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Unintended Detrimental Effects of Environmental Policy: 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 under what conditions this so-called 'Green Paradox' may occur. We review this literature and identify the key mechanisms behind these paradoxical policy outcomes and highlight avenues for future research.

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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

Climate change is a global environmental problem affecting current and future generations with potentially dramatic consequences. Ideally, economists would like to tackle this problem by correcting the underlying externality by introducing immediately a world-wide price on greenhouse gas (GHG) emissions.[1] Unfortunately, immediate and world-wide action against GHG emissions has proven impossible. In reality, climate policy is implemented in a rather ad hoc manner, via a wide array of domestic carbon taxes, subsidies on clean energy and tradable carbon permit systems, changing over time, and differing from country to country, with many countries having no or hardly any GHG emission reduction policy at all. The "far-from-first-best" nature of these policies have lead to worries about their actual effectiveness. As the opening sentences from Sinn's thought provoking article on imperfect climate policies (Sinn, 2008) nicely illustrate, 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. Indeed, Sinn claims that it is possible that a Green Paradox occurs: global emissions might *increase* in reaction to green policies.

Sinn's article spawned a rapidly growing literature on the effect of imperfect carbon emission abatement policies on global emissions. The aim of this paper is to review this literature and to provide the reader with an insight into the underlying economic drivers. We identify four mechanisms that have the potential to generate a Green Paradox, and assess whether each mechanism can be expected to lead to an increase in emissions in reality. While Sinn focus is on the response of the owners of deposits of non-renewable resources, such as oil and coal, to climate policy, our review also includes papers that discuss imperfect climate policy without this element.

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[1] A large literature exists on the optimal paths of a carbon price and carbon emissions, see for example Ulph and Ulph (1994), Farzin and Tahvonen (1996), Hoel and Kverndokk (1996), Tahvonen (1997), and Rickels and Lontzek (forthcoming).

The first path leading to a Green Paradox is what Sinn defines as "gradual greening" in the context of rising prices for carbon dioxide emissions. This theme has been widely studied since Peter Sinclair's classic article with the telling title "High does nothing and rising is worse: carbon taxes should keep declining to cut harmful emissions" (Sinclair, 1992). We present a simple model of non-renewable resources and discuss under which assumptions a carbon tax may induce an increase in emissions. Following Gerlagh (2011) distinguish between a 'strong' Green Paradox, which occurs when cumulative damages from climate change increase in response to climate policy, and a 'weak' Green Paradox, which arises when climate policy increases current, immediate emissions.

Another mechanism that may generate a Green Paradox 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 1998, came into force in February 2005, and its first commitment period 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 3.

The third mechanism operates through Sinn's "demand reductions by a subset of countries". Ever since the topic of internationally coordinated GHG emission reduction policies appeared on policy makers' agendas, economists have studied the possible effects of these policies in the context of sub-global action. When a country or a group of countries reduces emissions, strong incentive emerge for other countries to *increase* their emissions in response, a phenomenon known as international carbon leakage. We discuss this literature in section 4, 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 weak Green Paradox occurs when the emissions increase by non-abating countries is larger than the emission reduction by abating countries, so that global emissions increase in response to unilateral climate policy.

The fourth mechanism focuses on policies aimed at reducing demand for fossil fuels via subsidies to alternative energy sources and via support for innovation. As (optimal) price paths for carbon dioxide emissions are often not feasible, policy makers often use the politically more palatable instrument of subsidies for clean energy technologies. When resource owners realize that a cheap alternative technology becomes available in the future, or that renewable energy gets subsidized, they might accelerate extraction in order to exhaust their resource stocks before they become redundant, leading to front loading of emissions and a (weak) Green Paradox.

Although we focus on the effects of climate policy on greenhouse gas emissions, it is obvious that the mechanisms we identify also apply to other environmental problems. As many of the papers included in this review take a non-renewable resource as the starting point, the 'climate' policies they study can be interpreted as any policy affecting resource use. Indeed, while the climate problem is one of a stock pollutant, many papers do not explicitly model pollution accumulation and hence provide useful insights for other environmental policies (for example policies aimed at reducing NO_x and SO_2 emissions) as well. In addition, although global warming necessitates global policies, several of the policies reviewed may also be discussed or implemented at the local level. In this sense, the relevance of the Green Paradox literature is broader, both in terms of pollutants and scale, than usually recognized.

2 Carbon price paths

As noted in the introduction, most of the literature on the Green Paradox, including Sinn (2008), assumes that carbon dioxide emissions stem from the use of a non-renewable resource. Although a large literature exists on optimal carbon tax paths when emissions stem from the use of a non-renewable resource (see e.g. Ulph and Ulph, 1994, Farzin and Tahvonen, 1996, Hoel and Kverndokk, 1996, Tahvonen, 1997, Rickels and Lontzek, forthcoming) we are interested in the effects of imperfect climate policy on emissions and resource extraction. To illustrate some of the basic mechanisms behind the effects of suboptimal climate policy in the context of non-renewable resources, we first sketch the basic ingredients for a simple model of resource extraction (see e.g. Hoel, 2010b, Gerlagh, 2011).

