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Imperfect Environmental Policy and Polluting Emissions: The *Green Paradox* and Beyond*

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ABSTRACT

Well-intended policies aimed at reducing greenhouse gas emissions may have unintended undesirable consequences. Recently, a large literature has emerged showing that such a 'green paradox' may occur in response to particular policies. We review this literature and identify four different imperfect policy approaches that may induce a green paradox. We discuss under what conditions a green paradox may occur and highlight avenues for future research.

Keywords: Climate policy; green paradox; nonrenewable resources; scarcity; carbon tax; announcement effects; implementation lag; carbon leakage; backstop technology.

JEL Codes: F18, Q31, Q38, Q41, Q42, Q54, Q58

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> "The countries that have ratified the Kyoto Protocol have pledged to limit global warming by reducing the demand for fossil fuels. But what about supply? If suppliers do not react, demand reductions by a subset of countries are ineffective. They simply depress the world price of carbon and induce the environmental sinners to consume what the Kyoto countries have economized on. Even worse, if suppliers feel threatened by a gradual greening of economic policies in the Kyoto countries that would damage their future prices; they will extract their stocks more rapidly, thus accelerating global warming." Sinn (2008, p. 360)

1 Introduction

Global climatic change is probably the most serious environmental threat facing mankind, at the same time it also represents one of the hardest to tackle for governments all over the world. Indeed, tackling anthropogenic climate change represents the 'mother of all policy challenges' given climate's nature as a global public good, the lack of enforcement possibilities for international environmental agreements, the long and uncertain time lags between emissions and the emergence of damages, the lack of credible commitment on the part of policy makers, and the fact that green house gas (GHG) emissions are linked to essential energy inputs like fossil fuels.

From an economist's vantage point, the emission of GHGs entail a serious global negative externality, and in the absence of regulation excessive amounts of GHG are released in the atmosphere, relative to the social optimum. Moreover, emissions tend to be excessively concentrated towards the present. Thus, the full internalization of such externalities require a flattening of the extraction path of fossil fuel, and, whenever possible, an increase in the amount of hydrocarbons left untapped in the earth's crust.

Despite the fact that the optimal regulation of carbon emissions has been the object of numerous studies (e.g., Ulph and Ulph, 1994; Sinclair, 1994; Farzin and Tahvonen, 1996; Hoel and Kverndokk, 1996; Tahvonen, 1997; Van der Ploeg and Withagen, 2012a) and is well understood, the difficulties with implementing such optimal policies in reality have led economists to also study imperfect policy designs, and their possible implications for both environmental and welfare outcomes. This literature has emphasized that imperfect policies to combat global climatic change, might have unintended negative consequences. Indeed, as the quote from Sinn's (2008) thought provoking article nicely illustrates, emissions of carbon dioxide from fossil fuels — the largest source of GHG emissions — may not go down at all in response to demand reduction policies. More than that, Sinn's claim is that it is possible for global emissions to *increase* in reaction to green policies. Sinn (2008) refers to this possibility as a 'Green Paradox'.

Sinn's (2008) contribution spawned a rapidly growing literature on the effects of imperfect carbon emission abatement policies on global emissions. Our aim in this paper is to review this literature and to provide the reader with an insight into the underlying economic drivers. Our interpretation of the term 'Green Paradox' is somewhat broader than sometimes found in the literature, in that we — following Gerlagh (2011) — distinguish between a weak form of the green paradox and a strong form. A weak paradox arises when the introduction of imperfect climate policy leads to an increase in short-term emissions, relative to the unregulated ('laissez-faire') outcome. The strong version of paradox, instead, materializes when the net present value of the stream of future damages from climate change increases, relative to the laissez-faire level, as a consequence of an imperfect policy.

We classify contributions in this literature into four categories, depending on the type of policy imperfection they investigate. Table 1 presents an overview of the papers included in our survey, arranged according to the type of imperfect policy they study. As is clear even from a cursory look at the table, several papers contain multiple models and deal with different policy imperfections.

The first of our categories collects papers that look at what Sinn (2008) calls the ''gradual greening'' of climate policy, i.e., carbon taxes that rise over time, when owners of deposits of nonrenewable resources are forward-looking. As effectively stated by Sinclair (1992), in the context of carbon pricing, ''High does nothing and rising is worse''. In Section 2, we build on this insight and present a simple model of nonrenewable resource use. We discuss under what conditions a carbon tax may induce an increase in the early stages of extraction, and thus lead to a green paradox.

The second, closely related category, refers to policies aimed at reducing demand for fossil fuels via subsidies to alternative energy sources, and support for innovation. As (optimal) price paths for carbon dioxide emissions are often not politically achievable, policy makers often use the more palatable instrument of subsidies to clean energy technologies. When resource owners realize that a cheap alternative technology becomes available in the

Table 1. A schematic overview of the papers covered in this review.

	Model type	Forward looking	Alternative energy	Policy	Green paradox
Carbon price paths					
Hoel (2012)	Hotelling	Yes	No	Carbon tax	No/Weak
Hoel (2012)	Heal, 2-period	Yes	No	Carbon tax	No/Weak
Hoel (2011a)	Heal, 2-period	Yes	Backstop	Carbon tax	No/Weak
Support alternative energy					
Gerlagh (2011)	Hotelling	Yes	Backstop	Lower cost backstop	Strong
Van der Ploeg and Withagen (2012b)	Hotelling	Yes	Backstop	Lower cost backstop	Strong
Hoel (2011b)	Hotelling	Yes	Backstop	Lower cost backstop	Weak/Strong
Strand (2007)	Hotelling	Yes	Backstop	Possible backstop; short/long horizon	No/Weak
Gerlagh (2011)	Hotelling	Yes	Upward-sloping supply of backstop		No
Grafton *et al.* (2010)	Hotelling	Yes	Upward-sloping supply of backstop		No/Weak
Hoel and Jensen (2010)	Hotelling	Yes	Upward-sloping supply of backstop, CCS		Weak
Hoel and Jensen (2010)	Heal	Yes	Upward-sloping supply of backstop, CCS		Weak
Gerlagh (2011)	Heal	Yes	Backstop		Weak

(*Continued*)

Table 1. (*Continued*)

	Model type	Forward looking	Alternative energy	Policy	Green paradox
Van der Ploeg and Withagen (2012b)	Heal	Yes	Backstop	Carbon tax possible/not possible	Weak
Hoel (2011a)	Heal, 2-period	Yes	backstop		No/Weak
Announced policy					
Di Maria *et al.* (2012b)	Hotelling	Yes	No	Announced cap	Weak
Eichner and Pethig (2011)	Hotelling, 2-period, 3-country	Yes	No	Announced cap	No/Weak
Smulders *et al.* (2010)	CRTS KLE prod.	Yes	NA	Announced carbon tax	No/Weak
Unilateral policy					
Marginal damages channel					
Hoel (1991)	2-Country game	Static	NA	Endogenous domestic abatement	No
Hoel (1991)	2-Country game	Static	NA	Abatement	Weak
Energy market channel					
Burniaux and Oliveira Martins (2012)	Static AGE	No	Yes	Unilateral carbon tax	No
Harstad (2010)	Static, N-country	Static	No	Deposits purchase	No
Hoel (2011b)	Hotelling	Yes	Backstop	Unilateral increase in subsidy to backstop	Weak/Strong

(*Continued*)

Table 1. (*Continued*)

	Model type	Forward looking	Alternative energy	Policy	Green paradox
Eichner and Pethig (2011)	Hotelling, 2-period, 3-country	Yes	No	Tightening of initial cap	No/Weak
Harstad (2010)	Heal, 2-period	Yes	No	Deposit purchase	No
Terms of trade channel					
Copeland and Taylor (2005)	Static, N-country	Static	No	Unilateral emission reductions	No
Fullerton *et al.* (2011)	Static, N-country	Static	No	Unilateral carbon tax	No
Burniaux and Oliveira Martins (2012)	Static AGE	Static	Yes	Unilateral carbon tax	No
Babiker (2005)	Static CGE	Static	Yes	Unilateral carbon tax	Yes
Trade in production factors					
Burniaux and Oliveira Martins (2012)	Static AGE	Static	Yes	Unilateral carbon tax	No
Babiker (2001)	Dynamic AGE	Yes	Yes	Unilateral carbon tax	No
Technology spillovers					
Di Maria and Van der Werf (2012)	Dynamic, analytical	Yes	No	Unilateral cap on emissions	No
Gerlagh and Kuik (2007)	Static AGE	Static	Yes	Unilateral carbon tax	No

future, however, or that renewable energy gets subsidized, they might opt for a more rapid extraction of their resource stocks, leading to front-loading of emissions and a (weak) green paradox. We discuss papers that focus on such types of policies in Section 3.

The third type of policy imperfection we identify emerges when policy makers are not able to impose emission reduction policies immediately and unexpectedly. In other words, environmental policy suffers from long implementation lags. The Kyoto Protocol, for example, was agreed upon in December 1997 and came into force in February 2005, but its first commitment period only started in 2008. Alternatively, policy makers may find it politically expedient to allow firms and consumers time to prepare, in order to reduce adjustment and compliance costs. We discuss the role of such implementation lags in Section 4.

