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By Thomas Michielsen

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Brown Backstops versus the Green Paradox

Thomas Michielsen*
Tilburg University

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Abstract

Anticipated and unilateral climate policies are ineffective when fossil fuel owners respond by shifting supply intertemporally (the green paradox) or spatially (carbon leakage). These mechanisms rely crucially on the exhaustibility of fossil fuels. We analyze the effect of anticipated and unilateral climate policies on emissions in a simple model with two fossil fuels: one scarce and dirty (oil), the other abundant and dirtier (coal). We derive conditions for a 'green orthodox': anticipated climate policy may reduce current emissions, and unilateral measures may unintentionally reduce emissions in other countries. Calibrations suggest that intertemporal carbon leakage (between -3% and 1%) is less of a concern than spatial leakage (19-39%).

JEL-Classification: Q31, Q54

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 and vary substantially across countries. Fossil fuel owners, deciding when and to whom to sell their scarce resources, may respond by speeding up extraction and selling to environmentally lax countries. These side effects can occur when fossil fuel reserves are limited and cheap to exploit: a reasonable characterization for conventional oil and natural gas, but

*CentER, Department of Economics and Tilburg Sustainability Center, Tilburg University, P.O. Box 90153, 5000 LE Tilburg, The Netherlands. E-mail: t.o.michielsen@uvt.nl

much less for other important energy sources such as coal and unconventional oil. 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 (a clean backstop) 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

Likewise, when a group of countries reduces emissions unilaterally, pollution might move to other countries. This carbon leakage occurs through two 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, 2000; Paltsev, 2001; Babiker, 2005).²

The crucial feature that drives the above mechanisms 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 country 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 rates³. Coal and unconventional oil are much more abundant however. Coal reserves are sufficient to last another 250 years, and tar sand deposits in Alberta

¹The green paradox may vanish when the substitute has an upward-sloping supply curve (Gerlagh, 2011). Van der Ploeg and Withagen (2009) 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.

²Studies on international environmental agreements find a related effect. Because environmental standards are strategic substitutes, non-signatories will increase emissions (Barrett, 1994; Hoel, 1994).

³BP Statistical Review of World Energy 2010, p.6, p.12

are estimated at 1800 bln barrels⁴. The supply of these resources is primarily driven by costs rather than scarcity rents. Anticipated carbon taxes cause coal mines to shut down, 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 emissions⁵, outranking petroleum in emission intensity by 30-40%. The IEA expects coal supply to increase by 60% in 2035 under business-as-usual policies⁶; twice as much 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 unconventional oil reserves remain largely unexploited (Gerlagh, 2011). A comprehensive assessment of the effectiveness of climate policies should take into account these 'dirty backstops' and their unique characteristics.⁷

In this paper, we develop a simple model with two time periods or two regions. We do not derive optimal policies, but present a descriptive analysis of the effect of future or unilateral 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 backstop (coal) and a clean backstop (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 backstop. We calculate intertemporal or spatial carbon leakage as the increase in present emissions over the decrease in future emissions, or the increase in non-adopting regions over the decrease in adopting regions.

By virtue of the abundance of their resource, coal owners do not trade off present and future extraction or supplying one country and the other. When faced with a demand reduction in the future or in climate-conscious regions, they will therefore not increase supply today or to lax regions. Oil emissions may leak away to the present or to non-adopting regions, but the increased oil supply in these markets reduces demand for dirtier coal. Carbon taxes can

⁴Alberta's Energy Reserves 2010 and Supply/Demand Outlook 2011-2020, p.5

⁵International Energy Statistics, Energy Information Administration

⁶World Energy Outlook 2010, p.201, IEA

⁷Van der Ploeg and Withagen (2011) show that rising carbon taxes may not cause a green paradox when coal, rather than renewables, is the primary alternative for oil.

cause negative leakage when the substitutability between oil and coal differs between time periods or regions. We may call this a 'strong green orthodox' (Grafton et al., 2010). 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 backstop reduces intertemporal and spatial carbon leakage directly and indirectly, and may even cause negative leakage rates. By making more specific 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, we find negative intertemporal leakage rates and spatial leakage rates in the order of 19-39%. For reductions in the future cost of renewables, leakage is less than 1%. Our 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 (in a two-period model) or in one region (in a two-region model). Section 4 studies the impact of reductions in the future cost of a clean substitute. The models are calibrated with interfuel elasticity estimates from previous work. Section 5 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 costs⁸. 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 ⁹. An energy-importing country derives utility from consuming energy. Denote the exhaustible resource, the dirty and the clean backstop with super-

⁸An upward-sloping supply curve for the clean backstop reduces intertemporal carbon leakage (Gerlagh, 2011).

⁹Relaxing this assumption reduces intertemporal leakage (van der Ploeg and Withagen, 2009; Fischer and Salant, 2010).

scripts F , Z and C respectively. Demand functions are given by

$$d^i(p^i, p^{-i}), \quad i \in \{F, Z, C\} \quad (1)$$

Letting q^F denote the equilibrium quantity of the exhaustible resource, its inverse demand function is

$$p^F = \psi(q^F, p^Z, p^C) \quad (2)$$

Throughout the paper, we write shorthand d^i and ψ for (1) and (2), respectively. Partial derivatives of d^i and ψ are indicated by a subscript of the corresponding type. We make the following assumptions about energy demand

$$d_i^i < 0, \quad d_j^i \geq 0 \quad (A1)$$

$$|d_i^i| > |d_j^i|, \quad i \neq j \quad (A2)$$

$$d_j^i = d_i^j \quad (A3)$$

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). These assumptions hold for quasi-linear utility functions and, as we show in Appendix A, if we can rewrite the demand structure as demand for a composite good that is produced from F , Z and C according to a homogeneous function¹⁰. CES demand functions satisfy this property.

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

$$e = \zeta^F q^F + \zeta^Z d^Z, \quad 0 < \zeta^F < \zeta^Z$$

The model has a time or a space dimension and consists of two periods or two regions, respectively. For brevity, we refer to period 1 and period 2 in the theoretical analysis, but one may substitute this by non-adopting and adopting regions. All variables corresponding to the second period (adopting region) are denoted by capitals. Exhaustible resource owners discount future revenues at rate r . In equilibrium, they are indifferent between extracting now and in the future

$$p^F = \frac{1}{1+r} P^F \quad (3)$$

¹⁰Some energy carriers are also used to produce other goods (e.g. plastics from petroleum). This can be reconciled with assumption (A3) if the production function of the other good is homogeneous of the same degree as that of the composite good.

Substituting the stock constraint, the indifference condition (3) reads

$$\psi(q^F, p^Z, p^C) = \frac{1}{1+r} \Psi(S - q^F, P^Z, P^C) \quad (4)$$

We allow for emissions in the first period to be more harmful than emissions in the second period. Total emission damages are

$$\Sigma = e + \beta E, \quad \beta \leq 1 \quad (5)$$

When only cumulative emissions matter or when we use the model for a two-region analysis, 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*

$$\frac{\partial e}{\partial \Theta} > 0$$

The strong green paradox occurs if

$$\frac{\partial \Sigma}{\partial \Theta} > 0$$

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 β^* 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.*

$$\beta^* = - \frac{\partial e}{\partial \Theta} / \frac{\partial E}{\partial \Theta}$$

Both green paradoxes are related to the intertemporal leakage rate β^* 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 $\beta^* > 0$. The strong green paradox occurs if the leakage rate exceeds the emission discount rate ($\beta^* > \beta$).

