\sum_{i\in\{R,D,C\}} \alpha_i^k \left(p^i\right)^{\frac{1-\sigma_k}{\sigma_k}}\right)^{\frac{\sigma_k}{1-\sigma_k}} \tag{H.5}$$

where $\sum_{k\in\{N,E\}} \alpha_k^X = \sum_{i\in\{R,D,C\}} \alpha_i^k = 1$. Demand in the second period is described by a similar system. Exhaustible resource prices p^R and P^R are endogenously determined by (4) and $d^R + D^R = S$. The parameter values are listed in Table H.4. As (H.5) is homogenous of degree zero in S, y and Y, we normalize S to one. Income is chosen such that $Y = (1+r)\,y$ and $p^R = 60.4$ when $P^C = p^C$ in the second scenario. The interest rate equals 2% per annum compounded over 26 years. The coal price and emission intensities for coal and conventional oil are equal to those in Table H.1. Unconventional oil is 20% more emission-intensive than conventional oil. We set the unconventional oil price and the initial biofuel price to 80.

I Spatial and Intertemporal Leakage

In this section, we extend the model to include both a spatial and an intertemporal dimension, to analyze the effect on emissions when one region implements a unilateral carbon tax T_2 in the second period. We denote variables corresponding to the adopting country with capitals, and indicate time by subscripts. Then $D_{D,1}^R$ is the derivative of exhaustible resource demand with respect to the dirty backstop price in the adopting country in the first period. Exhaustible resource owners must now be indifferent between selling in either region in either period:

$$p_1^R = P_1^R = \frac{1}{1+r} p_2^R = \frac{1}{1+r}\left(P_2^R - T_2\zeta^R\right) \tag{I.1}$$

Similar to (8), the unilateral second-period tax increases exhaustible resource prices in the first period and in the non-adopting country if the tax increases exhaustible resource demand at constant producer prices

$$\frac{\mathrm{d}p_1^R}{\mathrm{d}T_2}, \frac{\mathrm{d}P_1^R}{\mathrm{d}T_2}, \frac{\mathrm{d}p_2^R}{\mathrm{d}T_2} \gtreqless 0 \Leftrightarrow \zeta^R D_{R,2}^R + \zeta^D D_{R,2}^D \gtreqless 0 \tag{I.2}$$

Table H.4: Parametrization of calibrations in sections 5.1, 5.2 and 5.3

Variable	Interpretation			
ζ^R	Emission intensity of exhaustible resource		0.3644	
r	Interest rate		0.6734	
S	Exhaustible resource stock		1	
y	First-period income		84.03	
Y	Second-period income		140.59	
σ_X	Elasticity of substitution between nests		1.5	
		Section		
		5.1	5.2	5.3
σ_N	Elasticity of substitution within non-electricity nest	5		5
σ_E	Elasticity of substitution within electricity nest		5	
α_N^X	Value share of non-electricity in aggregate energy	0.5	0.5	0.2
α_R^N	Value share of exhaustible resource in non-electricity nest	0.5	1	0.5
α_D^N	Value share of dirty backstop in non-electricity nest	0	0	0.5
α_C^N	Value share of clean backstop in non-electricity nest	0.5	0	0
α_R^E	Value share of exhaustible resource in electricity nest	0	0	0
α_D^E	Value share of dirty backstop in electricity nest	1	0.5	0
α_C^E	Value share of clean backstop in electricity nest	0	0.5	1
p^D	Dirty backstop price	20.84	20.84	80
p^C	Initial clean backstop price	80	46.25	46.25
ζ^D	Emission intensity of dirty backstop	0.5169	0.5169	0.437[illegible]

Proposition 5. *Following a unilateral carbon tax increase in the second period*
(i) D_2^D *decreases*
(ii) under (A3), E_2 *decreases*
(iii) under (A3), $e_1 + E_1 + e_2 + E_2$ *decreases*
(iv) e_1+E_1 *increases when* $\left(\zeta^R D_{R,2}^R + \zeta^D D_{D,2}^R\right)\left(\zeta^R \left(d_{R,1}^R + D_{R,1}^R\right) + \zeta^D \left(d_{R,1}^D + D_{R,1}^D\right)\right) > 0$
(v) under (A3), $e_2 + E_2$ *decreases*

Proof. The proof of (i) and (ii) is analogous to Propositon 2. Totally differentiating (I.1) with respect to T_2 yields

$$\frac{\mathrm{d}p_1^R}{\mathrm{d}T_2} = \frac{\mathrm{d}P_1^R}{\mathrm{d}T_2} = \frac{1}{1+r}\frac{\mathrm{d}p_2^R}{\mathrm{d}T_2} = \frac{1}{1+r}\left(\frac{\mathrm{d}P_2^R}{\mathrm{d}T_2} - \zeta^R\right) \tag{I.3}$$