Finally, policies can fall short of being fully optimal also when they fail to be adopted by everyone at the same time; Sinn (2008) refers to ‘‘demand reductions by a subset of countries’’. Indeed, ever since internationally coordinated GHG emission reduction policies have appeared on policy makers' agendas, economists have studied the possible effects of sub-global action. When a subset of countries unilaterally reduce their emissions, countries outside this group face strong incentives to optimally *increase* their emissions in response. This phenomenon is generally known as international carbon leakage. We discuss this literature in Section 5, where we identify five channels through which a unilateral emission reduction induces a change in emissions by other countries. In the context of carbon leakage, a green paradox occurs when the emissions increase by non-abating countries more than offset the emission reduction by abating ones, so that global emissions increase in response to unilateral climate policy.[1]

While the literature we review focuses on the effects of climate policy on greenhouse gas emissions, it should be clear that the imperfect policy approaches we identify here also apply to other environmental problems. Many of the papers included in this review take the use of a generic non-renewable resource as their point of departure, hence for the most part the

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[1] In the context of papers discussing static models, our distinction between a weak and strong version of the green paradox becomes irrelevant, as any increase in emissions leads to an increase in damages. For this reason, when dealing with static models, as most of those in the international carbon leakage literature, we simply refer to the green paradox, without further qualifiers.

policies they study can be interpreted as any policy affecting exhaustible resource use. Indeed, while the climate problem is conceptually one of a stock pollutant, a large number of papers in this review do not explicitly model pollution accumulation, and are ideally suited to provide useful insights into the impact of other environmental policies connected with the use of fossil fuels, for example policies aimed at reducing NO_x and SO_2 emissions. In addition, while a solution to the problem of global warming necessitates global policies, several of the policy options reviewed may also be introduced at the local — national or even regional — level. In this sense, the relevance of the green paradox literature is broader than usually recognized, and so is the potential usefulness of our review.

2 Carbon Price Paths

Although a large literature exists on optimal carbon tax paths when emissions stem from the use of a nonrenewable resource, our focus is on the effects of imperfect climate policy on emissions, and resource extraction. In this section, we study the effects of different (exogenous) carbon price paths in a closed economy. Both in the literature and in the policy arena, several carbon price paths have been proposed, notably increasing carbon taxes (see e.g., Nordhaus, 1994). To illustrate some of the basic mechanisms behind the impact of an exogenously imposed constant carbon tax path in the context of nonrenewable resource use, we use a simple model of resource extraction (see e.g., Gerlagh, 2011; Hoel, 2012).

Resource-owners are price takers and face an exogenous interest rate r. They maximize intertemporal profits by choosing an extraction path $x(t)$:

$$\max_{\{x(t)\}_0^\infty} \Pi = \int_0^\infty [p(t) - \tau(t) - c(X(t))]x(t)\mathrm{e}^{-rt}\mathrm{d}t \tag{1.a}$$

$$\text{s.t.} \quad \dot{X}(t) = x(t), \tag{1.b}$$

$$x(t) \geq 0\,\forall t, \tag{1.c}$$

$$X(t) \leq \bar{X}\,\forall\, t, \tag{1.d}$$

$$X(0) = 0, \tag{1.e}$$

where $p(t)$ is the consumer price for the resource, $\tau(t)$ is the carbon emissions tax (the units are set such that one unit of resource use generates one unit of emissions), and $c(X(t))$ is the unit extraction, which we allow to be an increasing function of the amount of cumulative extraction $X(t)$. Cumulative extraction cannot exceed the initially available resource stock $\bar{X}$. The market for the resource clears at each point in time as demand $D(p(t))$ is satisfied by supply, with $\lim_{p\to\infty} D(\cdot) > 0$. In addition to the nonrenewable resource, a clean and perfectly substitutable alternative energy technology (a so-called 'backstop') may be available at constant marginal cost b, so that $D(\cdot) = x(t) = 0$ for $p(t) > b$. We denote the instant of the switch to the backstop energy source as t_b, so that $p(t_b) = b$.

2.1 Constant Carbon Emission Price Paths[2]

Using small variations of the simple model described above, we can study the effects of exogenously imposed constant carbon price paths on resource extraction and emissions.

In the first version of this model (the 'Hotelling model'), we rule out the existence of a backstop technology, so that along any optimal extraction path total extraction equals the initial resource stock, $\bar{X}$:

$$\int_0^\infty x(t)\mathrm{d}t = \bar{X}. \tag{2}$$

Moreover, if we abstract from extraction costs, we recover the well-known Hotelling rule (after Hotelling, 1931), stating that the return to the producer (now equal to the consumer price) must grow at the rate of interest.

$$\hat{p}(t) \equiv \frac{\dot{p}(t)}{p(t)} = r. \tag{3}$$

This equilibrium condition guarantees that the resource owner is indifferent between extractions at any point of time. In the Hotelling model, the entire resource stock $\bar{X}$ will get extracted over time, so a carbon tax will only affect the timing of extraction and emissions.

Now assume, following Hoel (2012), that the carbon tax grows at a constant rate g. Then (1.a) becomes

$$\Pi = \int_0^\infty [p(t) - \tau(0)\mathrm{e}^{gt}]x(t)\mathrm{e}^{-rt}\mathrm{d}t. \tag{4}$$

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[2] This subsection builds on parts from Hoel (2012).

If the carbon tax grows at a rate r, the present value of the carbon tax is constant, so the carbon tax is effectively a lump sum tax:

$$\Pi = \int_0^{\infty} p(t)x(t)\mathrm{e}^{-rt}\mathrm{d}t - \tau(0)\bar{X}. \tag{5}$$

As a consequence, the path of extraction and emissions is not affected by climate policy: the carbon tax is ineffective from an environmental perspective.

Next, consider the case of $g > r$. In this case, initial discounted profits are higher than future discounted profits as $\tau(0)\mathrm{e}^{(g-r)t}$ grows over time. Hence, resource owners will shift extraction from the future to the present in response to the tax (the extraction path becomes steeper) and early emissions increase: a weak green paradox occurs.

The opposite result emerges when $g < r$, for example when the carbon tax is constant. In this case, the initial discounted profits are lower than future ones, the extraction path becomes flatter, and initial extraction decreases: emissions are postponed.

Thus far we have assumed that no backstop energy technology is ever available. Now assume, instead, that such a clean source of energy becomes available at a constant, finite marginal cost b. Then, a carbon tax satisfying

$$\int_0^{\infty} D(\tau(t))\mathrm{d}t < \bar{X} \tag{6}$$

would be large enough to push the scarcity rent to zero, and to induce the resource owners to leave part of their deposits unexploited. Hence, cumulative extraction over the entire time horizon falls. Whether this is good or bad for the climate, however, depends on the exact time path of emissions and, hence, on the time path of the carbon tax.

The next step is to add stock-dependent extraction costs back into the model, and study the effects of the introduction of a carbon price, in the presence of a backstop technology. In this case, it might be optimal for the resource owners to leave some of the resource unexploited. This happens when the cost of the backstop is low enough, or, equivalently when the stock of the resource, $\bar{X}$, is sufficiently large. We refer to this model as 'Heal model', after Heal (1976). In this model the amount of the resource that ultimately gets extracted, call it $\tilde{X}$, is endogenous even in the absence of climate policy, as it is determined by the condition $c(\tilde{X}) = b$. Deposits with extraction costs higher than b remain unexploited.

With a carbon tax, the equilibrium conditions for the optimal amount of cumulative extraction over the entire time horizon, X^*, become

$$c(X^*) = b - \tau(t_b), \tag{7}$$

$$\int_0^{t_b} x(t)\mathrm{d}t = X^*, \tag{8}$$

where t_b is the time of the switch to the backstop. From these equations it is immediately apparent that *any* carbon tax will induce some resource owners to leave deposits unexploited.[3] This is a much stronger result than in the Hotelling model where, over time, the entire physical resource stock $\bar{X}$ is fully exhausted, and where a 'sufficiently high' carbon tax was required when extended with a backstop — see Equation (6).

In order to discuss the effects of a constantly growing carbon tax, consider how the simple Hotelling rule (3) changes, when we allow for a carbon tax and stock-dependent extraction costs:

$$\dot{p}(t) = r(p(t) - c(X(t))) + (\dot{\tau}(t) - r\tau(t)). \tag{9}$$

Suppose the carbon tax is growing at rate r. Then the last term in this equation drops out and the resource price path grows at the same rate as in the case without climate policy. However, the *level* of the price path must be higher — and extraction and consumption lower — compared to no-tax case, since we have just concluded that with a Heal model, any carbon tax will reduce cumulative extraction. Hence a carbon tax that grows at the rate r reduces emissions at any point of time: once again a stronger result than in the pure Hotelling case.

This argument extends to the case where the carbon tax grows at a rate lower than r. In this case, the net return to the resource owner in (9) increases over time, so it pays to postpone extraction. Keeping initial extraction at the same level as in the case of no carbon tax then violates the result that a carbon tax reduces total extraction, so a carbon tax that grows at a rate lower than r reduces initial and total extraction and emissions.

It is then easy to see that when the carbon tax grows at a rate sufficiently higher than r, front-loading of extraction will arise. That is, early emissions rise, and a weak green paradox occurs, but still total cumulative extraction will be lower compared to the case of no carbon tax. Whether a strong green

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[3] This result has also been found by Habermacher and Kirchgäessner (2011).

paradox occurs or not then depends on the discount rate and the shape of the climate damage function.