The model has a spatial rather than intertemporal interpretation when $r = 0$ and $\beta = 1$. When one region implements a unilateral climate policy, β^* is the

share of emission reductions that leaks away to the other region. The unilateral policy reduces global emissions when $\beta^* < 1$, and reduces emissions in both regions when $\beta^* < 0$. 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 predictability are necessary"¹¹ in order to meet the 80-95% EU emission reduction target in 2050. Carbon taxes also vary between countries. Emission reduction is a global public good, so individual countries have an incentive to free-ride on others' efforts or misrepresent their preference for environmental quality. International environmental agreements suffer from enforcement problems (Barrett, 1994). When globally coordinated measures prove impossible, climate-conscious countries can only resort to unilateral policies.

Carbon emissions are taxed at a constant rate W 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:

$$p^F = \frac{1}{1+r} (P^F - W\zeta^F) \quad (6)$$

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

$$\frac{\partial e}{\partial p^F} \frac{\partial \psi}{\partial W} \quad (7)$$

We discuss the two components of this term in turn. The carbon tax increases the period 2 producer price of the exhaustible resource and, by (6), the period 1 price if and only if the tax increases period 2 exhaustible resource demand at

¹¹A Roadmap for moving to a competitive low carbon economy in 2050, p.7, European Commission COM(2011) 112

fixed producer prices.

$$\frac{\partial \psi}{\partial W} \gtrless 0 \Leftrightarrow \left(\frac{\partial D^F}{\partial W} \right)_{P^F - \zeta^F W} \gtrless 0 \quad (8)$$

Holding the producer price constant, the carbon tax directly reduces exhaustible resource demand in the second period by $-\zeta^F D_F^F$. 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 $\zeta^Z D_Z^F$. By assumption (A3) (symmetric cross-effects), this is equal to $\zeta^Z D_F^Z$. The period 1 exhaustible resource price goes up (down) if the net effect of the tax on period 2 exhaustible resource demand

$$\left(\frac{\partial D^F}{\partial W} \right)_{P^F - \zeta^F W} = \zeta^F D_F^F + \zeta^Z D_F^Z \quad (9)$$

is positive (negative), i.e. if the substitutability between the dirty backstop and the exhaustible resource is high (low) in period 2 and if the emission-intensity of the dirty backstop is high (low).

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 $-\zeta^F d_F^F$. Higher exhaustible resource prices also encourage substitution towards the dirty backstop, increasing emissions by $\zeta^Z d_F^Z$. The net change in emissions

$$\frac{\partial e}{\partial p^F} = \zeta^F d_F^F + \zeta^Z d_F^Z \quad (10)$$

is positive (negative) if the dirty backstop and the exhaustible resource are good (poor) substitutes in the first period and if the emission-intensity of the dirty backstop is high (low). This expression only differs from $\frac{\partial D^F}{\partial W}$ through the time indicator. In a spatial version of the model with two identical regions, the condition for $\frac{\partial \psi}{\partial W} \gtrless 0$ is identical to the one for $\frac{\partial e}{\partial p^F} \gtrless 0$. The leakage rate is then always nonnegative. We formalize this in the following Lemma.

Lemma 1. *If demand elasticities are equal in both periods, $\beta^* > 0$ except when*

$$\zeta^F D_F^F + \zeta^Z D_F^Z = 0$$

in which case $\beta^ = 0$.*

Proposition 1 describes the general case.

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

$$(\zeta^F d_F^F + \zeta^Z d_F^Z) (\zeta^F D_F^F + \zeta^Z D_F^Z) \geq 0 \quad (11)$$

The 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_F^Z and D_F^Z and how these cases relate to previous research.

When demand for the dirty backstop is relatively inelastic with respect to the exhaustible resource price in both periods (d_F^Z and D_F^Z are both low), the 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 demand for the dirty backstop is inelastic with respect to the exhaustible resource price in the first period but elastic in the second (d_F^Z is low, while D_F^Z is high), the tax increases exhaustible resource prices and reduces emissions in both periods. This case corresponds to a scenario in which coal is only used to generate electricity today, but can be converted to transportation fuel in the future. Oil owners delay extraction in response to the tax, as the tax puts them at a comparative advantage in the transportation market in the future. Since coal is a poor substitute for oil in the short term, the decline in period 1 oil supply does not cause a surge in coal 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 coal demand reacts strongly to the exhaustible resource price in the first period but not in the second (d_F^Z is high, but D_F^Z is low), the tax reduces exhaustible resource prices and emissions go down in both periods. This case corresponds to a large coal-to-liquids (CTL) user abandoning the technology in the future. Currently, only South Africa employs CTL processes on a large scale¹². As the substitutability between oil and coal is low in the second period, oil prices decrease. This makes oil an attractive alternative for coal in the transportation market in the first period. Lastly, suppose that exhaustible resource and the dirty backstop are good substitutes in both periods (d_F^Z and D_F^Z 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

¹²Sasol's Secunda CTL plant has a capacity of 160 kilobarrels per day (IEA, 2010).

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^Z decreases
- (ii) E decreases
- (iii) $\beta^* \leq 1$
- (iv) $\beta^* > \beta$ iff

$$-\frac{\zeta^F D_F^F + \zeta^Z D_Z^F}{d_F^F + (1+r) D_F^F} \Xi + \beta \zeta^Z (\zeta^F D_F^Z + \zeta^Z D_Z^Z) > 0, \text{ where}$$

$$\Xi = (1 - \beta) \zeta^F d_F^F + \zeta^Z (d_F^Z + \beta (1+r) D_F^Z) \quad (12)$$

- (v) β^* decreases in $|D_Z^Z|$

In a spatial interpretation of the model, unilateral carbon taxes always decrease global emissions. 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.¹³ Spatial leakage estimates in excess of 100% (e.g. Babiker (2005)) rely on industry relocation effects, which we do not model explicitly. Numerous authors argue that changes in energy prices are the most important determinant of carbon leakage however (Paltsev, 2001; Fischer and Fox, 2009; Kuik and Hofkes, 2010).

Although the tax increases future demand for the clean backstop, clean backstop prices, quantities and elasticities do not appear in the conditions for $\beta^* > 0$ and $\beta^* > \beta$. 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 $\frac{\partial e}{\partial W}$ and $\frac{\partial \Sigma}{\partial W}$ do not contain any derivatives with respect

¹³Albeit through a different mechanism (substitution between energy types rather than intertemporal substitution in consumption), Eichner and Pethig (2009) also find that a future emission constraint need not cause a green paradox.

Table 1: Occurrence of the weak green paradox for different values of d_F^Z and D_F^Z

d_F^Z	D_F^Z	$\frac{\partial \psi}{\partial \bar{W}}$	$\frac{\partial \epsilon}{\partial p^F}$	weak GP?	Interpretation	Related articles
low	low	-	-	yes	classic green paradox	Sinn (2008a); Hoel (2010)
low	high	+	-	no	future diesel from coal technology	Persson et al. (2007)
high	low	-	+	no	South Africa abandons CTL	
high	high	+	+	yes	dirty fuel used in pre-tax phase	Smulders and van der Werf (2008) Di Maria et al. (2008)

Table 2: Oil and coal demand

	Intertemporal Model		Spatial Model	
	2009	2035	ROW	EU
q^F	29842	39201	24808	5034
p^F	61.67	135	61.67	69.28
q^Z	24644	36106	22798	1846
p^Z	20.84	20.84	20.84	32.17

^a Quantities in mln boe, prices in \$ per boe ^b $\zeta^F = 0.37$, $\zeta^Z = 0.54$, t per boe ^c Definitions and sources are listed in Table 1

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 (12) is not straightforward, but we can calibrate β^* as estimates of all parameters in (12) are available. Own- and cross-price effects can be rewritten as $d_j^i = \eta_j^i q^i / p^j$, 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 and spatial carbon leakage in the next subsection.