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

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

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

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

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

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

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

When does a carbon tax τ lead to unintended detrimental effects for the environment?[2] When does it lead to a Green Paradox? In terms of the model above, the degree of success of climate policy can be measured along three dimensions. The first dimension is whether a policy decreases initial extraction (and hence emissions). Greenhouse gas emissions accumulate in the atmosphere and it is the stock or concentration level of GHGs in the atmosphere that determines the size of the enhanced greenhouse effect and causes global warming when it gets too large. As part of the stock of carbon dioxide in the atmosphere is taken up each year by natural carbon sinks such as forests and oceans, postponing emissions means giving the natural carbon cycle time to dissolve part of the stock of GHGs in the atmosphere. Increasing current emissions, however, implies increasing the stock of GHGs for a long time as natural uptake of the additional emissions is a slow process.

The second dimension considers the amount of cumulative extraction: does the policy induce some resource owners to leave their deposits unused? Allen, Frame, Huntingford, Jones, Lowe, Meinshausen, and Meinshausen (2009) propose to restrict global emissions in the 1750-2500 period to 1 trillion tonnes carbon (1 TtC, 3.67 trillion tonnes CO_2). The idea behind this proposal is that policy targets based on limiting cumulative emissions of carbon dioxide are likely to be more robust to scientific uncertainty than emission rate or concentration targets. The global intertemporal carbon budget they propose, implies that some of the stocks of fossil fuels, for example coal, will have to remain unexploited. The authors find that total anthropogenic emissions of 1 TtC, about half of which has already been emitted since industrialization began, results in a most likely peak in carbon-dioxide-induced warming of $2°C$ above pre-industrial temperatures.

The third dimension along which the success of climate policy can be measured is whether the net present value of climate damages goes down or not. Following Gerlagh (2011) we say that a 'strong' Green Paradox occurs when the net present value of cumulative damages increases in response to climate policy, whereas a 'weak' Green Paradox occurs when climate policy leads to front loading of extraction (initial or early extraction increases).

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[2] Whenever we write 'tax', the carbon price can alternatively be interpreted as the price of a tradable emission permit on a competitive and optimally designed permit market.

2.1 Constant carbon emission price paths[3]

In the simplest version of this model (henceforth called 'Hotelling model'), we have $c(\cdot) = 0$, $\tau(t) = 0\ \forall t$ and no backstop, so the optimal extraction path gives

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

that is, total extraction equals the available resource stock $\bar{X}$, and

$$\dot{p}(t) = rp(t). \tag{3}$$

The latter equation is the well-known Hotelling rule (after Hotelling, 1931) which says that the return to the producer (here equal to the consumer price) must grow at the rate of interest. This equilibrium condition guarantees that the resource owner is indifferent between extraction at any point in time. If there were some period of time $[t_1, t_2]$ such that for any $t' \in [t_1, t_2]$ she could earn more than $p(0)\mathrm{e}^{rt'}$, she would shift extraction towards this period of time. Alternatively, if during this interval she would earn less than $p(0)\mathrm{e}^{rt'}$, she would shift extraction out of this period of time. In this 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. However, as soon as extraction costs are positive – which is obviously true in reality – a sufficiently 'large' carbon tax satisfying

$$\int_0^\infty D\left(\tau(t) + c(\cdot)\right)\mathrm{d}t < \bar{X} \tag{4}$$

will push the scarcity rent to zero for resource deposits with the highest extraction costs and induce their owners to leave some of these deposits unexploited (Hoel, 2010b). Hence, cumulative extraction over the entire time horizon goes down. Whether this is good or bad for the climate, depends on the exact time path of emissions and hence the time path of the carbon tax.

Following Hoel (2010b), assume that the carbon tax grows at a constant rate g. In addition, assume (4) is not satisfied. Then (1.a) becomes

$$\Pi = \int_0^\infty \left(\left(p(t) - c(\cdot)\right)\right) x(t)\mathrm{e}^{-rt} - \tau(0)\mathrm{e}^{(g-r)t}x(t)\big)\,\mathrm{d}t. \tag{5}$$

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:

$$\Pi = \int_0^\infty \left(p(t) - c(\cdot)\right) x(t)\mathrm{e}^{-rt}\mathrm{d}t - \tau(0)\bar{X}. \tag{6}$$

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[3] This subsection builds on parts from Hoel (2010b).

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 $g > r$, and assume that extraction costs $c(\cdot)$ are constant and equal to $c \geq 0$. Then 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.

Finally, consider the case of $g < r$, for example a constant carbon tax (still assuming constant extraction costs). Then initial discounted profits are lower than future discounted profits, the extraction path becomes flatter and initial extraction decreases: emissions are postponed.

Thus far, we have assumed that either the entire resource stock gets extracted over time, or condition (4) is satisfied. Let's now assume that even without a carbon tax, some of the resource deposits remain unexploited. For this, we move away from the Hotelling model and introduce the backstop technology, and assume that unit extraction costs $c(\cdot)$ are increasing in accumulated extraction $c(X(t))$. We denote this model the 'Heal model', after Heal (1976). With this model the amount of the resource that ultimately gets extracted $\bar{X}$ is endogenous, even without climate policy: it is determined by $c(\bar{X}) = b$. 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

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

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

where t_b is the time of the switch to the backstop.

From these equations it is clear that *any* carbon tax will induce some resource owners to leave deposits unexploited. This is a stronger result than in the Hotelling model (where extraction costs were zero) where a 'sufficiently high' carbon tax was required (see equation (4)).

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

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

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 the level of extraction and consumption must be lower, compared to the case of no carbon tax, 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 in time: again a stronger result than in the case of the Hotelling model.