Hoel (2011a, 2012) uses a two-period version of the Heal model. For the simplest version of this model, an increase in the second period tax unambiguously leads to a weak green paradox. In Hoel (2012), he introduces endogenous investment in the backstop. Investments are made in period one, of which a fraction a of the returns are obtained in period 1 and the remainder in period 2. Unit investment costs (in units of the final energy good) for the alternative energy source are increasing in the level of investment and, by assumption, investment is always positive. The author then studies the effects of an increase in the second period carbon tax and finds that a weak green paradox only occurs when second-period marginal extraction costs increase sufficiently fast in cumulative extraction. If they do, and if the share of the returns to the alternative energy source that are obtained in the first period is not too high, first-period extraction increases, even though investment in alternative energy increases in response to the tax increase. When marginal extraction costs increase rapidly with cumulative extraction and a is large, a weak green paradox occurs and investment in alternative energy decreases. When the marginal extraction costs is relatively flat, however, first-period extraction is hardly affected by the higher tax, but investments in alternative energy become more profitable due to the tax increase. This reduces the demand for fossil energy in the first period, so no green paradox occurs, contrary to the case without endogenous investment.

Before concluding our discussion of this strand of literature, we need to address one final point. So far, we have assumed that the future price path for CO_2 emissions was known at each point in time. This assumes that the government is credible when committing to announce the price path at $t = 0$. Although this assumption is common made in the environmental economics literature, this clearly need not be true in reality. For example, if the current government gives a different weight to climate damages than future governments, or if firms make irreversible investments in clean technologies after the initial announcement, the future carbon tax set by the then government need not be the same as the one announced at $t = 0$.

Hoel (2012) uses the two-period version of model à la Heal without a backstop, to study this problem. In this version of his model, the second period is the 'distant future' for which it may not be possible to commit to a carbon price path in advance (the author suggests 10–15 years). He assumes full commitment is not possible and the expected second-period tax depends on the level of the first-period tax. Then, if the total stock is exogenous (Hotelling model), an increase in the first-period tax will induce an increase in first-period extraction, and hence a weak green paradox, if the discount factor times the marginal increase in the expected second-period carbon tax due to an increase in the current (first-period) carbon tax is larger than one. This result is not surprising as it corresponds to the Hotelling model discussed in the previous subsection with a tax rate growing at a rate higher than the rate of interest. With an endogenous stock (Heal model), this product should be ‘sufficiently large’, which corresponds to the Heal case with full commitment discussed above. Hoel (2012) concludes that “[f]or reasonable modeling of these expectations, a higher current carbon tax will reduce near-term emissions.”

2.2 Carbon Price Paths and the Green Paradox: Conclusions

From our discussion in this section, the difference between models of physical exhaustion à la Hotelling (1931) and models of economic exhaustion à la Heal (1976) emerges quite starkly. In models where the cumulative extraction level is endogenous, a weak green paradox is less likely to occur than in the Hotelling model. Indeed, in such models not only will any carbon tax reduce the overall amount of resources extracted, but even a carbon tax growing at a rate slightly higher than the interest rate need not induce an increase in initial extraction.

Within the class of (2-period) Heal models, it seems that increasing complexity, through endogenous investment in the backstop, makes a weak green paradox less likely to occur in response to an increase in the second period tax.

Clearly the effects of a carbon price path depend on how resource owners think it will affect the net present value of their profits. Hence, incentive compatible policies and perfect foresight play an important role, and represent an interesting direction for further research.

3 Supporting Alternative Energy Technologies

In this section, we study the effects of support for alternative energy technologies on resource extraction and GHG emissions. As politicians prefer giving away subsidies over taxing particular goods and sectors, a wide array of subsidies for clean energy technologies exists, ranging from support for fundamental research and development (R&D) for new nuclear energy technologies to subsidies for biofuel production and adoption subsidies for solar and wind energy. Although subsidies for alternative energy technologies may be warranted from a social welfare perspective due to knowledge spillovers from R&D and learning by doing (LBD), in practice those subsidies are used as an alternative to a price on GHG emissions and directly aimed at reducing those emissions. Hence those subsidies are generally not optimal and may induce responses by owners of fossil fuel deposits that were not taken into account during the decision-making process.

In Section 3.1 we look at clean energy technologies that are available at constant marginal cost (the backstop technology introduced in Section 2); these technologies could be thought of as nuclear or solar energy. In Section 3.2 we study energy technologies with upward-sloping supply curves (such as biofuels that compete for land with other uses). The support for these technologies comes in the form of R&D subsidies that induce a fall in the cost of the alternative energy source, or in the form of a subsidy per unit of alternative energy used.

3.1 Alternative Energy at Constant Marginal Cost

As in Section 2, we start with the simple Hotelling model, but now extended with a backstop technology available at constant marginal cost b. As we proceed, we increase the model's complexity to study the effects of increased realism on the possibility of a green paradox.

3.1.1 The Hotelling Model

Since the two energy technologies are perfect substitutes, and the price of the nonrenewable fossil fuel grows at the interest rate (see Equation (3)), there exists an instant t_b at which the economy switches from fossil fuel to the backstop. The initial resource price $p(0)$ and the instant t_b are determined by the condition that the resource stock gets exhausted before the switch to the backstop

$$\int_0^{t_b} D(p(0)\mathrm{e}^{rt})\mathrm{d}t = \bar{X} \tag{10}$$

and the condition that at t_b the backstop price b equals the scarcity rent:

$$p(0)\mathrm{e}^{rt_b} = b. \tag{11}$$

What is the effect of a policy that reduces the marginal cost of the clean backstop technology b (e.g. as result of a subsidy for R&D for alternative energy technologies) on emissions? From the last equation, it is easy to see that, ceteris paribus, a decrease in b brings the instant of the switch to the backstop closer. However, with unchanged initial resource price $p(0)$, this implies that some of the resource remains unexploited, which induces resource owners to supply more at each point in time, thus reducing the equilibrium resource price. Hence, the reduction of the marginal cost of the backstop increases extraction at each point in time where the polluting resource is still used: a weak green paradox occurs (see also Gerlagh, 2011).[4] Assuming that marginal damages grow at a rate lower than the interest rate, Gerlagh (2011) shows that in the simple Hotelling model a decrease in the marginal cost of the backstop induces an increase in the net present value of damages, and hence the *strong* green paradox arises as well.[5]

Van der Ploeg and Withagen (2012b) add complexity to the Hotelling model through (linear) stock-dependent extraction costs, and damages from the stock of CO_2 in the atmosphere through an additively separable quadratic damage function.[6] It then depends on the marginal costs of the backstop technology whether the resource stock will be fully exhausted (the Hotelling model) or not (model à la Heal).[7] In the case of full exhaustion, they confirm the result of Gerlagh: both the weak and the strong green paradox occur in response to a decrease in the marginal cost of the backstop.

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[4] These results can be shown taking total derivatives of (10) and (11) and calculating $\mathrm{d}t_b/\mathrm{d}b$ and $\mathrm{d}p(0)/\mathrm{d}b$, respectively. See e.g., Gerlagh (2011).

[5] Hoel (2011b) and Gerlagh (2011) assume that the social cost of carbon, or the net present value of marginal damages, does not grow at a rate higher than the discount or interest rate. In case of a ceiling on the stock of GHG in the atmosphere (e.g., through a stabilization target) and taking into account the uptake by natural carbon sinks, the growth rate of the social cost of carbon is *higher* than the (utility) discount rate as long as the ceiling has not been reached (see e.g., Chakravorty *et al.*, 2008). In models of optimal carbon pricing such as Hoel and Kverndokk (1996) and Tahvonen (1997), the social cost of carbon depends on the rate of natural uptake and the *level* of marginal damages. Hoel and Kverndokk (1996) show that the social cost of carbon starts to decline before the stock of accumulated greenhouse gases does. If one argues that the stock of GHGs should soon be stabilized, a growth rate of the social cost of carbon below the discount rate may not be far off the mark.

[6] Since they abstract from natural uptake of CO_2 from the atmosphere, each unit of emissions stays in the atmosphere forever, which reduces the two state variable optimization problem to a single stock problem. Due to this assumption, the social cost of carbon grows at a rate lower than the utility discount rate. See footnote 5 for a discussion.

[7] We abstract from the possibility that the policy induces a switch from full to partial exhaustion.

Hoel (2011b) extends the Hotelling model to a partial equilibrium two-country model. By assumption, the countries differ in the stringency of their emissions reduction policy. Hoel shows that for a sufficiently small difference between the tax rates of the two countries, the two regions combined respond to an exogenous decrease in b as in the continuous time closed economy model discussed above, and the switch to the backstop will be made at an earlier point in time in both countries. Hence emissions increase at each point in time and both the weak and the strong green paradox occur. Hoel (2011b) shows that, in response to the cost decrease, the country with the higher tax will always make the switch to the backstop earlier. However, if the tax difference between the two countries is large enough and the demand elasticity in the low-tax country is sufficiently low, this country will postpone the switch to the backstop. Although a weak green paradox will still occur, the strong Paradox will not if the social cost of carbon declines over time.

An alternative policy to subsidizing R&D in order to reduce the marginal cost of the backstop, is to directly support its use through a (constant) per-unit user subsidy σ, so the right-hand side of (11) becomes $b - \sigma$. Van der Ploeg and Withagen (2012b) show that in this case again both the weak and the strong green paradox occur.[8] For this case they find that a *tax* on the backstop is optimal. In this case, a subsidy would reduce the scarcity rent of fossil fuels, which increases resource demand and supply at each point of time. Once the resource gets exhausted, the tax should be abolished. If damages are large, an alternative policy to the tax would be to subsidize the backstop to such an extent that it becomes attractive to stop using the nonrenewable immediately, or compensate resource owners for not exploiting their resource. Note that this is related to condition (6) for the case of a carbon tax (rather than a subsidy for the backstop) in the presence of a backstop.