3.1 Empirical Calibration

Take oil as the exhaustible resource and coal as the dirty backstop. We observe current energy demand and prices, and the IEA forecasts future demand and prices. Table 2 presents an overview of these statistics. 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. In the spatial model, the EU accounts for a small part of global energy demand and uses relatively little coal. An empirical literature on interfuel substitution estimates demand elasticities. This literature typically distinguishes between coal and electricity as inputs in the industrial process. Since most coal is used for electricity generation, we take the elasticities for electricity as those for the dirty backstop¹⁴. We assume the elasticities to be equal across time periods and regions.

We first calculate the intertemporal leakage of a small global carbon tax in

¹⁴We 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 0.41 in 2008 (CIA World Factbook 2009)

Table 3: Literature estimates of energy demand elasticities and intertemporal leakage predictions

Study	η_F^F	η_Z^F	η_F^Z	η_Z^Z	$\frac{\partial q^F}{\partial W}$	$\frac{\partial e}{\partial W}$	$\frac{\partial E}{\partial W}$	β^*
Pindyck (1979)	-0.25	0.03	0.03	-0.12	-0.56	-0.18	-59.86	-0.00
Uri (1982)	-0.57	0.05	0.15	-0.50	2.54	0.63	-249.35	0.00
Hall (1986)	-0.70	0.09	0.24	-0.14	-7.82	-1.65	-54.32	-0.03
Magnus and Woodland (1987)	-0.33	0.04	0.09	-0.24	-1.20	-0.29	-117.43	-0.00
Renou-Maissant (1999)	-0.41	0.05	0.13	-0.19	-2.97	-0.66	-88.66	-0.01

^a Elasticity estimates presented are the median estimates over all countries included in the study. A complete overview is given in Table 2. ^b Equations for $\frac{\partial q^F}{\partial W}$, $\frac{\partial e}{\partial W}$ and $\frac{\partial E}{\partial W}$ are given by (32), (33) and (34), respectively. β^* is defined in Definition 2.

2035. The first four columns in Table 3 contain the estimated own- and cross-price elasticities for oil and electricity from five studies. Using the parameters from Table 2, for each set of estimates we determine the change in oil extraction and emissions and the intertemporal carbon leakage β^* as a result of a tax increase.

The intertemporal leakage rate is negative for most elasticity estimates. Because oil is expensive compared to coal in the future, a future carbon tax strongly decreases the oil-to-coal price ratio. The cross-price effect D_Z^F is relatively high compared to the own-price effect D_F^F . The tax-induced increase in future oil demand through substitution from coal to oil outweighs the decrease through higher own prices. As in Persson et al. (2007), the tax benefits oil exporters. Since oil is cheaper in the first period than in the second, the own-price effect of oil is stronger 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. The elasticity estimates in Uri (1982) produce a positive leakage rate as the high $|\eta_F^F|/|\eta_Z^F|$ ratio causes the tax to accelerate oil extraction. The low leakage for the estimates in Hall (1986) stems from the low values of $|\eta_Z^Z|$ and $|\eta_F^F|/|\eta_Z^F|$. The former results in smaller emission reductions from coal use in the second period; the latter causes oil prices to increase more strongly, which results in larger emission reductions in the first period. The sum of period 1 and 2 emission reductions is almost linear in η_Z^Z , suggesting that the most important effect of carbon taxes is the direct reduction in coal use. The estimated emission reductions in the second period may be biased downwards, since we conservatively assumed that oil reserves are fully exhausted.

Next, we estimate the magnitude of spatial carbon leakage. We disregard

Table 4: Literature estimates of energy price elasticities and spatial leakage predictions

Study	η_F^F	η_Z^F	η_F^Z	η_Z^Z	$\frac{\partial q^F}{\partial W}$	$\frac{\partial e}{\partial W}$	$\frac{\partial E}{\partial W}$	β^*
Pindyck (1979)	-0.25	0.03	0.03	-0.12	3.58	1.12	-3.22	0.35
Uri (1982)	-0.57	0.05	0.15	-0.50	8.96	2.09	-11.03	0.19
Hall (1986)	-0.70	0.09	0.24	-0.14	9.22	1.78	-4.58	0.39
Magnus and Woodland (1987)	-0.33	0.04	0.09	-0.24	4.75	1.09	-5.37	0.20
Renou-Maissant (1999)	-0.41	0.05	0.13	-0.19	5.66	1.17	-4.66	0.25

^a Elasticity estimates presented are the median estimates over all countries included in the study. A complete overview is given in Table 3. ^b Equations for $\frac{\partial q^F}{\partial W}$, $\frac{\partial e}{\partial W}$ and $\frac{\partial E}{\partial W}$ are given by (32), (33) and (34), respectively. β^* is defined in Definition 2.

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 current level of €15 per tonne.

Table 4 shows the effects of a carbon tax increase in the EU. The spatial leakage rates are positive, unlike most intertemporal rates in Table 3. 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. The spatial leakage rates are also 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. 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, also increasing the absolute value of the leakage rate. Still, industry relocation effects have to be large in order to generate full leakage. Leakage is lower when coal demand is more elastic (as the tax then decreases coal demand more strongly in the EU) and when oil demand is less elastic (this weakens the reaction of oil suppliers).

4 A Cheaper Clean Backstop

In addition to implementing a carbon tax, climate-conscious countries 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 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 technology 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 q^F 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 $D_C^F > 0$. When the clean backstop becomes cheaper in period 2, $\beta^* \gtrless 0$ iff*

$$\zeta^F d_F^F + \zeta^Z d_F^Z \lesseqgtr 0 \quad (13)$$

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 (13). 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 $\psi_F \frac{\partial q^F}{\partial P^c}$. 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.

In order to calibrate Proposition 3, we rewrite the condition for the weak green paradox as

$$\frac{\zeta^F}{\zeta^Z} > \frac{\eta_F^Z}{-\eta_F^F} \frac{q^Z}{q^F}$$

Table 2 shows that $\zeta^F/\zeta^Z = 0.65$ and $q^Z/q^F = 0.91$. Intertemporal leakage is positive for $-\eta_F^Z/\eta_F^F < 0.72$. The elasticity ratio is considerably smaller than 0.72 for all studies in Tables 3 and 4, so the development of clean technologies is likely to bring about the weak green paradox.