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 (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 Paradox occurs then depends on the discount rate and the shape of the climate damage function.

Hoel (2010b) then introduces a two-period version of the Heal model. He assumes that extraction costs in the first period are zero whereas unit extraction costs are nondecreasing in cumulative extraction in the second period: $c'(X) \geq 0$.[4] Including a discount factor for the second period, Hoel is then able to study the effects of changes in (expectations about) the second period carbon tax using a simple model in which a discrete time version of the simple Hotelling rule (3) holds. Given some carbon tax levels for the two periods, an increase in the expected second-period tax unambiguously increases extraction and hence emissions in the first period: a weak Green Paradox. As energy becomes more expensive in the second period, resource owners increase their supply in the first period, inducing a lower scarcity rent and higher supply in period 1. As the time interval during which fossil fuels are extracted is fixed (and hence no backstop technology is needed), this result is stronger than in the continuous time version of the Heal model discussed above, where only tax growth rates sufficiently higher than the rate of interest induced a weak Green Paradox.

Hoel (2010a) extends this 2-period model with a backstop technology, but contrary to the Heal-with-backstop model discussed above, this energy source requires investment 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 investment is always positive. The author then studies the effects of

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[4] Note that $c'(X) >$ is needed to have an intertemporal problem; otherwise the resource is available at constant marginal cost and in infinite supply.

an increase in the second period carbon tax and finds that the results depend on marginal extraction costs and the share of the returns to investment in the clean energy source that are obtained in the first period. For sufficiently low (second-period) marginal extraction costs, an increase in the second-period tax induces a decrease in first-period extraction and an increase in investment in the alternative energy source. When marginal extraction costs are not too low and the share of the returns to the alternative energy source that are obtained in the first period is not too high, a weak Green Paradox occurs as first-period extraction increases, even though investment in alternative energy increases in response to the tax increase. When both marginal extraction costs and a are large, a weak Green Paradox occurs and investment in alternative energy decreases. The last two results are in line with the Heal model without endogenous investment, but the first result (no Green Paradox despite a rise in the future carbon tax) is different. In Hoel (2010a), due to low marginal extraction cost, first-period extraction is hardly affected by the higher tax. However, investments in alternative energy become more profitable due to the tax increase, which reduces the demand for fossil energy in the first period.

In sum: in the more realistic Heal model, a weak Green Paradox is less likely to occur than in the Hotelling model. Not only will any carbon tax induce some of the resources to remain unexploited in the former model, even a carbon tax growing at a rate slightly higher than the interest rate need not induce an increase in initial extraction. Endogenous investment in the alternative energy source may prevent a Green Paradox when marginal extraction costs are sufficiently low.

2.2 The problem of commitment and the role of expectations

In the previous subsection we 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 announcing the price path at $t = 0$, and (hence) is able to commit to this path. Although this is a common assumption 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 (2010b) uses the two-period version of the Heal model without a backstop, outlined above, to study this problem. In this 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 to 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 total stock is exogenous ($c' \to \infty$, so we have a 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 no surprise and 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', corresponding to the Heal case with full commitment discussed above. Hoel (2010b, p.22) concludes that "[f]or reasonable modeling of these expectations, a higher current carbon tax will reduce near-term emissions."

2.3 Carbon price paths and the Green Paradox: conclusions

As summarized above, a weak Green Paradox is less likely to occur in the more realistic Heal model than in the Hotelling model as any carbon tax will induce some of the resources to remain unexploited in the Heal model, and even a carbon tax growing at a rate slightly higher than the interest rate need not induce an increase in initial extraction, both contrary to the Hotelling model.

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 are a possible line for further research. In addition, it is clear that modeling alternative energy sources as a perfectly substitutable alternative is too simple, as non-renewable resources and clean alternatives need not serve the same markets. Indeed, different non-renewables need not serve the same markets: coal is near-exclusively used in electricity generation; most oil is used in transportation (although some countries have a significant share of electricity from oil); most gas is used in electricity generation, but some of it is used in space heating and transport as well.

3 Announcing climate policy in advance

Above we have assumed that the carbon tax is immediately and unexpectedly introduced, and that there is only one resource in the economy. 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 in case of an international agreement such as the Kyoto Protocol), administrative procedures and the idea that announcing policy before actually implementing it gives agents time to adjust, and hence reduce the costs of compliance, all make for a time lag between the instant at which agents first learn or expect that a policy will be introduced and the instant of actual implementation. During this ‘interim phase’, 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 in 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.

3.1 Announcement effects with non-renewable resources

Di Maria, Smulders, and Van der Werf (2008) use a model related to the Hotelling model outlined above (with demand stemming from a general, strictly concave utility function) and assume that a cap on the flow of emissions is announced at $t = 0$ and 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, then it jumps up at $t = T$ to make sure the emission cap is not violated, and then it declines until at some point in time the resource stock has become sufficiently small, so that without climate policy, extraction and hence emissions are so low that the cap is no longer binding. Di Maria, Smulders, and Van der Werf (2008) 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). They then show that the announcement of the cap induces an increase in the level of energy use and hence resource extraction during the interim phase.[5] As the resources become abundant during the period in which the ceiling is binding since less can be extracted than what agents prefer, and as resource owners want to exhaust their resource stocks, the resource price (scarcity rent) during the interim phase is 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.