From $d_1^R + D_1^R + d_2^R + D_2^R = S$, we get

$$d_{R,1}^R\frac{\mathrm{d}p_1^R}{\mathrm{d}T_2} + D_{R,1}^R\frac{\mathrm{d}P_1^R}{\mathrm{d}T_2} + d_{R,2}^R\frac{\mathrm{d}p_2^R}{\mathrm{d}T_2} + D_{R,2}^R\frac{\mathrm{d}P_2^R}{\mathrm{d}T_2} + D_{D,2}^R\zeta^D = 0 \tag{I.4}$$

Solve (I.3) and (I.4) in $\frac{\mathrm{d}p_1^R}{\mathrm{d}T_2}$, $\frac{\mathrm{d}P_1^R}{\mathrm{d}T_2}$, $\frac{\mathrm{d}p_2^R}{\mathrm{d}T_2}$ and $\frac{\mathrm{d}P_2^R}{\mathrm{d}T_2}$

$$\frac{\mathrm{d}p_1^R}{\mathrm{d}T_2} = -\frac{\zeta^R D_{R,2}^R + \zeta^D D_{D,2}^R}{\Gamma} \tag{I.5a}$$
$$\frac{\mathrm{d}P_1^R}{\mathrm{d}T_2} = -\frac{\zeta^R D_{R,2}^R + \zeta^D D_{D,2}^R}{\Gamma} \tag{I.5b}$$
$$\frac{\mathrm{d}p_2^R}{\mathrm{d}T_2} = -\frac{(1+r)\left(\zeta^R D_{R,2}^R + \zeta^D D_{D,2}^R\right)}{\Gamma} \tag{I.5c}$$
$$\frac{\mathrm{d}P_2^R}{\mathrm{d}T_2} = \frac{\left(d_{R,1}^R + D_{R,1}^R + (1+r)\, d_{R,2}^R\right)\zeta^R - \zeta^D (1+r)\, D_{D,2}^R}{\Gamma} \tag{I.5d}$$

where $\Gamma \equiv d_{R,1}^R + D_{R,1}^R + (1+r)\, d_{R,2}^R + (1+r)\, D_{R,2}^R$. Analogous to Proposition 2, we prove (iii) by showing that total dirty backstop use goes down.

$$\begin{aligned}
\frac{\mathrm{d}\left[d_1^D + D_1^D + d_2^D + D_2^D\right]}{\mathrm{d}T_2} =& d_{R,1}^D \frac{\mathrm{d}p_1^R}{\mathrm{d}T_2} + D_{R,1}^D \frac{\mathrm{d}P_1^R}{\mathrm{d}T_2} + d_{R,2}^D \frac{\mathrm{d}p_2^R}{\mathrm{d}T_2} + D_{R,2}^D \frac{\mathrm{d}P_2^R}{\mathrm{d}T_2} + \zeta^D D_{D,2}^D \\
=& - d_{R,1}^D \frac{\zeta^R D_{R,2}^R + \zeta^D D_{D,2}^R}{\Gamma} - D_{R,1}^D \frac{\zeta^R D_{R,2}^R + \zeta^D D_{D,2}^R}{\Gamma} \\
& - (1+r)\, d_{R,2}^D \frac{\zeta^R D_{R,2}^R + \zeta^D D_{D,2}^R}{\Gamma} \\
& + D_{R,2}^D \frac{\left(d_{R,1}^R + D_{R,1}^R + (1+r)\, d_{R,2}^R\right) \zeta^R - \zeta^D (1+r)\, D_{D,2}^R}{\Gamma} + \zeta^D D_{D,2}^D \\
=& \frac{1}{\Gamma} \left[\zeta^D D_{D,2}^D \left(d_{R,1}^R + D_{R,1}^R + (1+r)\, d_{R,2}^R + (1+r)\, D_{R,2}^R\right)\right. \\
& -\zeta^D D_{D,2}^R \left(d_{R,1}^D + D_{R,1}^D + (1+r)\, d_{R,2}^D + (1+r)\, D_{R,2}^D\right) \\
& -\zeta^R D_{R,2}^R \left(d_{R,1}^D + D_{R,1}^D + (1+r)\, d_{R,2}^D\right) \\
& \left. +\zeta^R D_{R,2}^D \left(d_{R,1}^R + D_{R,1}^R + (1+r)\, d_{R,2}^R\right)\right] \\
& < \frac{1}{\Gamma} \left[\underbrace{\zeta^D D_{D,2}^D \left(d_{R,1}^R + D_{R,1}^R + (1+r)\, d_{R,2}^R\right)}_{I} \right. \\
& \underbrace{-\zeta^D D_{D,2}^R \left(d_{R,1}^D + D_{R,1}^D + (1+r)\, d_{R,2}^D\right)}_{II} \\
& \underbrace{-\zeta^R D_{R,2}^R \left(d_{R,1}^D + D_{R,1}^D + (1+r)\, d_{R,2}^D\right)}_{III} \\
& \left. \underbrace{+\zeta^R D_{R,2}^D \left(d_{R,1}^R + D_{R,1}^R + (1+r)\, d_{R,2}^R\right)}_{IV} \right]
\end{aligned} \tag{I.6}$$