Proposition 4 (strong green paradox). *When the clean backstop becomes cheaper in period 2,*

- (i) $\beta^* \leq 1$
- (ii) $\beta^* > \beta$ iff

$$\frac{D_C^F}{-d_F^F - (1+r)D_F^F} [(1-\beta)\zeta^F d_F^F + \zeta^Z (d_F^Z + \beta(1+r)D_F^Z)] + \beta\zeta^Z D_C^Z < 0 \quad (14)$$

- (iii) β^* increases in D_C^F and $|d_F^F|$
- (iv) β^* decreases in d_F^Z , D_F^Z , D_C^Z and $|D_F^F|$

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 $(1-\beta)\zeta^F d_F^F$ exceeds the benefits of reduced dirty backstop consumption in both periods. This is more likely when D_C^F is high, as a decrease in P^C then poses a larger threat to exhaustible resource demand in period 2. An increase in $|d_F^F|$ increases leakage by making it more attractive to shift exhaustible resource supply to period 1 (the reverse applies to $|D_F^F|$). Lastly, β^* decreases in d_F^Z , D_F^Z and D_C^Z , as high values of these parameters induce more substitution away from the dirty backstop. We calibrate Proposition 4 at the end of this section.

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. The energy market can be divided into a submarket for electricity and one for transport. Natural gas (F), coal (Z) and wind and solar energy (C) more readily lend themselves for electricity generation, whereas oil (F), tar sands (Z) and biofuels (C) are primarily used in the transportation sector. Two energy types that are employed in the same submarket are close substitutes.

4.1 Developing Alternative Fuels

Suppose that the exhaustible resource and the clean backstop are perfect substitutes. We may think of the clean backstop as ethanol from sugarcane or corn, competing with petroleum-based fuel. 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 $P^C > \Psi$, a decrease in P^C has no effect*
- (ii) *if $P^C = \Psi$, then $\beta^* > \beta$ if*

$$(1 - \beta) \zeta^F d_F^F + \zeta^Z (d_F^Z + \beta (1 + r) D_F^Z) < 0 \quad (15)$$

When P^C is sufficiently low, it fully determines exhaustible resource prices in both periods and the last term in (14) 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 the emission damages may go down as a result of lower clean backstop prices.

4.2 Renewable Energy for Electricity

An empirically relevant case is perfect substitutability between the clean and dirty backstop. 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, 2010). Investing in hydro-, wind- and solar power may reduce coal use without causing a strong an increase in short-term oil extraction.

Corollary 2. *With perfect substitution between the clean and the dirty backstop*

- (i) *if $P^C > P^Z$, a decrease in P^C has no effect*
- (ii) *if $P^C = P^Z$, the strong green paradox does not occur*
- (iii) *if $p^C > p^Z$, $P^C < P^Z$, then $\beta^* > \beta$ iff*

$$(1 - \beta) \zeta^F d_F^F + \zeta^Z d_F^Z < 0 \quad (16)$$

- (iv) *if $p^C < p^Z$ and $P^C < P^Z$, then $\beta^* = 1$*

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. When the period 2 prices of the clean and the dirty backstop are equal, a reduction in the price of the clean backstop does not cause a strong green paradox as it eliminates all demand for the dirty backstop. 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. When the clean backstop is cheaper than the dirty backstop in both periods, the latter is never used. The model then reduces to a classic green paradox model and both the weak and the strong green paradox occur.

Keeping global warming within acceptable limits largely depends on replacing coal as the largest source of electricity with clean alternatives. Our results suggest that from an environmental point of view, investing in alternatives is primarily attractive while they are more expensive than coal. Investment then directly reduces future coal use, without bringing forward emissions from oil. When cost parity is reached in the future, additional investment does not cause a further reduction in future coal use, and only reduces present coal use indirectly. The green paradox then becomes more likely. The above analysis is complementary to Fischer and Salant (2010) and van der Ploeg and Withagen (2011). 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 the high-cost oil to remain in the ground and thus improve the environment. Beyond that point, further investments will bring forward extraction of the low-cost oil and cause a 'renewed' green paradox. Van der Ploeg and Withagen (2011) assume perfect substitutability between a clean and a dirty backstop and note that subsidizing renewables to the cost of the dirty backstop always reduces emissions.

4.3 Conventional and Unconventional Oil

In this subsection, we look at the effects of cheaper renewable electricity on the use of unconventional oil.

Corollary 3. *With perfect substitution between the exhaustible resource and the dirty backstop*

- (i) if $\psi < p^Z$ and $\Psi < P^Z$, $\beta^* = 1$
- (ii) if $\psi < p^Z$ and $\Psi = P^Z$, $\beta^* = 0$

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. When renewable energy sources become economically viable as transportation fuel, they first eat into demand for unconventional oil without causing a green paradox.

4.4 Empirical Calibration

Finally, we calibrate Proposition 4. The interfuel substitution estimates in section 3 do not distinguish between carbon- and non-carbon energy inputs. We thus follow the CGE literature on carbon leakage and assume a nested CES demand structure with two nests: electricity E and non-electricity N . Oil (F) is the only energy source in the non-electricity nest; coal (Z) and solar energy (C) are the only inputs for electricity generation. We have set the elasticity of substitution between N and E at 1.5 and between Z and C at 5. Appendix I contains a full description of the model and parameter values.

Figure 4.4 depicts the period 1 oil price. The oil price is decreasing in P^C . The effect of P^C on p^F is modest for small cost reductions, owing to the limited substitutability between oil and electricity. When the clean backstop becomes very cheap, it emerges as an attractive substitute for oil and the oil price reacts more strongly.

The pattern of intertemporal carbon leakage is similar (Figure 4.4). When the reduction in P^C is not too large, it mainly induces substitution from coal- to solar-based electricity. The change in oil extraction is very small, giving rise to very modest intertemporal leakage rates. The leakage rate goes up only when the clean backstop becomes very cheap in the future: coal is then hardly used anymore, and subsequent cost reductions mostly serve to bring forward oil extraction. This finding 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.

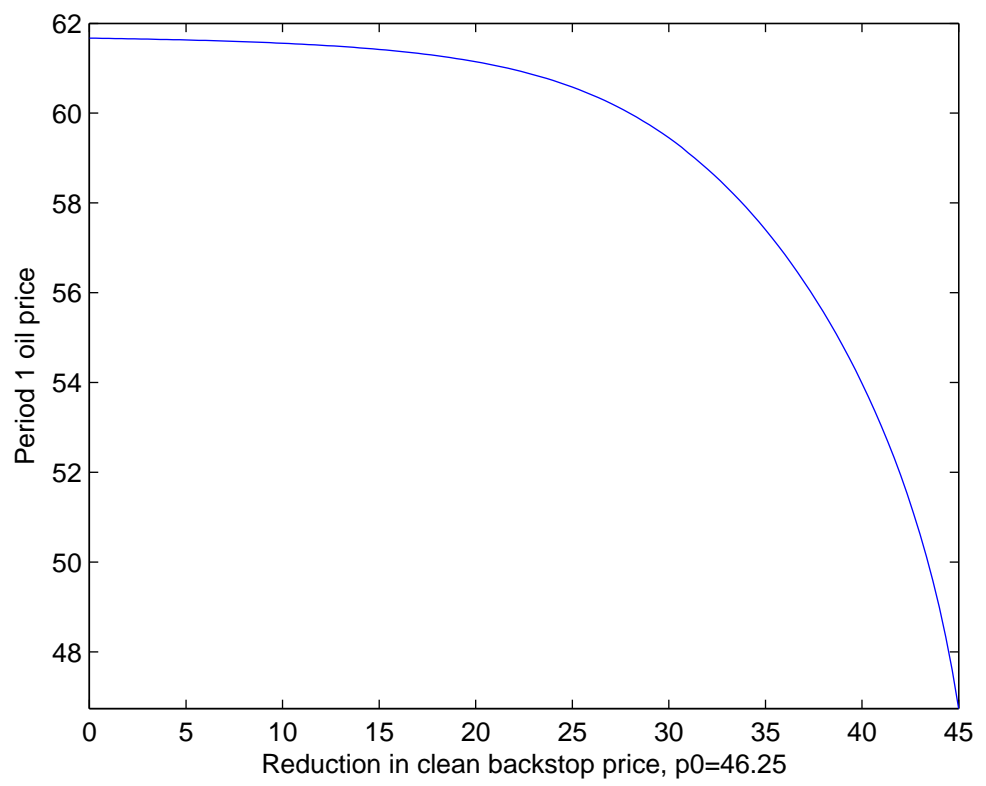


Figure 1: Period 1 oil price as a function of period 2 cost reduction for the clean backstop