A similar result is found in Eichner and Pethig (2010) for the case of one resource but multiple countries. They use a 3-region, 2-period Hotelling-type model where one region exports a non-renewable 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

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[5] Interestingly, Di Maria, Smulders, and Van der Werf (2008) 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.

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 above, the entire resource stock will get exhausted over time. Apart from climate policy the resource-importing regions are symmetric. All agents are price takers and the final good and resource markets clear at each point in time. Among other things, the authors are interested in the effect of a change in the emissions cap of the abating region on carbon leakage, which they define as an increase in emissions by the non-abating region in the first period. A (weak) Green Paradox occurs when global emissions increase in the first period. 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) the 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 in response to a tightening of the second period cap by the abating region may occur when the intertemporal elasticity is sufficiently small and the period-2 cap is not too tight.

The results found by Di Maria, Smulders, and Van der Werf (2008) do not depend on parameter values, since they study the case of a closed economy, and besides the resources, no other goods are produced in the economy. However, 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). To study the effect on relative extraction, and hence emissions intensity of energy use, Di Maria, Smulders, and Van der Werf (2008) assume that two perfectly substitutable resources that differ in their carbon content exist. In the period during which the cap is binding, a positive emissions price (e.g. a permit price, or a carbon tax) exists, which makes high-carbon inputs relatively less attractive than low-carbon inputs. Indeed, since – given the cap – the highest level of energy use can be obtained by using only the low-carbon input, as this gives more energy per unit of emissions, this input becomes relatively scarce if the stock of this resource is too small to use this fuel exclusively during the period in which the emissions cap is binding. If this is the case, the relative price (scarcity rent) of the cleaner fuel will be higher as compared to the case of laissez faire. The authors show that (expected) emissions intensity will not decrease due to the announcement, and that it will go up when the initial stock of the low-carbon input (e.g. natural gas) is too small to warrant exclusive use during the constrained period, and the initial stock of the high-carbon input (e.g. coal) is large. In this case, 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, Smulders, and Van der Werf (2008) 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.

3.2 Announcement effects *without* non-renewable resources

Smulders, Tsur, and Zemel (2010) approach the same problem – announcement of a carbon price – from a different perspective. Like Di Maria, Smulders, and Van der Werf (2008) they use a closed-economy continuous time model, but they abstract from non-renewable resources and instead assume that fossil energy is never scarce, and available at constant marginal costs. A second, perfectly substitutable energy source comes from a specific capital stock at zero marginal cost (and can be thought of as solar energy). Output comes from a constant returns to scale production function with a capital stock, inelastically supplied labour, and energy. Consumers have the standard strictly concave instantaneous utility function and can choose between investment in the general capital stock or the capital stock for solar energy. Without (announcement of) climate policy, and assuming fossil energy is not 'too cheap', there will ultimately be a transition from fossil to solar energy as investment in the initially more productive general capital stock drives down the rate of return in investment in this stock, which makes investment in solar energy more attractive over time. The authors assume that announcement at $t = 0$ that a carbon price will be introduced at time $T > 0$ does *not* make solar energy competitive during the interim phase. However, it may become competitive from the instant of implementation of the carbon tax onward.

The positive carbon price from $t = T$ onward implies lower fossil energy use and lower productivity of the general 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 general 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, Tsur, and Zemel (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. This weak Green Paradox occurs whether or not solar energy becomes competitive from the instant of policy implementation onward. 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.

3.3 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.

For this announcement effect to occur it is not necessary that emissions stem from a non-renewable 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 stem from non-renewable 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, depends on the time path of the social cost of carbon, which is not modeled in any of the papers discussed in this section.

Although only few papers have studied the effects of policy announcement on emissions, the result that a weak Green Paradox may occur seems robust as the fundamentals underlying those papers differ significantly. Of course, more research in this area is warranted, preferably using models based on real-world data.

4 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 – a problem that was already touched upon above when discussing Eichner and Pethig (2010) in the context of announced policy.

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.[6] 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".[7] In this context, a Green Paradox is said to occur when global emissions increase in response to a unilateral emission reduction.

4.1 Five channels of carbon leakage

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 ele-

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[6] 'Unilateral' here means any subset of countries that fails to cover all countries.

[7] 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.

ments 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 non-renewable 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.

4.1.1 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 and is based on the public good aspect of unilateral emission reductions. Emissions of GHGs stem to a large extent from the use of particular products (in the context of CO_2 mostly fossil fuels) by firms and consumers. National authorities can (partially) correct for this externality by imposing policies (e.g. a carbon price) aimed at emission reductions. However, emission reductions are a public good: 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 damage cost 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 cost. If emissions are reduced in a particular country, marginal environmental costs will go down 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 damage costs. When countries behave non-cooperatively, global emissions will still go down.[8] This basic result has

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[8] 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.

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.

4.1.2 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 price for these goods will fall. As a consequence, the demand for these energy sources will increase in non-abating countries. 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. Demand responses depend, among other things, on the degree of market integration of each fossil fuel. Oil is a relatively homogeneous good, so the demand by one region can easily be substituted by demand from another region. Coal, however, differs strongly in type and quality over regions, and has higher transport costs per unit of energy. A fall in the price of a particular type of coal in a particular region will then not induce large substitution effects towards this type of coal in other regions. In AGE models, this effect is reflected by relatively low Armington elasticities for coal, compared to oil. In addition, the response to lower prices depends on the degree of intra-fuel substitutability as well as the degree of substitutability between energy and other inputs, such as labor and capital.