Hoel (2011b) also studies a user-subsidy for the backstop in his two-country model. When both countries introduce an identical adoption subsidy (and b stays constant), both the strong and the weak green paradox occur when the difference in tax rates is sufficiently small. These results are identical to those following a fall in the (constant) marginal cost of the backstop, described above, as this is equivalent to an ‘eternal’ and identical subsidy.

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[8] Contrary to the other papers discussed in this review, Van der Ploeg and Withagen (2012b) use a damage function to study the welfare effects of policy. When a strong green paradox occurs, overall welfare may still increase.

However, when the tax difference is sufficiently large, the strong green paradox may or may not occur, depending on demand elasticities. In the more interesting case of a unilateral subsidy increase, a weak Paradox will occur when both countries have the same tax rates but different subsidy rates. If the subsidy increase takes place in the country that initially has the lowest subsidy, a strong green paradox occurs as well since both countries switch to the backstop sooner, while total extraction increases at each point of time. When the country with the higher subsidy increases its subsidy rate, however, the results regarding a strong Paradox are not obvious.

Another interesting contribution to the literature on the effects of lower (constant) marginal cost on resource extraction and carbon dioxide emissions comes from Strand (2007), who introduces uncertainty regarding the discovery of a clean backstop technology to the (closed economy) Hotelling model in the context of a technology treaty. Once such a treaty has been agreed upon, there is a probability that a clean energy source, available at constant marginal cost, will be discovered. By assumption, the marginal cost of the backstop is lower than the (constant marginal) extraction cost of the resource. In addition, the author assumes that the period until the technology has been developed is exponentially distributed with parameter λ (Poisson process), so that the price net of extraction costs has to grow at rate $r + \lambda$. Then there are two effects of the treaty on cumulative extraction at any point of time. First, the positive probability of the resource becoming redundant increases the extraction rate, which works in favor of a (weak) green paradox. Second, there is an effect in the opposite direction: the longer the time horizon, the larger the probability that the technology has already arrived, so the more likely it is that cumulative extraction is lower than it would be without the possibility of a backstop being discovered. Using simulations, the author shows that for a short time horizon, cumulative extraction increases with λ: the larger the probability of finding a clean energy source, the more likely it is that a weak green paradox will occur (first effect dominates). For a longer time horizon, however, the second effect dominates, and cumulative extraction *decreases* with λ.[9]

Next, Strand (2007) studies the case where, once a treaty is signed (at $t = 0$), it takes T years before the probability λ plays a role. This lag seems

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[9] In the context of Section 2, Habermacher and Kirchgäessner (2011) use an analytical model with similar properties and show that in this model, a constant carbon tax rising at a rate higher than $r + \lambda$ induces a weak green paradox.

realistic, since first the treaty must be agreed upon, then the technological effort must be financed and undertaken, and once developed, the technology must be adopted by different firms and countries. Using simulations the author shows that at all times smaller than or equal to T, cumulative extraction increases as a result of the technology treaty.[10]

3.1.2 The Heal Model

We now move to the case of the Heal model, i.e. endogenous cumulative resource extraction. We again start with the effects of a lower marginal cost of the backstop. Van der Ploeg and Withagen (2012b) show that, for this model, a marginal reduction in the cost of the backstop b does *not* induce a strong green paradox, as cumulative extraction and emissions are lower. A weak green paradox still arises as the drop in price of the backstop tends to speed up fossil fuel extraction.

Gerlagh (2011) also discusses the effect of a cheaper backstop technology in the context of the Heal model, using a linear demand function and an extraction cost function that is linear in cumulative extraction (both as in Van der Ploeg and Withagen, 2012b). The fall in the marginal cost of the backstop induces a fall in the scarcity rent of the resource, which in turn induces an increase in (initial) extraction. Also Gerlagh (2011) finds a weak green paradox when the marginal cost of the backstop falls in the case of a Heal model. However, the instant of the switch to the backstop t_b falls sufficiently to offset this emissions increase in terms of marginal damages: with linear functional forms, a strong green paradox does not arise in Gerlagh's model, just as in Van der Ploeg and Withagen (2012b).

Van der Ploeg and Withagen (2012b) also study the case of a user-subsidy for the backstop, σ, and find that no green paradox occurs in response to the subsidy as the switch to the backstop is made earlier and more reserves remain unexploited.

3.2 Alternative Energy with an Upward-sloping Supply Curve

A more realistic description of alternative energy sources, at least regarding biofuels, is that marginal costs are not constant but rather increasing with supply. Gerlagh (2011, Section 3) and Grafton *et al.* (2010) model linear

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[10] This resembles the announcement effects studied in Section 4.

supply functions $S(\cdot)$ for alternative energy, and the demand for fossil fuels as a residual demand:

$$S(p(t)) = \psi_0 + \psi_1 p(t); \tag{12}$$

$$\int_0^{t_b} D(t) - \frac{p(t) - \psi_0}{\psi_1} \mathrm{d}t = \bar{X}. \tag{13}$$

Furthermore, it is assumed in both papers that marginal cost of resource extraction are constant and the resource stock is finite, so the resources side of the model reflects the Hotelling model of Section 2. Under these assumptions, there is a period of joint use of the two energy sources.

Continuing with the assumption of linear demand, Gerlagh (2011) shows that lower marginal costs of the backstop — either through lower ψ_0 or lower ψ_1 — induces neither a weak, nor a strong green paradox. The cheaper substitute reduces resource demand at each point of time and lengthens the period over which the resource is used, while the (joint) use of the alternative energy source is higher.

Although Grafton *et al.* (2010) study the effects of an *ad valorem* subsidy for the alternative energy source rather than a cost reduction, they find similar results: neither Paradox occurs after an increase in the subsidy rate. With nonlinear demand, however, a weak green paradox may occur, depending on parameter values. They confirm these results for the case of monopoly extraction.

Hoel and Jensen (2010) introduce carbon capture and storage (CCS) to the Hotelling model with an upward-sloping supply curve for renewables (and zero extraction costs). CCS is a technology that can capture the largest part of carbon dioxide during or before the production process of electricity. The captured CO_2 can then be (near-permanently) stored so that emissions from electricity production go down. Hoel and Jensen (2010) assume not only that CCS is capable of bringing emissions from fossil fuel use to zero, but also that it comes at a money cost (the cost of investment) and at the expenses of lower generation efficiency, and such entails an additional energy cost, both per unit of final energy produced (y and z respectively). Furthermore, they assume that CCS is only available in the second period of their two-period model, as is renewable energy (supplied competitively at increasing marginal cost: $S(p - \sigma)$, where σ is a per-unit cost reduction). By assumption, only energy from a nonrenewable resource is available during the first period, while all three energy sources (fossil, fossil with CCS, and renewable) may be used in the second period, even though their respective outputs can be traded one for one (e.g., electricity). They impose a cumulative emission constraint to their model (see Allen *et al.*, 2009), such that without CCS, part of the carbon stock has to remain unexploited, while with CCS this same amount must be captured. A carbon tax is imposed in both periods. They abstract from natural uptake so each unit of emissions reduces the remaining carbon budget with one unit. Before discussing the case of lower costs for CCS, we first address the effects of lowering the cost for renewable energy.

Suppose the ceiling on cumulative emissions is enforced in both periods, so the intertemporally efficient carbon (shadow) price grows at the interest rate. A lower cost of the alternative energy source (increase in σ) increases the supply of renewable energy, which reduces the value of the fossil fuel. As the Hotelling price path shifts down, extraction in the first period increases, but second-period extraction declines due to the given stock and the increased use of the renewable: although the ceiling will not be violated, a weak green paradox occurs. This result deviates from the results found by Gerlagh (2011) and Grafton *et al.* (2010), who did not find a green paradox following a cost reduction for the alternative energy source. In Hoel and Jensen (2010), by assumption, only the nonrenewable is used in the first period. The fall in the value of the nonrenewable due to the cheaper alternative induces an increase in first-period demand. This result also holds when it is not possible to impose a carbon price in the first period.

Next, the authors study the effects of lower costs of CCS. If the ceiling on cumulative emissions is enforced in both periods, lower non-energy costs y do not affect the amount of CCS in period 2, as this is given by the difference between the ceiling and the initial resource stock. Hence the extraction path is not affected either. Lower energy cost for CCS z, however, reduces the opportunity cost of CCS in period 2, so it becomes attractive to emit more in period 1. Although the ceiling will not be violated, a weak green paradox occurs.

When it is not possible to impose a carbon price in the first period, lower money cost for CCS (y) reduces the opportunity cost for CCS in the second period, so the regulator lowers the carbon price compared to the case of no cost reduction. This makes fossil energy use in the second period more attractive and extraction is postponed, so that first-period emissions decrease. The effects of a decrease in the energy cost (z) on first-period extraction in this case are undetermined. On the one hand, postponing extraction becomes more interesting as the opportunity costs of CCS and hence the tax decrease. The resulting lower consumer price for energy makes it less attractive to supply renewable energy in the second period. On the other hand, energy use for CCS will increase as the costs of CCS go down, which increases period 2 fossil energy demand. Compared to the case of an efficient carbon tax, a (weak) green paradox is less likely to occur when the first-period carbon tax is zero. Hoel and Jensen (2010) show that these results also hold for a model with endogenous total extraction (Heal model).