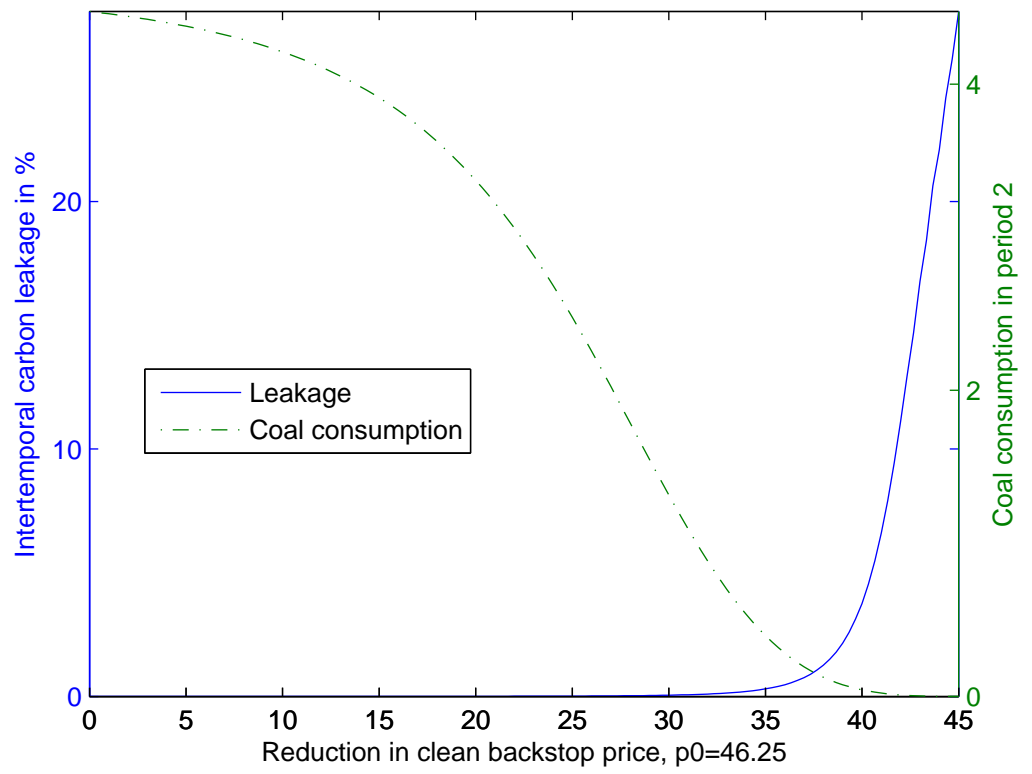


Figure 2: Intertemporal carbon leakage and period 2 coal consumption as a result of a cheaper clean backstop in period 2

5 Conclusion

We employ a general model to analyze carbon leakage in the presence of an abundant dirty backstop such as coal or unconventional oil. Our framework can be used to study both intertemporal and spatial carbon leakage. 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 negligible compared to future emission reductions. Interestingly, we find that a future carbon tax reduces present emissions. When the EU unilaterally increases its carbon price, we find carbon leakage rates of 19-39%. From these results, it appears that spatial leakage is a stronger concern than intertemporal leakage.

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 Cross-Effects

In this section, we show that cross-effects are symmetric if we can define a demand function for a composite good that is produced from the three energy types according to a homogeneous function of degree k . Let

$$\vec{q} = \begin{bmatrix} q^F \\ q^Z \\ q^C \end{bmatrix}, \quad \vec{p} = \begin{bmatrix} p^F \\ p^Z \\ p^C \end{bmatrix}$$

The production function for the composite good can be written as $X = Y^k = (f(\vec{q}))^k$, where $f(\vec{q})$ is homogeneous of degree one. Define the conditional expenditure function $e(Y, \vec{p})$ as the minimum cost to produce Y given prices \vec{p} . Conditional demand for energy types exhibits symmetric cross-effects:

$$\frac{\partial e}{\partial p^i} = q^i \equiv \tilde{d}^i(Y, \vec{p})$$

$$\frac{\partial e^2}{\partial p^i \partial p^j} = \frac{\partial \tilde{d}^i}{\partial p_j} = \frac{\partial \tilde{d}^j}{\partial p_i}$$

By first-degree homogeneity of $f(\vec{q})$, we have

$$\frac{\partial \tilde{d}^i}{\partial Y} = \tilde{d}^i(1, \vec{p})$$

Let $\pi(\vec{p})$ be the marginal cost of Y . Since $f(\vec{q})$ is homogeneous of degree one

$$\frac{\partial \pi}{\partial p^i} = \tilde{d}^i(1, \vec{p})$$

Lastly, define demand for Y as $d^Y(\pi(\vec{p}))$ and the unconditional demand for energy types $d^i(\vec{p}) = \tilde{d}^i(d^Y(\pi(\vec{p})), \vec{p})$. Then

$$\frac{\partial d^i}{\partial p^j} = \frac{\partial \tilde{d}^i}{\partial Y} \frac{\partial d^Y}{\partial \pi} \frac{\partial \pi}{\partial p^j} + \frac{\partial \tilde{d}^i}{\partial p^j} = \tilde{d}^i(1, \vec{p}) \frac{\partial d^Y}{\partial \pi} \tilde{d}^j(1, \vec{p}) + \frac{\partial \tilde{d}^i}{\partial p^j} \quad (17)$$

$$\frac{\partial d^j}{\partial p^i} = \frac{\partial \tilde{d}^j}{\partial Y} \frac{\partial d^Y}{\partial \pi} \frac{\partial \pi}{\partial p^i} + \frac{\partial \tilde{d}^j}{\partial p^i} = \tilde{d}^j(1, \vec{p}) \frac{\partial d^Y}{\partial \pi} \tilde{d}^i(1, \vec{p}) + \frac{\partial \tilde{d}^j}{\partial p^i} \quad (18)$$

Since the conditional cross-effects are equal, the unconditional cross-effects are equal for good Y . Denote demand functions for good X with bold letters. We have

$$\frac{\partial \mathbf{d}^i}{\partial p^j} = kY^{k-1} \frac{\partial d^i}{\partial p^j}, \quad \frac{\partial \mathbf{d}^j}{\partial p^i} = kY^{k-1} \frac{\partial d^j}{\partial p^i}$$

so from (17) and (18) it follows that $\frac{\partial \mathbf{d}^i}{\partial p^j} = \frac{\partial \mathbf{d}^j}{\partial p^i}$.

B Proof of Proposition 1

The weak green paradox occurs when (7) is positive. Using (8), the condition becomes

$$\frac{\partial e}{\partial p^F} \left(\frac{\partial D^F}{\partial W} \right)_{P^F - \zeta^F W} > 0 \quad (19)$$

The result follows by substituting (9) and (10).