Burniaux and Oliveira Martins (forthcoming) discuss the sensitivity of leakage results for changes in the values of particular parameters in a simplified static AGE model. They use a 2-region (Annex I and the rest of the world) model with five inputs (a labour-fixed-factor composite, capital, oil, coal, low-carbon energy) and a non-energy final good. In their central case, oil is treated as a globally homogenous good, whereas the final good and coal are differentiated by region (i.e. non-homogenous; Armington assumption); the other inputs are non-tradable. The authors simulate the implementation of a carbon abatement target in Annex I equivalent to that of the first commitment period of the Kyoto Protocol. 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.

Their sensitivity analysis shows that their leakage result is insensitive to changes in the supply elasticity of oil, but rather sensitive to changes in the supply elasticity of coal, for low values of this elasticity. This reflects the fact that a zero supply elasticity leads to a leakage rate of 100%. For coal supply elasticities above 2 the leakage rate is below 20%. Unfortunately there is very little empirical evidence on coal supply elasticities, and values used in the AGE literature differ strongly. For example, Burniaux and Oliveira Martins (forthcoming) choose an elasticity of 20 in their central case, whereas Paltsev (2001) has a unit supply elasticity and Babiker (2005) has a value of 0.5. Paltsev (2001) also presents the results of sensitivity analyses regarding fossil fuel supply elasticities and finds a leakage rate of 4.7% when all supply elasticities are equal to 20, and a rate of 14.7% when all fossil energy supply elasticities are equal to 0.5.

Only few papers have studied international carbon leakage through the energy market channel using a model with non-renewable resources. Hoel (2011) uses a 2-country, continuous time, partial equilibrium model. The global resource market is based on the Hotelling model introduced in section 2: the resource is in fixed supply and extraction costs are zero, so the resource price grows at the interest rate. A perfectly substitutable clean backstop resource exists, supplied an constant marginal costs b. The two countries have the same domestic demand function for energy. Each country has an exogenous and constant carbon tax. 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 both countries then have the same constant tax rate, an increase in this rate in both countries has the same effects as the introduction of a constant tax in the Hotelling model, as discussed in section 2.1: the instant of the switch to the backstop is postponed, the extraction path becomes flatter, and initial extraction declines, so no Green Paradox occurs.

If the two countries differ in their initial carbon tax, things become more complicated. If one country increases its (constant) carbon tax, emissions unambiguously increase at each point in 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 (2011) 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.[9]

While Hoel (2011) uses a partial equilibrium model, abstracting from trade, Eichner and Pethig (2010) use a small general equilibrium model with a non-renewable to study the energy-market channel of 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 non-renewable 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. The resource stock is given and extraction costs are zero, so over time, the entire resource stock will get exhausted (over time fuel supply is perfectly inelastic, which favors carbon leakage). Apart from climate policy the resource-importing regions are symmetric. All agents are price takers and the final good and resource markets clear at each point in time. The authors are interested in the effect of a change in the emissions cap of the abating region on carbon leakage, which they define as an increase in emissions by the non-abating region in the first period. A weak Green Paradox occurs when this emissions increase is such that global emissions increase in the first period.

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[9] Hoel (2011) and, as we will see later, 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, Moreaux, and Tidball, 2008). In models of optimal carbon pricing such as Hoel and Kverndokk (1996) and Tahvonen (1997), the growth rate of the social cost of carbon depends on the rate of natural uptake and the *level* of marginal damages: the growth rate is smaller than the discount rate if the latter are higher than the rate of natural uptake. Hoel and Kverndokk (1996) show that the social cost of carbon starts to decline before the stock of accumulated greenhouse gases. 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.

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. The second effect is smaller the more price elastic aggregate fuel demand is in period 2, and the more price elastic the fuel demand of the non-abating region is in period 1. The third effect is larger the more price elastic is the aggregate fuel demand in period 2; the more price elastic is the fuel demand of the non-abating region in period 1, and the greater is the decline in the second-period price of the consumption good (which depends on the intertemporal elasticity of substitution of consumption). 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.

Next, Eichner and Pethig (2010) 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 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 (2010) show that the results are qualitatively unchanged when the abating region has a cap in both periods, and the second-period cap is unchanged.[10]

If the abating region faces a cap in period 2 and announces at $t = 0$ that the second-period cap is tightened, then the conditions for a Green Paradox are reversed as compared to a tightening of the period 1 cap, and in addition a lower period-2 final good price reduces likelihood of a Green Paradox. However, the authors also show that negative leakage – an emission *reduction* by the non-abating region in response to a tightening of the second period cap by the abating region – may occur when the intertemporal elasticity is sufficiently small.

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[10] 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.

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 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).

4.1.3 Terms of trade effects for non-energy goods

Unilateral carbon pricing increases the costs of producing carbon-intensive goods in countries that aim at emission reductions, 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) explicitly varies the values of the elasticity of substitution between domestic goods and imports, and the elasticity of substitution between imports from different regions to study the consequences for carbon leakage. Reducing the former from 4 to 1 and the latter from 8 to 4 reduces the leakage rate from 10.5% to 6.9%; increasing the former to 8 and simultaneously increasing the latter to 16 gives a leakage rate of 15.4%. Burniaux and Oliveira Martins (forthcoming) start with an elasticity of substitution between domestic and foreign goods (recall that they model only Annex I and non-Annex I) equal to 4. Increasing it to 20 does not push the leakage rate beyond 4%. However, a very *low* elasticity 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.