In the Heal-type model in Hoel (2011a), investments in the alternative energy technology are endogenous (see Section 2.1). A fraction a of the returns to these investments accrues in the first period, the rest in the second. A per-unit investment subsidy increases investment in clean energy, but its effect on first-period emissions is ambiguous. Hoel (2011a) shows that for any rate of increase of marginal extraction costs, there exists a threshold level of a below which a weak green paradox occurs. He argues that if only a small fraction of the returns to investment are obtained in period 1, encouraging investment will reduce demand for the resource in the future considerably more than in the present, which induces resource owners to speed up extraction.

3.3 Alternative Energy Technologies and the Green Paradox: Conclusions

Policies that affect the cost of an alternative energy source generally have two effects. They reduce the value of the resource stock *in situ*, which induces a lower resource price and increased resource demand. In addition, the instant of the switch from the fossil fuel to the alternative energy source is affected. In the simplest model, this induces both a weak and a strong green paradox. With constant marginal costs for the backstop, in both the Hotelling model and the Heal model a weak green paradox occurs after a fall in the price of the backstop, or after an increase in a subsidy. However, the strong green paradox has only been found for the Hotelling model.

In the presence of an increasing supply function for renewable energy and linear demand, no green paradox occurs in response to lower marginal cost of the backstop or a user subsidy in the Hotelling models discussed above. In two-period models, a weak paradox may or may not occur, depending on the model's specification. It seems that subsequent extensions of the models imply that a strong paradox is less likely to occur, while for the weak paradox results are ambiguous. Still, more research is needed to be able to provide a clear conclusion.

4 Announcing Climate Policy in Advance

The third imperfect policy approach considers a lag between the instant of announcement of a GHG emission reduction policy and the instant of its implementation. In Section 2 we assumed that the carbon tax is immediately and unexpectedly introduced. In reality, most environmental policies (or even government policies in general) do not come as a surprise. Coming to an agreement (within a government, or between different governments) and administrative procedures cost time. Furthermore, announcing policy before actually implementing it gives agents time to adjust, and may reduce the costs of compliance. During the 'interim phase' between the instant at which agents first learn or expect that a policy will be introduced and the instant of actual implementation, agents are not bound by the policy. In the case of a carbon tax or emissions cap, agents are still free to emit and to emit for free, although they know that from a known point of time onward a policy will be imposed. Indeed, the knowledge or expectation that a future policy will be introduced ('announcement' for short) may itself induce agents to change their behavior.

4.1 Announcement Effects with Nonrenewable Resources

Di Maria *et al.* (2012b) use a model related to the Hotelling model introduced in Section 2 and assume that a cap on the flow of emissions is announced at $t = 0$ but implemented from an exogenous date $T > 0$ onward. In its simplest form, this is a special case of the rising carbon tax, with $g > r$ discussed in Section 2.1: during the interim phase the price for carbon dioxide emissions is zero, but it jumps up at $t = T$ to make sure the emission cap is not violated. Di Maria *et al.* (2012b) generalize the model for the case of any number of resources, that possibly differ in their emissions intensity (for example, coal, oil and natural gas). Since less can be extracted than what agents prefer during the period in which the ceiling is binding, and as resource owners want to exhaust their resource stocks, the resources become abundant outside the constrained period. The resource price (scarcity rent) during the interim phase is therefore lower than in the case where government intervention would never take place ('laissez faire'), inducing higher demand and extraction rates. Assuming that emissions per unit of energy do not change, or fall proportionally less than the increase in the level of energy use, emissions in the interim phase are higher than in the case no policy would have been announced, so a weak Green Paradox occurs.[11]

A similar result is found in Eichner and Pethig (2011) for the case of one resource but multiple countries. They use a 3-region, 2-period Hotelling-type model where one region exports a nonrenewable resource and imports a final good while the other regions (one of which is subject to an existing emissions cap in either one or both periods) import the resource to produce the final good. This final good is produced from the resource (which emits CO_2 when used in final good production) and a fixed factor. As in the Hotelling model introduced in Section 2, the entire resource stock will get exhausted over time. The resource-importing regions only differ in their climate policy. All agents are price takers and the final good and resource markets clear at each point of time. Eichner and Pethig show that when the abating region faces a cap in period 2 and announces at $t = 0$ that the second-period cap is tightened, a weak green paradox may occur, depending on parameter values. A high intertemporal elasticity of substitution of consumption, or a high (absolute value of) period-2 demand elasticity for fossil fuels in the non-abating country, or a tight constraint, or low first-period emissions of the non-abating country, all ceteris paribus, may induce an increase in global emissions in the first period in response to the announced tightening of the second-period cap by the abating region. The intuition behind this condition is as follows. The higher the substitution elasticity, the larger is the consumption response to the change in the second-period price of the final good, and the more production (and hence fossil fuel consumption and emissions) are shifted to the first period. As a consequence, the period-1 emissions increase by the non-abating region must be larger. However, the authors also show that an emission *reduction* by the non-abating region will occur, in response to a tightening of the second period cap by the abating region, when the intertemporal elasticity is sufficiently small and the period-2 cap is not too tight.

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[11] Di Maria *et al.* (2012b) also show that utility — which solely comes from resource use — and resource use jump down at the instant of implementation, despite the fact that forward-looking agents know at $t = 0$ that a constraint will be imposed at a known future date. This counter-intuitive result assures a weak green paradox.

The results found by Di Maria *et al.* (2012b) do not depend on parameter values, since they study a cake-eating problem. However, while they find that while initial resource extraction will increase due to the announcement, the effect on *emissions* will depend on relative extraction of high- and low-carbon fossil fuels (e.g. coal and gas) and hence the emissions intensity of energy use. Di Maria *et al.* (2012b) assume that energy is produced using two perfectly substitutable resources that differ in their carbon content. During the period in which the cap is binding, the highest level of energy use can be obtained by using only the low-carbon input. Hence, if the stock of this resource is too small to use this fuel exclusively during the period in which the emissions cap is binding (i.e., if the dirty input is relatively abundant), announcement of the future cap makes this input relatively scarce. In this case, the relative price (scarcity rent) of the cleaner fuel will be higher as compared to the case of laissez faire: it is optimal to preserve the low-carbon input for use during the constrained phase, and (expected) use of the high-carbon input increases during the interim phase, as compared to laissez faire. In sum, Di Maria *et al.* (2012b) show that announcement of climate policy, in the context of a Hotelling-type model, induces a weak green paradox, both because the level of energy use increases in the interim phase, and because the order of resource extraction may change in favor of the dirty input.

The increase in initial energy due to announcement not only holds for the case of a cap on the flow of emissions. Amigues *et al.* (2010) find a weak green paradox for the tightening of a ceiling on the stock of pollution when the ceiling is initially not binding.

4.2 Announcement Effects without Nonrenewable Resources

Smulders *et al.* (2010) approach the same problem — announcement of a carbon price — from a different perspective. Like Di Maria *et al.* (2012b) they use a closed-economy continuous time model, but they abstract from nonrenewable resources and instead assume that fossil energy is never scarce, and available at constant marginal costs. Output comes from a constant returns to scale production function with a capital stock, inelastically supplied labour, and energy. Forward-looking consumers have the standard strictly concave instantaneous utility function and have to decide at each point in time how much to invest and how much to consume.[12]

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[12] Smulders *et al.* (2010) include endogenous investment in a backstop energy source, but this does not affect the main results regarding the timing of emissions.

The positive carbon price from $t = T$ onward implies lower fossil energy use and lower productivity of the capital stock, relative to laissez faire, as well as lower consumption, from this instant onward. Agents may mitigate this shock through increased investment in the stock of capital during the interim phase. This involves a trade-off between lower utility during the interim phase due to increased savings, and higher productivity of labour and energy once the tax is introduced, due to a larger capital stock. Smulders *et al.* (2010) show that if the product of the intertemporal elasticity of substitution (which is typically smaller than one) and the capital elasticity of GDP is smaller than one, the willingness to prevent the shock is so strong that consumers increase savings during the interim phase in order to invest in capital. As the increased savings lead to a higher capital stock during the interim phase as compared to laissez faire, and since capital and energy are complements, emissions during the interim phase increase due to announcement of the carbon tax: announcement of a future carbon price induces a weak green paradox even in the absence of exhaustibility of the energy resource. The authors also show that this result also holds when the government is not able to fully commit to the announced policy, and consumers and firms take the instant of implementation to be uncertain.

4.3 Announcement of Climate Policy and the Green Paradox: Conclusions

In practice, most (environmental) policies do not come as a surprise to consumers and firms. Political or legal constraints, or the desire to give agents time to prepare to the policy in order to reduce adjustment and implementation costs, all make that agents are informed about a policy before its actual implementation. When agents know that at some future date emissions of carbon dioxide will be subject to a tax or cap, they may be induced to increase their emissions in the interim phase between announcement and implementation, such that a weak green paradox occurs. Although implementation lags have not yet been studied in models with endogenous total extraction, the results from Section 2 suggest that in this case the tax should be sufficiently high (the cap should be sufficiently tight) to induce a weak paradox.

For this announcement effect to occur it is not necessary that emissions stem from a nonrenewable resource. Consumption smoothing can induce consumers to save more during the interim phase, to build up the stock of capital, and mitigate the negative effect on production from reduced energy use once the policy is implemented. When emissions do originate from nonrenewable resources, a weak green paradox may also occur in case of emission reduction policies by a group of countries. Furthermore, the announcement may induce owners of high-carbon resources to increase extraction during the interim phase, as their resource becomes less valuable once the policy is in place. This increases the carbon content of energy use and enhances the effect on emissions from the increase in energy use itself. Whether a strong green paradox occurs or not, depends on the time path of the social cost of carbon, which is not modeled in any of the papers discussed in this section.