The last inequality follows from (A2). In (I.6), $I,\ III > 0$ and $II,\ IV < 0$. When the tax decreases oil demand in the adopting country in the second period, that is if $\zeta^R D_{R,2}^R + \zeta^D D_{D,2}^R \leq 0$, we have $II + III \geq 0$. From $I + IV > 0$ (by (A2)) it then follows that $\frac{\mathrm{d}\left[d_1^D + D_1^D + d_2^D + D_2^D\right]}{\mathrm{d}T_2} < 0$. Conversely, when $\zeta^R D^R_{R,2} + \zeta^D D^R_{D,2} > 0$, (A2) gives

$$
\begin{aligned}
\frac{\mathrm{d}\left[d^D_1 + D^D_1 + d^D_2 + D^D_2\right]}{\mathrm{d}T_2} <& \frac{1}{\Gamma}\left[\zeta^D D^D_{D,2}\left(d^R_{R,1} + D^R_{R,1} + (1+r)\, d^R_{R,2}\right)\right.\\
&+\zeta^D D^R_{D,2}\left(d^R_{R,1} + D^R_{R,1} + (1+r)\, d^R_{R,2}\right)\\
&+\zeta^R D^R_{R,2}\left(d^R_{R,1} + D^R_{R,1} + (1+r)\, d^R_{R,2}\right)\\
&\left.+\zeta^R D^D_{R,2}\left(d^R_{R,1} + D^R_{R,1} + (1+r)\, d^R_{R,2}\right)\right]\\
=& \frac{\overbrace{d^R_{R,1} + D^R_{R,1} + (1+r)\, D^R_{R,2}}^{>0}}{\Gamma}\\
&\underbrace{\left(\zeta^D D^D_{D,2} + \zeta^D D^R_{D,2} + \zeta^R D^R_{R,2} + \zeta^R D^D_{R,2}\right)}_{<0} < 0
\end{aligned}
$$

The underbraced term is negative by (A2) and (A3), completing the proof of (iii). The effect of the tax on first-period emissions is

$$
\begin{aligned}
\frac{\mathrm{d}\left[e_1 + E_1\right]}{\mathrm{d}T_2} =& \frac{\mathrm{d}p^R_1}{\mathrm{d}T_2}\left(\zeta^R d^R_{R,1} + \zeta^D d^D_{R,1}\right) + \frac{\mathrm{d}P^R_1}{\mathrm{d}T_2}\left(\zeta^R D^R_{R,1} + \zeta^D D^D_{R,1}\right)\\
=& -\frac{\left(\zeta^R D^R_{R,2} + \zeta^D D^R_{D,2}\right)\left(\zeta^R d^R_{R,1} + \zeta^D d^D_{R,1}\right)}{\Gamma} - \frac{\left(\zeta^R D^R_{R,2} + \zeta^D D^R_{D,2}\right)\left(\zeta^R D^R_{R,1} + \zeta^D D^D_{R,1}\right)}{\Gamma}\\
=& -\frac{\left(\zeta^R D^R_{R,2} + \zeta^D D^R_{D,2}\right)\left(\zeta^R\left(d^R_{R,1} + D^R_{R,1}\right) + \zeta^D\left(d^D_{R,1} + D^D_{R,1}\right)\right)}{\Gamma}
\end{aligned}
\tag{I.7}
$$