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 the two countries are homogenous (no Armington assumption; this favors strong terms of trade effects), and one good is pollution-intensive. By assumption, one region reduces emissions, while the unconstrained region is a dirty good exporter. Unilateral emission reductions induces free-rider effects as described in section 4.1.1, but in addition they cause substitution effects in production (working in favor of leakage) as well as substitution effects in consumption and income effects in the demand for environmental quality (both working against leakage). The first and last effect are not present in CGE models as these do not allow for damages to affect utility and thereby a demand for environmental policy. Whether, in the Copeland and Taylor (2005) model, unilateral emission reductions induce leakage, depends on the elasticities of marginal damage with respect to emissions and real income, the price elasticity of the dirty good with respect to emissions, as well as on the pattern of production and trade. The authors argue that *negative* leakage cannot be ruled out.

4.1.4 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).[11]

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

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[11] A related literature studies the effects of environmental policy on capital flight through manufacturing plant relocation decisions. Jeppesen, List, and Folmer (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.

by Burniaux and Oliveira Martins (forthcoming), who use a static model using data for 1995. They even find that with high capital mobility, *negative* leakage rates are possible when the Armington elasticity for non-energy goods is low.[12]

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 in 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.

4.1.5 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. However, only few papers brought this dimension into the discussion regarding carbon leakage. 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 (2008) endogenize the nature of technological change. They use a dynamic analytical 2-region 2-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

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[12] 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.

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. In their first model, both sectors have the same (endogenous) rate of technological change and a tightening of the unilateral emissions cap induces an increase in emissions by the other region (carbon leakage) through a terms of trade effect, but global emissions decrease. Next they study the case where the rate of technological change can differ endogenously between sectors. That is, 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 (2008) show that carbon leakage will be *negative* if the elasticity of substitution in the final goods sector is sufficiently high.[13]

Gerlagh and Kuik (2007) build the mechanisms developed in Di Maria and Van der Werf (2008) into the static GTAP-E AGE model to study carbon leakage in the context of the Kyoto Protocol. They find that without technological change and the knowledge spillover channel, leakage is 13.8% in the case where Annex I countries comply with their Kyoto targets, while it is 16.8% for the case where the US and Australia do not comply. Introducing technology spillovers unambiguously reduces carbon leakage, while if more than 30 percent of the input-substitution induced by unilateral climate policy would be due to input-saving technical change and if this technical knowledge would freely spill over between countries, carbon leakage could indeed become negative.

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[13] Di Maria and Van der Werf (2008) 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.

4.2 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 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.

The leakage rates presented above range from negative (in Gerlagh and Kuik, 2007, due to knowledge spillovers) to some 15%. The only exception – discussed in section 4.1.2 – is the case of low coal supply elasticities in Burniaux and Oliveira Martins (forthcoming), where leakage rates approach 100% as supply elasticities approach zero.[14] Other papers find moderate leakage rates (for a range of policies and assumptions) as well: Felder and Rutherford (1993), Perroni and Rutherford (1993), Elliott, Foster, Kortum, Munson, Pérez Cervantes, and Weisbach (2010) and Böhringer, Fischer, and Rosendahl (2010) do not find leakage rates higher than 28%.

Only one paper in the AGE modeling literature presents a case where a Green Paradox occurs. Babiker (2005) studies the effect of the obligations agreed upon in the Kyoto Protocol on international carbon leakage using a static model of the world economy, with unit supply elasticities for oil and gas, an elasticity of 0.5 for coal, and data for 1992. 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). The model without increasing returns, and with the assumption of regionally differentiated goods (Armington assumption) gives a leakage rate of 20%, which is close to the upper bound of the rates found by the models discussed above. Introducing increasing returns to scale in the production of energy-intensive goods increases the leakage rate to 25%. Introducing a globally integrated world market for these goods (Armington elasticity going to infinity), but assuming constant returns to scale, increases the leakage rate from 20% to 60%. 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.

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[14] Recall that Paltsev (2001) only finds a leakage rate of 14.7% in the case of a supply elasticity of 0.5 for all fossil fuels.

4.3 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 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).

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 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 of cooperative behaviour through side payments, depending on the concavity of abatement cost functions. Since marginal damage costs levels are hard to quantify in reality (see the wide range of estimates in Tol, 2009), let alone exact marginal damage *functions*, it is hard to include the marginal damage channel in the quantitative literature on carbon leakage.

Eichner and Pethig (2010) use a two-period model with a non-renewable 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 the requirement of clearing the market for the consumption good in both periods combined with the Hotelling rule 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 non-renewable 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.

Babiker (2005) uses an 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). 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. Hence, further research on the effect of increasing returns to scale on carbon leakage is required.

Clearly, 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 could provide important further insights. Taking into account the role of non-renewable resources seems especially interesting, as the (analytical) Hotelling models of Eichner and Pethig (2010) and Hoel (2011) 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 the world market, as this could induce higher leakage rates.