5 Unilateral Carbon Pricing and International Carbon Leakage

The previous section has shown that a weak green paradox may occur when carbon abatement policies fail to cover the entire time horizon. In this section we focus on the case where policies fail to cover all countries. Although climate change is a global problem, international negotiations have failed to deliver a global approach to emission reductions. Underlying this problem is the classic market failure of emission reductions being a global public good: when some country decides to introduce emission reduction policies to correct the externality stemming from GHG emissions, all other countries benefit from slower global warming, and they cannot be excluded from doing so. This observation has led to the concern that unilateral emission reductions will simply lead to an increase in emissions by other countries, a phenomenon known as ‘carbon leakage’, which has been a much-addressed topic both in politics and in research for some two decades.[13] Indeed, it has been an important argument in the decision of the United States not to ratify the Kyoto Protocol. For example, U.S. senator Chuck Hagel — co-sponsor of the 1997 Byrd–Hagel Resolution, which states that the U.S. Senate will not be a signatory to the Kyoto Protocol — argued that ‘‘[t]he main effect of the assumed policy [i.e., the Kyoto Protocol] would be to redistribute output, employment, and emissions from participating to non-participating countries’’.[14] In this context, we define a weak green paradox as an increase

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[13] ‘Unilateral’ here means a coalition, smaller than the grand coalition, that reduces its emissions below a ‘laissez-faire’ or ‘business as usual’ scenario.

[14] Remarks by Senator Hagel at ‘Countdown to Kyoto — International Conference on The Consequences of Mandatory Global CO_2 Emission Reductions’, August 21, 1997, Canberra, Australia.

in global initial or early emissions in response to a unilateral emission reduction. Many papers in the carbon leakage literature use a static model. In case of a static model, we denote an increase in global emissions simply as a green paradox.

5.1 Five Channels of Carbon Leakage

In this section, we identify five different channels through which emission reductions by a group of countries affect emissions by non-abating countries. First we discuss the mechanisms behind each channel and whether the respective channel is likely to increase or decrease carbon leakage. We then move to the quantitative results from the applied general equilibrium (AGE) modeling literature. This literature uses numerical multi-sector multi-country models to simulate the effects of emission reduction policies on several variables, including carbon leakage. We conclude this section with a brief discussion on whether carbon leakage is likely to lead to a green paradox, i.e., a global increase in emissions in response to unilateral emission reductions.

Before we present the five channels of carbon leakage, we briefly discuss some of the main elements of AGE models, as these models have been widely used to assess carbon leakage issues. The AGE models discussed in this section do not include nonrenewable resources and, to the extent that they are dynamic, they are not forward-looking. This is a major deviation from the models discussed in the previous sections. Generally, multi-region AGE models use a representative firm with a constant returns to scale technology for each sector in each region. Consumers and firms buy goods from each sector from different regions, as usually the output produced by sector X in country A is an imperfect substitute to the output produced by the same sector in region B. This is usually modeled through constant elasticity of substitution preference functions with finite elasticities. This so-called 'Armington assumption' (named after Armington, 1969) allows for intra-industry trade and prevents extreme specialization effects. Hence, with the Armington assumption, international prices do not equalize.

5.1.1 The Marginal Damages Channel

The first channel through which a unilateral emission reduction induces a change in emissions by other countries is the marginal damages channel. It is based on the public good aspect of unilateral emission reductions and noncooperative Nash behavior of governments that maximize national welfare: as damages stem from the stock of GHGs in the atmosphere, and hence depend on emissions from all countries, a unilateral emission reduction brings costs to an abating country, while the benefits are enjoyed by all countries. As a consequence, all countries have an incentive to free ride on other countries' policies.

In Hoel (1991), environmental benefit functions are convex in the sum of emission reductions from the two countries, while abatement costs are increasing and convex in each region's own level of abatement. For given emissions from the other country, it is individually rational for each country to equate its marginal abatement costs with its marginal environmental benefit. If emissions are reduced in a particular country, marginal environmental benefits will go up in all other countries. Each country will therefore adjust its emissions upwards (carbon leakage), so that marginal abatement costs again are equal to their marginal environmental benefits. When countries behave non-cooperatively, global emissions will still go down.[15] This basic result has been confirmed by many authors, see e.g., Barrett (1994).

Hoel (1991) also shows that when allowing for side payments, a green paradox may occur, depending on the marginal cost functions for emission reductions. If in a two-country world a country unilaterally reduces emissions beyond the point where marginal benefits equal marginal cost, its payoff will decrease while the payoff of the other country will increase. It then depends on the concavity of the abatement cost functions of the two regions whether total emissions will increase or decrease; when marginal abatement costs for the first region are steeply increasing relative to those of the second region, a green paradox is more likely to occur.

5.1.2 The Energy Market Channel

The energy market channel is based on the supply and demand responses to changes in energy prices, notably the prices of coal and oil (see e.g., Bohm, 1993). If unilateral emission reduction policies induce a drop in the global demand for (especially carbon-intensive) energy sources, the world

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[15] Based on these notions, a large literature on coalition formation for emission reduction policies has developed. However, as we focus on carbon leakage rather than the possibility of forming and the stability of coalitions, we disregard this literature.

price for these goods will fall. As a consequence, the demand for these energy sources will increase in non-abating countries. In static models, the size of the response will depend, among other things, on supply and demand elasticities. If fossil fuels are inelastically supplied, the rate of carbon leakage (the share of emission reductions by abating countries that is offset by emission increases by non-abating countries) will be 100%, since prices will adjust such that the demand reduction by abating countries will be exactly offset by a demand increase in other countries. Burniaux and Oliveira Martins (2012) discuss the sensitivity of leakage results for changes in the values of particular parameters in a simplified static AGE model. Their central case has a leakage rate of 4%, that is, 4% of emission reductions by Annex I is offset by an emissions increase by non-Annex I countries. They find that this rate approaches 100% when the supply elasticity of coal approaches zero. However, low supply elasticities do not induce a green paradox.

Only few papers have studied international carbon leakage through the energy market channel using a model with forward-looking agents and nonrenewable resources. As discussed in Section 3.1.1, in the context of policies in support of alternative energy sources, Hoel (2011b) uses a two-country, continuous time, partial equilibrium Hotelling model. A perfectly substitutable clean backstop resource exists, supplied an constant marginal costs b. The two countries have the same domestic demand function for energy. The author abstracts from trade and income effects: the resource is the only good and changes in the value of the resource does not affect the purchasing power of consumers.

If one country increases its (constant) carbon tax, emissions unambiguously increase at each point of time in the other country due to a lower resource price (scarcity rent). In addition, this country will extend its period of resource use and switch to the backstop at a later date. The country with the tax increase faces the same effect, but in addition the tax increase will make its consumer price path flatter, shifting consumption from the present to the future. The net effect on the instant of the switch to the backstop depends on the demand elasticities in the two countries. If they are such that this instant is postponed in the country with the tax increase, the global effect will be the same as with identical tax rates, and initial global emissions decrease. If demand elasticities are such that the tax increase induces the country with the tax increase to make to switch to the backstop at an earlier date, then still initial global emissions decrease if it is the country with the higher tax that increases its tax rate. If, however, the country with the lower tax rate increases its emissions price and in response makes the switch to the backstop at an earlier date, the total extraction period is shortened and with sufficiently low price elasticities, a weak green paradox occurs. Indeed, assuming that the social costs of carbon do not increase at a rate higher than the discount rate (i.e., the present value of the social cost of carbon declines over time), Hoel (2011b) finds that the increase in early emissions due to the unilateral tax increase leads to a *strong* green paradox: the net present value of damages increases.[16]

While Hoel (2011b) uses a partial equilibrium model, abstracting from trade, Eichner and Pethig (2011) use a small general equilibrium model with a nonrenewable to study carbon leakage. As noted in the previous section, they use an analytical 3-region, 2-period Hotelling-type model in which one region exports a nonrenewable resource and imports a final good while the other regions (one of which is subject to an existing emissions cap in either one or both periods) import the resource to produce the final good. This final good is produced from the resource (which emits CO_2 when used in final good production) and a fixed factor and is identical between countries (Armington elasticity going to infinity). All agents are price takers and the final good and resource markets clear at each point of time.

When the abating region tightens an existing first-period cap (but its second-period emissions are free), the world price for fuels falls (in both periods, due to the Hotelling price path), and first-period consumption becomes more expensive relative to second period consumption. Hence for the non-abating region the price of the input goes down while the relative price of its output goes up. The global change in first-period emissions consists of three parts: a direct effect from the tighter cap in the abating region, an indirect effect from the fall in the price for fossil fuel, and an indirect effect through the change in the relative price of the final good. Combined, these effects lead to an increase in output and emissions in the non-abating region in the first period, so carbon leakage is positive.