C 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 2. $\frac{\partial P^F}{\partial W} < \frac{\partial P^Z}{\partial W}$

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 $P^F - W\zeta^F$ as $\frac{\partial P^Z}{\partial W} = \zeta^Z$ and $\zeta^F < \zeta^Z$. By the Hotelling condition (6), p^F increases and demand for the exhaustible resource goes down in period 1. This violates the requirement that the stock is fully exhausted. \square

Lemma 2 and (A2) entail $\frac{\partial D^Z}{\partial W} < 0$, establishing (i). If the tax speeds up extraction, i.e. if (9) is negative, we also have $\frac{\partial d^Z}{\partial W} < 0$. Then (ii) and (iii) are satisfied. We proceed to prove (ii) and (iii) when (9) is positive. The effect of W on E is

$$\begin{aligned} \frac{\partial E}{\partial W} &= \zeta^Z \frac{\partial D^Z}{\partial W} + \zeta^F \frac{\partial Q^F}{\partial W} \\ &= \zeta^Z \left(D_Z^Z \zeta^Z + D_F^Z \left(\Psi_F \frac{\partial Q^F}{\partial W} + \Psi_Z \zeta^Z \right) \right) + \zeta^F \frac{\partial Q^F}{\partial W} \\ &= \underbrace{(\zeta^Z)^2 D_Z^Z}_I + \underbrace{\zeta^Z \frac{D_F^Z}{D_F^F} \frac{\partial Q^F}{\partial W}}_{II} + \underbrace{(\zeta^Z)^2 D_F^Z \frac{D_Z^F}{-D_F^F}}_{III} + \underbrace{\zeta^F \frac{\partial Q^F}{\partial W}}_{IV} \end{aligned} \quad (20)$$

By the inverse function theorem

$$\psi_F = 1/d_F^F, \quad \psi_j = -d_j^F/d_F^F, \quad j \in \{Z, C\} \quad (21)$$

The last equality in (20) follows from (21). In (20), I and II are negative and III and IV positive. By (A2), $I + III < 0$. When (9) is positive, $II + IV < 0$.

This completes the proof of (ii). To prove (iii), we show that the sum of period 1 and 2 dirty backstop demand goes down.

$$\begin{aligned}
\frac{\partial [d^Z + D^Z]}{\partial W} &= d_F^Z \psi_F \frac{\partial q^F}{\partial W} + D_F^Z \left(\Psi_F \frac{\partial Q^F}{\partial W} + \Psi_Z \zeta^Z \right) + \zeta^Z D_Z^Z \\
&= d_F^Z \psi_F \frac{\partial q^F}{\partial W} + D_F^Z \left((1+r) \psi_F \frac{\partial q^F}{\partial W} + \zeta^F \right) + \zeta^Z D_Z^Z \\
&= \psi_F \frac{\partial q^F}{\partial W} (d_F^Z + (1+r) D_F^Z) + \zeta^F D_F^Z + \zeta^Z D_Z^Z \\
&= \underbrace{-\frac{d_F^Z + (1+r) D_F^Z}{d_F^F + (1+r) D_F^F}}_{<1} (\zeta^F D_F^F + \zeta^Z D_Z^F) + \zeta^F D_F^Z + \zeta^Z D_Z^Z \\
&< \zeta^F (D_F^F + D_F^Z) + \zeta^Z (D_Z^F + D_Z^Z) < 0
\end{aligned} \tag{22}$$

Totally differentiate the Hotelling condition (6) with respect to W

$$\psi_F \frac{\partial q^F}{\partial W} = \frac{1}{1+r} \left(\Psi_F \frac{\partial Q^F}{\partial W} + \Psi_Z \zeta^Z - \zeta^F \right)$$

Use $\frac{\partial q^F}{\partial W} = -\frac{\partial Q^F}{\partial W}$ and (21) to find

$$\Psi_F \frac{\partial Q^F}{\partial W} = (1+r) \psi_F \frac{\partial q^F}{\partial W} + \zeta^F + \zeta^Z \frac{D_Z^F}{D_F^F} \tag{23}$$

$$\frac{\partial q^F}{\partial W} = -\frac{\zeta^F D_F^F + \zeta^Z D_Z^F}{1 + (1+r) \frac{D_F^F}{d_F^F}} \tag{24}$$

The second equality in (22) follows by substituting (23); the fourth by substituting (21) and (24). The fraction in (22) is smaller than one by (A2). The first inequality holds when (9) is positive; the second by (A2). Therefore, (22) is negative when (9) is positive, completing the proof of (iii). Lastly, calculate the effect on emission damages

$$\begin{aligned}
\frac{\partial \Sigma}{\partial W} &= (1-\beta) \zeta^F \frac{\partial q^F}{\partial W} + \zeta^Z \left(d_F^Z \psi_F \frac{\partial q^F}{\partial W} + \beta \left(D_F^Z \left(\Psi_F \frac{\partial Q^F}{\partial W} + \Psi_Z \zeta^Z \right) + \zeta^Z D_Z^Z \right) \right) \\
&= (1-\beta) \zeta^F \frac{\partial q^F}{\partial W} + \zeta^Z \left(\psi_F \frac{\partial q^F}{\partial W} (d_F^Z + \beta(1+r) D_F^Z) + \beta (\zeta^F D_F^Z + \zeta^Z D_Z^Z) \right) \\
&= \frac{\partial q^F}{\partial W} \left[(1-\beta) \zeta^F + \zeta^Z \frac{1}{d_F^F} (d_F^Z + \beta(1+r) D_F^Z) \right] + \beta \zeta^Z (\zeta^F D_F^Z + \zeta^Z D_Z^Z) \\
&= -\frac{\zeta^F D_F^F + \zeta^Z D_Z^F}{d_F^F + (1+r) D_F^F} \left[(1-\beta) \zeta^F d_F^F + \zeta^Z (d_F^Z + \beta(1+r) D_F^Z) \right] + \\
&\quad \beta \zeta^Z (\zeta^F D_F^Z + \zeta^Z D_Z^Z)
\end{aligned} \tag{25}$$

The second equality in (25) follows from (23).

D Proof of Proposition 3

The change in first-period emissions is

$$\frac{\partial e}{\partial PC} = \zeta^F d_F^F \psi_F \frac{\partial q^F}{\partial PC} + \zeta^Z d_F^Z \psi_F \frac{\partial q^F}{\partial PC} = \psi_F \frac{\partial q^F}{\partial PC} (\zeta^F d_F^F + \zeta^Z d_F^Z) \quad (26)$$

Analogously to C, we can back out $\frac{\partial q^F}{\partial PC}$. Totally differentiate (3) with respect to PC

$$\psi_F \frac{\partial q^F}{\partial PC} = \frac{1}{1+r} \left(\Psi_F \frac{\partial Q^F}{\partial PC} + \Psi_C \right) \quad (27)$$

Using $\frac{\partial q^F}{\partial W} = -\frac{\partial Q^F}{\partial W}$ and (21), we obtain

$$\frac{\partial q^F}{\partial PC} = -\frac{D_C^F}{1 + (1+r) \frac{D_F^F}{d_F^F}} \quad (28)$$

The weak green paradox occurs when $\frac{\partial e}{\partial PC} < 0$. As $\psi_F < 0$ and $\frac{\partial q^F}{\partial PC} < 0$, $\frac{\partial e}{\partial PC} < 0$ iff $\zeta^F d_F^F + \zeta^Z d_F^Z < 0$.