5 Supporting alternative energy technologies

Thus far we have discussed the effects of imperfect policies aimed at reducing GHG emissions through a price on CO_2. Alternatively, one can try to promote the use of clean energy sources, so less of the carbon-emitting kind is needed, and the costs of meeting a particular emission target can be reduced. However, large-scale affordable clean energy sources do not exist at the moment (except for nuclear energy, which has its own disadvantages). In order to stabilize GHG concentrations, a 'technological revolution' is required (Barrett, 2009), which in turn requires support for clean energy technologies that currently are not more than ideas, or are at most about to enter the stage of diffusion. Indeed, Barrett (2006) argues that an effective climate treaty must promote both the public good consisting of emissions reductions, and the public good consisting of knowledge of new technologies that can lower mitigation costs.

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 R&D for new nuclear energy technologies to subsidies for biofuel production and adoption subsidies for solar and wind energy. In this section, we make a distinction between clean energy technologies available at constant marginal cost (the backstop technology introduced in section 2; these technologies could be thought of as nuclear or solar energy) and energy technologies with upward-sloping supply curves (such as biofuels that compete for land with other uses). The support for these technologies can come 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.

5.1 Alternative energy at constant marginal cost

As in section 2, we start with the simple Hotelling model with zero marginal extraction costs, but now extended with a backstop technology available at constant marginal cost b. Since the two energy technologies are perfect substitutes and the price of the non-renewable 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

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

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, e.g. a subsidy for R&D for alternative energy technologies, that reduces the marginal cost of the clean backstop technology on the extraction and emissions path? From the last equation it is easy to see that this 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, which in turn reduces the equilibrium resource price. Hence the reduction of the marginal cost of the backstop increases extraction at each point in time: a weak Green Paradox occurs (see also Gerlagh, 2011). As a consequence, the instant of the switch to the backstop is earlier, as compared to the case of the higher backstop price.[15] Assuming that marginal damages grow at a rate lower than the interest rate, Gerlagh (2011) also 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.[16]

Van der Ploeg and Withagen (2010) extend the Hotelling model with damages from the stock of CO_2 in the atmosphere through an additively separable quadratic damage function (a common assumption in this literature, see e.g. Hoel and Kverndokk, 1996, Tahvonen, 1997), and assume that unit extraction costs are linearly increasing in cumulative extraction.[17] These two assumptions make that along the socially optimal extraction path the (finite) resource stock need not be exhausted at the instant of the switch to the backstop. However, if the marginal cost of the alternative energy source is sufficiently high, or marginal damages are sufficiently low when the entire resource stock is exhausted, the resource stock will be exhausted at this instant, and the model is *de facto* of the Hotelling type, as in Gerlagh (2011). Using a linear demand function, van der Ploeg and Withagen (2010) find both the weak and the strong Green Paradox for the Hotelling model as well.[18]

Hoel (2011) shows that the weak Green Paradox also occurs in a partial equilibrium two-country Hotelling model, with countries differing in the stringency of their emissions reduction policy: as the scarcity rent and hence the consumer price go down in response to the lower price of the

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

[16] See footnote 9 for a discussion of the assumption that the social cost of carbon grows at a rate lower than the interest rate.

[17] 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 9 for a discussion.

[18] Despite the strong Green Paradox, total welfare (i.e. discounted welfare from energy use minus discounted damages) increases in response to the (free) decrease in marginal cost of the backstop.

backstop, near-term emissions increase. For a sufficiently small difference between the tax rates of the two countries, the two regions combined respond as in the closed economy model 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 the strong Green Paradox occurs as well. Hoel (2011) shows that the country with the higher tax will always make the switch earlier, but the instant of the switch by the low-tax country depends on its elasticity of demand for energy. 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, and, if the social cost of carbon declines over time, the strong Green Paradox need not occur.

When instead of a cost reduction both countries introduces an identical subsidy, a strong and weak Green Paradox occur when the difference in tax rates is sufficiently small and both countries introduce an identical subsidy. 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. However, when the tax difference is sufficiently large, the strong Green Paradox need not occur, depending on demand elasticities. A weak Paradox will also occur following a unilateral subsidy increase when both countries have the same tax rates but different subsidy rates. If the subsidy is increased in the country that initially has the lowest subsidy, a strong Green Paradox occurs as well.

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. 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 (constant marginal) extraction costs has to grow at rate $r + \lambda$. Then there are two effects of the treaty on cumulative extraction at any point in 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’s 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.

Next, Strand (2007) studies the case where once a treaty is signed (at $t = 0$), it takes S years before the probability λ plays a role. This lag seems 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 S, cumulative extraction increases as a result of the technology treaty.[19]

Next to studying the effects of a lower marginal cost of the backstop in the context of the Hotelling model, Gerlagh (2011) and van der Ploeg and Withagen (2010) also study the case of the Heal model introduced in section 2. The model of van der Ploeg and Withagen (2010) has the properties of the Heal model when, in their model, the marginal cost of the backstop is sufficiently low such that the resource stock will not be exhausted at the instant of the switch to the backstop. In this case, a marginal reduction in the cost of the backstop does *not* induce a Green Paradox as extraction and emissions are lower at each point in time compared to the case of a higher backstop price.

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, 2010). 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. So contrary to van der Ploeg and Withagen (2010), Gerlagh 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, as in van der Ploeg and Withagen (2010).