Eichner and Pethig (2011) show the conditions under which a green paradox may occur. A low intertemporal elasticity of substitution of consumption, or a high (absolute value of) the demand elasticity for fossil fuels in the non-abating country, or a tight constraint, or high first-period emissions of the non-abating country — all ceteris paribus — all may induce a green paradox. The intuition behind this condition is as follows. The

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[16] See footnote 5 for a discussion of the assumption that the social cost of carbon grows at a rate lower than the interest rate.

lower the substitution elasticity, the smaller is the consumption response to the change in the second-period price of the final good, and the less production (and hence fossil fuel consumption and emissions) are shifted to the second period. As a consequence, period-1 leakage must be larger. This effect is enhanced, the higher is the first-period price elasticity in the non-abating region. Eichner and Pethig (2011) show that the results are qualitatively unchanged when the abating region has a cap in both periods, and the second-period cap is unchanged.[17]

Using an analytical, static, multi-region model, Harstad (2010) shows that carbon leakage through the energy market channel can be prevented through trade in resource deposits. In his (static) Heal-type model, a coalition of countries has damages from emissions included in the utility function, whereas several other countries don't. A carbon resource is the only good in the economy, and firms in all regions take prices as given. However, trade in a deposit affects the world fuel price, as these are non-marginal changes in the amount of fuel available. Extraction costs are increasing in the level of extraction and deposits differ in their extraction costs. Hence, the marginal deposit has extraction costs that are close to the world fuel price (so its scarcity rent is close to zero). Then its owner is almost indifferent about exploiting, and supply is locally inelastic, while the coalition has a higher valuation for *not* exploiting due to environmental damages. If the coalition buys and does not exploit the resource, the coalition does not need to fear supply-side leakage, it does not need to regulate demand, there is no consumption leakage, and the marginal benefits of fossil fuel are equalized across countries. When allowing for a two-period Heal-type model (total extraction costs are given; allocation over time matters), leakage is still zero when the coalition buys deposits at $t = 0$; this is a time-consistent policy. The costliest deposits should again be set aside (for example through a Pigouvian tax of equal present-discounted value in the two periods).

5.1.3 Terms of Trade Effects for Non-energy Goods

In response to a unilateral carbon price, not only the relative prices of energy goods, but also those of non-energy goods change: production costs of

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[17] Interestingly, Eichner and Pethig find that extending the abating region at the expense of the non-abating region — increasing the cap proportionally so that the cap is as stringent as before enlargement — reduces total first-period emissions and hence the likelihood of a green paradox.

carbon-intensive goods in countries that aim at emission reductions increase relative to the costs of carbon-intensive goods in other countries (see e.g., Felder and Rutherford, 1993). As a consequence, firms and consumers in *any* country have an incentive to substitute towards goods produced in the latter group of countries. If firms in these countries expand their production of carbon-intensive goods at the expense of production in abating countries, emissions in non-abating countries increase. This, in a nutshell, is the terms of trade channel of carbon leakage.

The degree to which leakage occurs through the terms of trade channel depends on the ease with which one can substitute between goods from different regions. In AGE models, this is represented by the Armington elasticity: the larger the elasticity, the more homogenous the goods, and the easier one will switch to goods from (cheaper) non-abating countries, inducing higher leakage. Paltsev (2001) and Burniaux and Oliveira Martins (2012) fail to find a green paradox for very high values of the Armington elasticities. However, Burniaux and Oliveira Martins (2012) find that a very *low* elasticity, combined with full international capital mobility, might induce *negative* leakage: as imports and domestic goods are complements, an increase in the domestic price reduces imports, thereby reducing production and emissions in non-Annex I. Using a two-country two-input analytical model, Fullerton *et al.* (2011) find that full international capital mobility is not needed for this result: they find a negative leakage rate when the Armington elasticity for the final good is smaller than the elasticity of substitution between the energy input and the clean input.

The contribution by Babiker (2005) introduces the issue of increasing returns to scale in this literature. The author studies the effect of the obligations agreed upon in the Kyoto Protocol on international carbon leakage using a static model of the world economy, calibrated using 1992 data. The major contribution of this paper is the introduction of increasing returns to scale in the production of energy-intensive goods (due to a sunk cost; firms impose a mark-up over marginal cost; profits are still zero due to free entry and exit of firms). Under increasing returns to scale and perfectly homogenous goods, he finds that a green paradox (increase in global emissions) eventuates as a result of the introduction of the Kyoto commitments.

Copeland and Taylor (2005) introduce environmental damages due to a global pollutant in an analytical static two-good two-factor k-country trade model. Goods from different countries are homogenous (no Armington assumption; this favors strong terms of trade effects), and one good is pollution-intensive. The authors study the effect of an emission reduction by $k - 1$ countries on emissions by the kth country. Unilateral emission reductions induce free-rider effects as described in Section 5.1.1, but in addition they cause substitution effects in production (working in favor of leakage) as well as substitution effects in consumption (which works against leakage) and income effects in the demand for environmental quality (which works against leakage of country k is a dirty good exporter). The first and last effects are not present in CGE models as these do not allow for damages to affect utility and thereby a demand for environmental policy. Copeland and Taylor (2005) argue that *negative* leakage cannot be ruled out.

5.1.4 International Trade in Factors of Production

If environmental regulations in the cooperating countries reduce the rate of return to capital, and capital is internationally mobile, we may observe capital flight towards the non-cooperating countries. If more capital in the foreign country increases the marginal productivity of polluting inputs, foreign pollution will increase and thus offset emission reductions at home (see e.g., Maestad, 2007.[18]

Babiker (2001) studies the effect of different degrees of international capital mobility on carbon leakage using a forward-looking CGE model, based on data for 1992. He finds that carbon leakage is virtually unaffected by changes in the mobility of international capital. A similar result is found by Burniaux and Oliveira Martins (2012), who use a static model using data for 1995. As noted above, they even find that with high capital mobility, *negative* leakage rates are possible when the Armington elasticity for non-energy goods is low.[19] Using a two-country two-input analytical model, Fullerton *et al.* (2011) find a negative leakage rate when the Armington elasticity for the final good is smaller than the elasticity of substitution between the energy input and the clean input.

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[18] A related literature studies the effects of environmental policy on capital flight through manufacturing plant relocation decisions. Jeppesen *et al.* (2002) review the empirical literature through a quantitative meta-analysis and conclude that it is not possible to draw firm conclusions regarding the effects of environmental regulations on capital flows.

[19] Since the paper does not report the value of the elasticity of substitution between energy and value added, it is unclear where this result exactly comes from.

Kuik (2005) concludes that the CGE literature seems to suggest that capital flight to non-abating countries will not be of major significance in the context of the Kyoto Protocol, at least during the first commitment period (2008–2012). According to him, a major factor behind this result is the lack of absorptive capacity in developing countries. It should be noted, however, that most of these studies were performed using data from the 1990s. Since then, globalization has taken off and some countries — notably China — have found a central place in the world economy. Since trade with these countries as well as investments in developing countries have taken a big flight in the last 20 years, it is now easier to shift capital and production abroad than it was in the 1990s. Hence it would be interesting to study the effect of the trade in capital channel on carbon leakage using recent data.

5.1.5 Technological Change and Technology Spillovers

The fifth and most recent channel through which emissions by non-abating countries are affected after an emission reduction in other countries is through technology spillovers. Inspired by the literature on endogenous technological change (see e.g., Romer, 1990; Acemoglu, 2002), a literature on the effects of technological change and knowledge spillovers on (the costs of) climate policy has developed. Although only few papers brought this dimension into the discussion regarding carbon leakage, the effect of this channel is to *reduce* emission leakage, relative to models without endogenous technology spillovers.

Golombek and Hoel (2004) introduce knowledge spillovers in a static analytical model where two countries have to decide how much to abate and how much to invest in R&D. By assumption, this investment reduces abatement costs. An exogenous fraction of R&D expenditures spills over to the other country. They show that under several model specifications it is possible that in response to increase in abatement in one country (due to greener preferences), abatement in the other country may increase as well, i.e., leakage may be *negative*.

Whereas in Golombek and Hoel (2004) R&D expenditures are beneficial for the environment by assumption, Di Maria and Van der Werf (2012) endogenize the nature of technological change. They use a dynamic analytical two-region two-sector model where both countries are technologically developed and have fully enforced intellectual property rights, but only one region has a cap on emissions (for example the EU vs. the US). Knowledge developed in one country fully spills over to the other as firms in each country can buy licenses to use blueprints developed in the other country. One sector emits carbon dioxide in its production process while the other is clean, and the two goods are used as an input for a final good through a CES production function. When investors can decide whether to invest in blueprints in one sector or the other (directed technical change), the tightening of the cap in the abating country decreases the size of the energy-intensive sector and hence the market for energy-complementing innovations, but at the same time this increases the price of energy. The net effect of these two mechanisms is always to increase the productivity of the abundant factor, thereby increasing the marginal productivity of the clean sector and reducing the share of energy. They find that, except for the case of a unit elasticity of substitution in final goods production, carbon leakage will be smaller with directed technical change than when the rates of technology of both sectors develop at an equal rate. Di Maria and Van der Werf (2012) show that carbon leakage will be *negative* if the elasticity of substitution in the final goods sector is sufficiently high.[20]

Gerlagh and Kuik (2007) build the mechanisms developed in Di Maria and Van der Werf (2012) into the static GTAP-E AGE model to study carbon leakage in the context of the Kyoto Protocol. They confirm that technology spillovers may lead to negative carbon leakage.

5.2 Leakage Rates Due to Unilateral Policy: Results From the Applied General Equilibrium Literature

In the previous subsection, we have presented five possible channels for a unilateral cutback in emissions to affect emissions in other countries. Three of these channels are present in most of the numerical models used in the applied general equilibrium literature. The technological change channel is only present in Gerlagh and Kuik (2007) while the marginal damages channel is absent in all models.

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[20] Di Maria and Van der Werf (2012) argue that a transformation of this elasticity can be interpreted as the demand elasticity for a composite fossil energy product, and the condition for negative leakage is then that this elasticity should be larger than 2. Empirical estimates for ‘broad’ energy tend to be lower than this value, while estimates for individual fossil products can be higher, so the elasticity for ‘composite fossil energy’ (which is broader than individual fossil energy products but narrower than aggregate energy) may indeed be higher than 2.