E Proof of Proposition 4

We established that $\psi_F \frac{\partial q^F}{\partial PC} < 0$, so by (3), exhaustible resource prices in both periods are increasing in PC . Then d^Z , D^Z , $e + E$ and E are increasing in PC . It follows that $\beta^* = -\frac{\partial e}{\partial PC} / \frac{\partial E}{\partial PC} \leq 1$, proving (i). The change in emission damages is

$$\begin{aligned} \frac{\partial \Sigma}{\partial PC} &= (1-\beta) \zeta^F \frac{\partial q^F}{\partial PC} + \zeta^Z \left(d_F^Z \psi_F \frac{\partial q^F}{\partial PC} + \beta \left(D_F^Z \left(\Psi_F \frac{\partial Q^F}{\partial PC} + \Psi_C \right) + D_C^Z \right) \right) \\ &= (1-\beta) \zeta^F \frac{\partial q^F}{\partial PC} + \zeta^Z \left(d_F^Z \psi_F \frac{\partial q^F}{\partial PC} + \beta \left(D_F^Z \left((1+r) \psi_F \frac{\partial q^F}{\partial PC} \right) + D_C^Z \right) \right) \\ &= \frac{\partial q^F}{\partial PC} \left[(1-\beta) \zeta^F + \zeta^Z \frac{1}{d_F^F} \left(d_F^Z + \beta (1+r) D_F^Z \right) \right] + \beta \zeta^Z D_C^Z \\ &= \frac{D_C^F}{-d_F^F - (1+r) D_F^F} \left[(1-\beta) \zeta^F d_F^F + \zeta^Z \left(d_F^Z + \beta (1+r) D_F^Z \right) \right] + \beta \zeta^Z D_C^Z \end{aligned} \quad (29)$$

The second equality in (29) follows from (27); the last from (28). The leakage rate is

$$\begin{aligned}
\beta^* &= - \frac{\psi_F \frac{\partial q^F}{\partial P^C} (\zeta^F d_F^F + \zeta^Z d_F^Z)}{\zeta^F \frac{\partial Q^F}{\partial P^C} + \zeta^Z \left(D_F^Z \left(\Psi_F \frac{\partial Q^F}{\partial P^C} + \Psi_C \right) + D_C^Z \right)} \\
&= \frac{D_C^F}{d_F^F + (1+r) D_F^F} (\zeta^F d_F^F + \zeta^Z d_F^Z) \\
&= \frac{\zeta^F \frac{d_F^F D_C^F}{d_F^F + (1+r) D_F^F} + \zeta^Z \left(\frac{D_F^Z}{D_F^F} \left(\frac{d_F^F D_C^F}{d_F^F + (1+r) D_F^F} - D_C^F \right) + D_C^Z \right)}{D_C^F (\zeta^F d_F^F + \zeta^Z d_F^Z)} \\
&= \frac{D_C^F (\zeta^F d_F^F + \zeta^Z d_F^Z)}{\zeta^F d_F^F D_C^F + \zeta^Z \left(-D_F^Z (1+r) D_C^F + D_C^Z (d_F^F + (1+r) D_F^F) \right)} \quad (30)
\end{aligned}$$

The second equality follows from (21) and (28). By taking derivatives of (30), we obtain (iii) and (iv).

F 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

$$\begin{aligned}
&\lim_{(D_F^F, D_F^C) \rightarrow (-\infty, +\infty)} \left(\Psi_F \frac{\partial Q^F}{\partial P^C} + \Psi_C \right) = \\
&\lim_{(D_F^F, D_F^C) \rightarrow (-\infty, +\infty)} \left(-\frac{1}{D_F^F} \frac{D_C^F}{1 + (1+r) \frac{D_F^F}{d_F^F}} - \frac{D_C^F}{D_F^F} \right) = 1 \quad (31)
\end{aligned}$$

The D_C^Z term in (29) is superfluous because of (31) and since dirty backstop users are indifferent between substituting to the exhaustible resource and to the clean backstop. $\frac{\partial \Sigma}{\partial P^C}$ then has the same sign as the term in square brackets in (29).

G Proof of Corollary 2

We omit the proof of (i). For (ii), D^Z is infinitely elastic with respect to P^C at $P^C = P^Z$. From (30), we see that $\lim_{D_C^Z \rightarrow \infty} \beta^* = 0$. For (iii), $D_C^Z = D_F^Z = 0$ when $P^C < P^Z$. It then follows that $\frac{\partial \Sigma}{\partial P^C}$ has the same sign as $(1-\beta) \zeta^F d_F^F + \zeta^Z d_F^Z$. For (iv), $d_F^Z = D_C^Z = D_F^Z = 0$ when $p^C < p^Z$ and $P^C < p^Z$. We then have $\frac{\partial \Sigma}{\partial P^C} < 0$.

H Proof of Corollary 3

The proof of (i) is analogous to the proof of (iv) in Corollary 2. For (ii), we see in (30) that $\lim_{(D_F^F, D_F^Z) \rightarrow (-\infty, +\infty)} \beta^* = 0$.

I Calibrations

In Table 3, the expressions for $\frac{\partial q^F}{\partial W}$, $\frac{\partial e}{\partial W}$ and $\frac{\partial E}{\partial W}$ are given by (24), (19) and (20) respectively¹⁵. Substituting elasticities for the partial derivatives of the demand function and using the assumption that the elasticities are equal across periods and regions, we get

$$\frac{\partial q^F}{\partial W} = \frac{\zeta^F \eta_F^F \frac{Q^F}{P^F} + \zeta^Z \eta_Z^F \frac{Q^F}{P^Z}}{-1 - (1+r) \frac{Q^F}{P^F} \frac{p^F}{q^F}} \quad (32)$$

$$\frac{\partial e}{\partial W} = \frac{\partial q^F}{\partial W} \left(\zeta^F + \zeta^Z \frac{\eta_Z^Z}{\eta_F^F} \frac{q^Z}{q^F} \right) \quad (33)$$

$$\frac{\partial E}{\partial W} = (\zeta^Z)^2 \eta_Z^Z \frac{Q^Z}{P^Z} + \zeta^Z \eta_Z^F \frac{Q^Z}{P^F} \left(\frac{-\partial q^F}{\partial W} \frac{\eta_F^F Q^F}{P^F} + \zeta^Z \frac{\eta_Z^F P^F}{-\eta_F^F P^Z} \right) - \zeta^F \frac{\partial q^F}{\partial W} \quad (34)$$

Table 1 lists the definitions and sources of the variables used for the calibrations in Tables 3 and 4. In the calibrations for spatial leakage, P^F and P^Z are inclusive of a €15 per tonne carbon tax. For each study in Tables 3 and 4, we list the leakage estimates using per-country elasticity estimates in Tables 2 and 3.

For the calibrations in section 4.4, we employ the following model. Let X denote composite 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

¹⁵The derivation of these equations does not depend on assumption (A3).