The difference in the results regarding the Heal model stems from the different conditions of the resource stock and (marginal) damages in the two papers. Whereas Gerlagh (2011) assumes the resource to be inexhaustible, van der Ploeg and Withagen (2010) assume an exhaustible resource, which leads to a slightly different extraction cost function. More importantly, whereas Gerlagh (2011) looks at *any* extraction path, van der Ploeg and Withagen (2010) study the effects of a lower marginal cost of the backstop along an *optimal* extraction path. These two differences in modeling lead to different results for the quantity of the resource left *in situ* at the instant of the switch to the

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[19] Note that this resembles the announcement effects studied in section 3.

backstop and the timing of this instant.

Van der Ploeg and Withagen (2010) also study the policy of a subsidy to the alternative energy source, in the absence of a carbon tax. Assuming that the social marginal cost of public funds is equal to unity (no deadweight loss), van der Ploeg and Withagen (2010) show that if the extraction cost of the last unit of the resource are lower than the marginal cost of the backstop and the marginal damage from carbon dioxide is sufficiently high (so it is optimal to exhaust the resource stock), a per-unit subsidy for the backstop induces both a weak and a strong Green Paradox. Indeed, under these conditions 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 in 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 non-renewable immediately, or compensate resource owners for not exploiting their resource. If marginal costs of the backstop and of extraction are such that it is optimal to leave some of the resource deposits *in situ*, no Green Paradox occurs in response to the subsidy as the switch to the backstop is made earlier and more reserves remain unexploited, and it is optimal to subsidize the alternative energy source.

In sum: with constant marginal costs for the backstop, in both the Hotelling model and the Heal model a weak Green Paradox may occur 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.

5.2 Alternative energy with an upward-sloping supply curve

As noted above, 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, Kompas, and Long (2010) model linear 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 in time and lengthens the period over which the resource is used, while the (joint) use of the alternative energy source is higher.

Although Grafton, Kompas, and Long (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 emissions from electricity production go down. However, CCS reduces the efficiency of a power plant (more energy per unit of electricity is needed due to the CCS capture process) and comes with monetary costs for capture, transport and storage. Hoel and Jensen (2010) assume that CCS is capable of bringing emissions from fossil fuel use to zero, but do assume that it comes at a money cost and an 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 non-renewable resource is available during the first period, while all three energy sources (fossil, fossil with CCS, and renewable) are 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, Frame, Huntingford, Jones, Lowe, Meinshausen, and Meinshausen, 2009), such that without CCS, part of the resource stock has to remain unexploited, while with CCS this same amount has to be captured. They abstract from natural uptake so each unit of emissions reduces the remaining carbon budget with one unit. Before we discuss the case of lower costs for CCS, we first continue the discussion of lower 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, Kompas, and Long (2010), who did not find a Green Paradox following a cost reduction for the alternative energy source. However, in the latter two papers, a lower backstop price reduced demand for the non-renewable in each point in time. In Hoel and Jensen (2010), by assumption, only the non-renewable is used in the first period. The fall in the value of the non-renewable 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 reduces the opportunity cost for CCS in the second period, so the regulator has to lower the carbon price compared to the case of no cost reduction. This makes fossil energy use in the second period more attractive so extraction is postponed and first-period emissions decrease. The effects of a decrease in the energy cost 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 (2010a), investments in the alternative energy technology are endogenous (see section 2.1). A fraction a of the returns to these investments are obtained in the first period, the rest in the second. A per unit investment subsidy increases investment in the clean energy, but its effect on first-period emissions is ambiguous. Hoel (2010a) shows that for any level 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.

In sum: the case of an increasing supply function for renewable energy has mostly been studied using a Hotelling model. In the simplest version of this model, with linear demand and supply, no Green Paradox occurs in response to lower marginal cost of the backstop or a user subsidy. A weak Green Paradox has been found for two-period models.

5.3 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. Subsequent extensions of the Hotelling and models make a strong Green Paradox less likely to occur, if the model is in continuous time. Obviously, those extensions make the model more realistic, so perhaps Sinn's (2008) worries are justified based on simple theoretical models, but less so in reality.

Still, further research is needed. Imperfect substitution between fossil and renewable energy types and the combination of renewable energy policies with unilateral carbon taxes seem an interesting path for future research, although this will probably require the use of numerical models.

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 non-renewable 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, combining the mechanisms and insights from different models may very well lead to new or mutually reinforced unintended policy outcomes.

An important direction for further research would be to incorporate more realistic market 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 important issue 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 (2010b) and Hoel (2010a), 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 non-renewable resources. Clearly more research on these issues is needed.

An alternative strategy for future research could be to simplify rather than complicate models, as decision makers in the real world may not be as forward looking as assumed in current models. For example, 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.

Overall, the most striking void in this literature is an empirical assessment of the Green Paradox. Although some authors use numerical methods to solve models with non-renewable resources that are too complicated to solve analytically, these simulations provide no evidence as to the relevance of the Green Paradox. The large literature on carbon leakage on the other hand has a long history using simulation models calibrated using actual data, but these models usually lack non-renewable resources and forward-looking agents. Although such models do exist and have been used for climate policy simulations (see e.g. Bosetti, Carraro, and Tavoni, 2009, Blanford, Richels, and Rutherford, 2009), they have so far not focused on the kind of imperfect policies underlying the Green Paradox. Furthermore, past policy changes have hardly been used to study Green Paradoxes using econometric techniques. Since, as noted in the introduction, the Green Paradox is not only relevant for climate policy but also for other branches of environmental economics, the obvious next stage in the Green Paradox literature would be to take the theory to the data.

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