The leakage rates found in the AGE literature are generally moderate and range from negative (Gerlagh and Kuik, 2007, due to knowledge spillovers; Burniaux and Oliveira Martins, 2012, for the case with low non-energy Armington elasticities and high capital mobility) to some 30% (see, e.g., Felder and Rutherford, 1993; Perroni and Rutherford, 1993; Elliott *et al.*, 2010; Böehringer *et al.*, 2010). The only exception — discussed in Section 5.1.2 — is the case of low coal supply elasticities in Burniaux and Oliveira Martins (2012), where leakage rates approach 100% as supply elasticities approach zero.[21]

The only paper in the AGE modeling literature to find a green paradox is Babiker (2005). In the version of his model without increasing returns, and with the assumption of regionally differentiated goods (Armington assumption) the author finds a leakage rate of 20%. Introducing increasing returns to scale in the production of energy-intensive goods, the leakage rate increases to 25%. With a globally integrated world market for these goods (Armington elasticity going to infinity), and assuming constant returns to scale, the leakage rate further raises from 20% to 60%. Finally, combining increasing returns with an integrated world market for energy-intensive goods leads to a leakage rate of 130%: global emissions increase in response to the Kyoto Protocol, and a green paradox occurs.

5.3 Carbon Leakage and the Green Paradox: Conclusions

Unilateral emission reductions can induce non-abating countries to change their emissions in response. We have identified five channels through which this may occur. None of the papers discussed above combines all the five channels, and the applied general equilibrium literature usually allows for three of them (energy market channel, terms of trade channel, and international trade in capital).

Within the large literature on carbon leakage, only two analytical papers and one AGE paper found that under specific assumptions a green paradox may occur, that is, that non-abating countries increase their emissions by a larger amount than the cut-back by abating countries such that global emissions increase in response to a unilateral emission reduction.

Hoel (1991) studied the marginal damages channel using an analytical model where a country's environmental damages depend on emission

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[21] However, in their base model, the leakage rate is a modest 4%.

reductions from its own abatement and the abatement level of the second country. With strictly convex damage and abatement cost functions, a green paradox may occur in the case where one country reduces emissions beyond the point where marginal benefits equal marginal costs, depending on the concavity of abatement cost functions.

The second paper is by Eichner and Pethig (2011), who use a two-period model with forward-looking agents and a nonrenewable resource and focus on the energy market channel. They find that a unilateral emission reduction may induce a global increase in first-period emissions if — in the case of an emission reduction in the first period — the intertemporal elasticity of substitution is sufficiently low or the demand elasticity for fossil fuels in the non-abating region is sufficiently high. They conclude that combining the Hotelling rule with the requirement of clearing the market for the consumption good in both periods tends to exacerbate carbon leakage when the first-period cap is tightened. This suggests interesting paths for new, quantitative research. Most AGE models are either static or recursively dynamic, i.e., they are not forward-looking models, let alone including nonrenewable resources. Simulations and sensitivity analysis using models with these characteristics (such as MERGE) could provide further insights in whether it is likely that a (weak) green paradox will occur due to international carbon leakage.

The third paper, Babiker (2005), uses a static AGE model, where leakage effects occur through the energy market channel (low supply elasticities for fossil fuels) and especially the terms of trade channel: increasing returns to scale in the production of energy-intensive goods combined with an integrated world market for these goods led him to conclude that the Kyoto Protocol will induce an increase in global emissions (weak green paradox). However, it should be noted that, when comparing the effect of an integrated world market for energy intensive goods with the case of Armington elasticities, Babiker also doubles the elasticity of substitution between the capital–labour–land composite on the one hand and energy on the other (from 0.5 to 1), and increases the elasticity of substitution between the capital–labour–land–energy composite on the one hand and intermediate inputs on the other (from 0 — the usual assumption in AGE models — to 1). The first change seems to suppress leakage effects (easier to substitute to non-energy inputs in Annex I countries and hence smaller price effects), while the effect of the second change is unclear. In addition, the benchmark mark-up and hence the degree of market power due to the increasing returns assumption depends on the benchmark market shares of each region. Hence, a scale effect occurs: the larger the aggregated region (a modeling assumption), the larger the degree of market power, and the larger the leakage effects due to increasing returns. By aggregating China and India in one region, and combining other countries as well (e.g., dynamic Asian countries, dynamic economies of South America, and — emissions reducing and hence working in opposite direction — OECD), stronger relocation effects can be expected compared to the case of no aggregation. It is therefore unclear what effects exactly are driving the green paradox result in Babiker (2005), and further research on the effect of increasing returns to scale on carbon leakage is required.

From this section it has become clear that the green paradox is not a general conclusion from the literature on carbon leakage. Its occurrence rather depends on specific assumptions. Indeed, several papers have shown the possibility of *negative* leakage: a reduction in emissions by countries (initially) without climate policy, in response to unilateral emission reductions by other countries. Still, it would be interesting to study the assumptions underlying the green paradox results more closely and include those elements that induce a green paradox under some conditions in other models. Using forward-looking models with nonrenewable resources seems especially interesting, as the (analytical) Hotelling models of Eichner and Pethig (2011) and Hoel (2011b) find the possibility of a Green Paradox occurring due to a unilateral in the stringency of climate policy. Furthermore, it is important that AGE models use recent data, due to the currently larger market shares of (generally non-abating) emerging economies on an increasingly integrated world market, as this could induce higher leakage rates.

6 Concluding Remarks

Based on the opening words of Sinn (2008), it is easy to get worried about the effectiveness of the suboptimal climate policies currently imposed. These worries are supported by the simple textbook models of nonrenewable resources: steeply rising carbon tax paths, implementation lags and subsidies for alternative energy sources all encourage resource owners to increase current extraction, leading to a (weak) green paradox as current emissions rise rather than fall. Indeed, this emissions rise may even lead to an increase in the net present value of climate damages: a strong green paradox. However, more complicated and realistic analyses — which include increasing extraction costs, upward-sloping supply curves for alternative energy, and an international dimension — seem to view the emergence of a green paradox less likely. Still, more research is needed to be able to draw any firm conclusions.

Several paths for future research seem promising. First, most papers discussed in this review model only one type of fossil fuel, and if a second energy type is included, it will be usually a perfectly substitutable clean alternative. In reality, however, different nonrenewable resources and different clean alternatives are directed at very different uses. As a matter of fact, even different nonrenewables need not be perfectly substitutable: coal is predominantly used in (base-load) electricity generation, whereas most oil is used in transportation (although some countries do have significant shares of electricity from oil), and gas is very effectively used in (peak) electricity generation, and tends to be used for space heating. Solar and nuclear energy serve to provide electricity, but are not used — not even in the distant future — for transport purposes. Identifying different demand sectors and more realistic modeling of substitution possibilities will probably further reduce the possibility for a green paradox to occur.

A second important direction for further research would be to incorporate more realistic market and policy features, such as the interaction between resource owners, who may have some market power (e.g., on the oil market), and governments aiming at emission reductions for fossil fuels, as for example studied in Gerlagh and Liski (2011). Another issue to consider would be the extent to which the policies studied in the green paradox literature are incentive compatible. As mentioned in for example Hoel (2012) and Hoel (2011a), governments may not be able to commit to the projected tax or subsidy paths. Expectations and hence credibility about future tax and subsidy paths are extremely relevant for climate policy, especially in the context of nonrenewable resources. Clearly more research on these issues is needed.

An alternative strategy for future research could be to simplify rather than to complicate models, as decision makers in the real world may not be as forward looking as assumed in the current models. Many oil-exporting countries do not think in long-term horizons, while Saudi Arabia (one of the main players on the market for one of the most important fossil fuels: oil) seems to act more like a market-maker — increasing oil supply when prices rise too fast in order to stabilize the price — than as an intertemporally optimizing resource owner.[22]

Based on the current green paradox literature, it is hard to draw any conclusions regarding the effect of imperfect policy designs on supply behavior, GHG emissions and climate damages. Clear-cut policy conclusions are even harder to draw. As noted above, more research using analytical models with more realistic features is needed. Overall, the most striking void in this literature is an empirical assessment of the green paradox, without which it is hard (if not impossible) to provide even order of magnitude estimates of green paradox effects. The only paper, to our knowledge, that confronts the green paradox with data on fossil fuel use is Di Maria *et al.* (2012a). They study the announced policy channel for emissions of sulfur dioxide (SO_2) in response to the signing into law of the 1990 U.S. Clean Air Act Amendments, using data on coal use at power plants in the period 1987–1999. Among other things, these amendments introduced a cap and trade system for SO_2 in the continental U.S. for the dirtiest (‘‘Phase I’’) power plants from 1995 onwards. The authors are able to identify a significant drop in the price of coal following the introduction of the 1990 CAAA, as predicted by the theoretical literature. Despite this drop in price, however, they are unable to find evidence that energy use and sulfur intensity increased in response to the announcement of the cap. Their explanation hinges upon the nature of the power generating industry in the U.S. and the degree of economic and environmental regulation that power generators are subject to. Whether these results can be generalized to other industries and countries, is up for discussion. Still, much more empirical research on the effects of imperfect environmental policies on resource use is needed.

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[22] Carl Christian von Weizsäcker at the Munich Economic Summit, 2009. See CESifo Forum 10(3), 2009, p. 20.

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