Table 1: Data definitions and sources for calibrations in section 3

Variable	Definition	Source
Intertemporal Model		
q^F, q^Z	Consumption in 2009, mln boe ^a	International Energy Statistics, EIA
Q^F, Q^Z	Demand in 2035 in Current Policies scenario, mln boe ^b	World Energy Outlook 2010 p.103, p.201, IEA
p^F	Brent crude spot price in 2009, \$ per barrel	BP Statistical Review of World Energy 2010, p. 16
P^F	Oil price in 2035 in Current Policies scenario, \$ per barrel	World Energy Outlook 2010, p.101, IEA
p^Z, P^Z	Average EU steam coal import costs, \$ per boe ^b	Coal Information 2010, p. III.44, IEA
Spatial Model		
q^F, q^Z	Consumption in 2009 for ROW, mln boe ^a	International Energy Statistics, EIA
Q^F, Q^Z	Consumption in 2009 for EU27, mln boe ^a	International Energy Statistics, EIA
P^F, P^Z	$p^i + \text{€} 15^c \zeta^i, i \in \{F, Z\}$	
ζ^F, ζ^Z	$\frac{\text{CO2 emissions from consumption by type in 2009, t}}{\text{Consumption by type in 2009, boe}}$	International Energy Statistics, EIA

^a Converted from quad in source data ^b Converted from toe or tce in source data ^c Exchange rate: \$1 = €0.719

Table 2: Intertemporal leakage estimates per study per country

Country	η_F^F	η_Z^F	η_F^Z	η_Z^Z	$\frac{\partial q^F}{\partial W}$	$\frac{\partial e}{\partial W}$	$\frac{\partial E}{\partial W}$	β^*
Pindyck (1979)								
Canada	-0.81	0.25	0.28	-0.14	-73.45	-15.40	-13.32	-1.16
France	-0.20	-0.03	-0.03	-0.16	23.65	10.22	-89.79	0.11
Italy	-0.29	0.05	0.04	-0.13	-6.66	-2.02	-61.39	-0.03
Japan	-0.20	0.01	0.01	-0.12	5.53	1.89	-63.10	0.03
Netherlands	-0.11	0.00	0.00	-0.07	3.22	1.18	-37.01	0.03
Norway	-0.34	0.12	0.12	-0.08	-38.80	-8.01	-11.43	-0.70
Sweden	-0.27	0.05	0.04	-0.12	-9.38	-2.80	-54.97	-0.05
UK	-0.22	-0.02	-0.01	-0.15	17.32	6.67	-83.11	0.08
USA	-1.10	0.35	0.11	-0.08	-103.66	-33.16	9.52	3.49
Germany	0.03	-0.09	-0.05	-0.12	38.49	-14.75	-120.31	-0.12
Uri (1982)								
UK	-0.57	0.05	0.15	-0.50	2.54	0.63	-249.35	0.00
Hall (1986)								
France	-0.70	0.09	0.24	-0.14	-7.82	-1.65	-54.32	-0.03
Magnus and Woodland (1987)								
Netherlands	-0.33	0.04	0.09	-0.24	-1.20	-0.29	-117.43	-0.00
Renou-Maissant (1999)								
US	-0.03	-0.03	-0.01	-0.06	15.87	8.16	-33.55	0.24
Canada	-0.50	0.15	0.14	-0.27	-42.34	-10.13	-107.54	-0.09
Japan	-0.34	0.12	0.13	-0.17	-36.98	-7.14	-57.34	-0.12
UK	-0.49	0.06	0.17	-0.31	-4.75	-0.99	-146.85	-0.01
France	-0.37	0.05	0.18	-0.26	-4.80	-0.70	-120.25	-0.01
Italy	-0.41	0.05	0.09	-0.15	-1.16	-0.31	-71.42	-0.00
Germany	-0.42	0.04	0.13	-0.19	2.92	0.66	-92.02	0.01

Table 3: Spatial leakage estimates per study per country

Country	η_F^F	η_Z^F	η_F^Z	η_Z^Z	$\frac{\partial q^F}{\partial W}$	$\frac{\partial e}{\partial W}$	$\frac{\partial E}{\partial W}$	β^*
Pindyck (1979)								
Canada	-0.81	0.25	0.28	-0.14	-9.63	-1.85	1.45	1.28
France	-0.20	-0.03	-0.03	-0.16	8.14	3.58	-7.27	0.49
Italy	-0.29	0.05	0.04	-0.13	1.49	0.44	-3.74	0.12
Japan	-0.20	0.01	0.01	-0.12	3.58	1.22	-4.40	0.28
Netherlands	-0.11	0.00	0.00	-0.07	2.01	0.73	-2.57	0.29
Norway	-0.34	0.12	0.12	-0.08	-6.05	-1.14	0.82	1.39
Sweden	-0.27	0.05	0.04	-0.12	0.59	0.17	-3.15	0.05
UK	-0.22	-0.02	-0.01	-0.15	6.76	2.62	-6.43	0.41
USA	-1.10	0.35	0.11	-0.08	-14.06	-4.43	3.67	1.21
Germany	0.03	-0.09	-0.05	-0.12	9.36	-4.38	-7.38	-0.59
Uri (1982)								
UK	-0.57	0.05	0.15	-0.50	6.87	1.60	-14.86	0.11
Hall (1986)								
France	-0.70	0.09	0.24	-0.14	5.68	1.10	-4.54	0.24
Magnus and Woodland (1987)								
Netherlands	-0.33	0.04	0.09	-0.24	3.30	0.76	-7.04	0.11
Renou-Maissant (1999)								
US	-0.03	-0.03	-0.01	-0.06	4.32	2.30	-3.15	0.73
Canada	-0.50	0.15	0.14	-0.27	-5.19	-1.17	-4.38	-0.27
Japan	-0.34	0.12	0.13	-0.17	-5.59	-0.97	-1.65	-0.59
UK	-0.49	0.06	0.17	-0.31	4.16	0.80	-8.79	0.09
France	-0.37	0.05	0.18	-0.26	2.83	0.35	-6.94	0.05
Italy	-0.41	0.05	0.09	-0.15	4.19	1.07	-5.01	0.21
Germany	-0.42	0.04	0.13	-0.19	5.33	1.12	-6.29	0.18

Table 4: Parametrization of calibration in section 4.4

Parameter	Value
σ_X	1.5
σ_E	5
α_N^X	0.5
α_F^N	1
α_Z^E	0.5
α_C^E	0.5
r	0.6734
S	1
y	86.32
Y	144.43
p^C	46.25

^a p^Z , P^Z , ζ^F and ζ^Z are the same as in Table 2

$$d^i = \left(\frac{y}{p^X} \right) \sum_{k \in \{N, E\}} \alpha_k^X \left(\frac{p^X}{p^k} \right)^{\sigma_X} \alpha_i^k \left(\frac{p^i}{p^k} \right)^{\sigma_k} \quad (35)$$

$$p^X = \left(\sum_{k \in \{N, E\}} \alpha_k^X (p^k)^{\frac{1-\sigma_X}{\sigma_X}} \right)^{\frac{\sigma_X}{1-\sigma_X}}, \quad p^k = \left(\sum_{i \in \{F, Z, C\}} \alpha_i^k (p^i)^{\frac{1-\sigma_k}{\sigma_k}} \right)^{\frac{\sigma_k}{1-\sigma_k}} \quad (36)$$

where $\sum_{k \in \{N, E\}} \alpha_k^X = \sum_{i \in \{F, Z, C\}} \alpha_i^k = 1$. Demand in the second period is described by a similar system. Exhaustible resource prices p^i and P^i are endogenously determined by (3) and $d^F + d^Z = S$. The parameter values are listed in Table 4. As (36) 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 $p^F = 61.67$ when $P^C = p^C$. The interest rate equals 2% per annum compounded over 26 years.

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