As $\Gamma < 0$, first-period emissions increase when the numerator in (I.7) is positive, establishing (iv). The effect of the tax on second-period emissions is

$$
\begin{aligned}
\frac{\mathrm{d}\left[e_2+E_2\right]}{\mathrm{d}T_2} =& \frac{\mathrm{d}e_2}{\mathrm{d}T_2}+\frac{\mathrm{d}E_2}{\mathrm{d}T_2}\\
=&\zeta^D\frac{\mathrm{d}d_2^D}{\mathrm{d}T_2}+\zeta^R\frac{\mathrm{d}d_2^R}{\mathrm{d}T_2}+\frac{\mathrm{d}E_2}{\mathrm{d}T_2}\\
=&\zeta^D d_{R,2}^D\frac{\mathrm{d}p_2^R}{\mathrm{d}T_2}+\zeta^R\frac{\mathrm{d}d_2^R}{\mathrm{d}T_2}+\frac{\mathrm{d}E_2}{\mathrm{d}T_2}\\
=&\frac{\mathrm{d}p_2^R}{\mathrm{d}T_2}\left(\zeta^D d_{R,2}^D+\zeta^R d_{R,2}^R\right)+\frac{\mathrm{d}E_2}{\mathrm{d}T_2}\\
=&\frac{\mathrm{d}p_2^R}{\mathrm{d}T_2}\left(\zeta^D d_{R,2}^D+\zeta^R d_{R,2}^R\right)+\zeta^D\left(D_{D,2}^D\zeta^D+D_{R,2}^D\frac{\mathrm{d}P^R}{\mathrm{d}T}\right)+\zeta^R\left(D_{R,2}^R\frac{\mathrm{d}P^R}{\mathrm{d}T}+D_{D,2}^R\zeta^D\right)\\
=&-\frac{(1+r)\left(\zeta^R D_{R,2}^R+\zeta^D D_{D,2}^R\right)\left(\zeta^R d_{R,2}^R+\zeta^D d_{R,2}^D\right)}{\Gamma}+\left(\zeta^D\right)^2 D_{D,2}^D+\zeta^D\zeta^R D_{D,2}^R\\
&+\frac{\left(\zeta^D D_{R,2}^D+\zeta^R D_{R,2}^R\right)\left(\left(d_{R,1}^R+D_{R,1}^R+(1+r)\,d_{R,2}^R\right)\zeta^R-\zeta^D(1+r)\,D_{D,2}^R\right)}{\Gamma}\\
=&\frac{1}{\Gamma}\Bigg[\zeta^D(1+r)\Bigg[\overbrace{\zeta^D D_{D,2}^D D_{R,2}^R-\zeta^D D_{R,2}^D D_{D,2}^R}^{>0}-\overbrace{\zeta^D d_{R,2}^D D_{D,2}^R}^{I}-\overbrace{\zeta^R d_{R,2}^D D_{R,2}^R}^{II}+\overbrace{\zeta^D D_{D,2}^D d_{R}}^{III}\ldots\\
&+\overbrace{\zeta^R D_{R,2}^D d_{R,2}^R}^{IV}\Bigg]+\underbrace{\left(d_{R,1}^R+D_{R,1}^R\right)}_{<0}\underbrace{\left[\left(\zeta^D\right)^2 D_{D,2}^D+\zeta^D\zeta^R D_{D,2}^R+\zeta^D\zeta^R D_{R,2}^D+\left(\zeta^R\right)^2 D_{R}^R\ldots\right.}_{V}
\end{aligned}
\tag{I.8}
$$

The fifth equation follows by substituting the analog of (B.5) and the sixth from (I.5). When $d_{R,2}^R=-d_{R,2}^D$

$$
-I-II+III+IV=d_{R,2}^D\left(-\zeta^D D_{D,2}^R-\zeta^R D_{R,2}^R-\zeta^D D_{D,2}^D-\zeta^R D_{R,2}^D\right)>0
$$

The inequality follows from (A3). Because $III+IV>0$, by induction we also have $-I-II+III+IV>0$ when $d_{R,2}^R<-d_{R,2}^D$. For V, we have

$$
\begin{aligned}
&\left(\zeta^D\right)^2 D_{D,2}^D+\zeta^D\zeta^R D_{D,2}^R+\zeta^D\zeta^R D_{R,2}^D+\left(\zeta^R\right)^2 D_{R,2}^R<\\
&-\left(\zeta^D\right)^2 D_{R,2}^D+\zeta^D\zeta^R D_{D,2}^R+\zeta^D\zeta^R D_{R,2}^D-\left(\zeta^R\right)^2 D_{D,2}^R=\\
&-\left(\zeta^D D_{R,2}^D-\zeta^R D_{D,2}^R\right)^2<0
\end{aligned}
$$

The first inequality follows from (A2); the last equality from (A3). As $\Gamma < 0$, $\frac{\mathrm{d}[e_2+E_2]}{\mathrm{d}T_2} < 0$. □

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