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Global Warming and the Green Paradox

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GLOBAL WARMING AND THE GREEN PARADOX*

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Abstract

Announcing a future carbon tax or a sufficiently fast rising carbon tax encourages fossil fuel owners to extract reserves more aggressively, thus exacerbating global warming. These policies also encourage more fossil fuel to be locked in the crust of the earth which can offset adverse weak Green Paradox effects. A renewables subsidy has similar weak Green Paradox effects. Green welfare drops (strong Green Paradox) if the beneficial effects for the climate of locking up more fossil fuel outweigh the short-run weak Green Paradox effects. Neither the weak nor the strong Green Paradox occurs for the first-best Pigovian carbon tax. Within the context of a green Ramsey growth model the qualitative nature of the different phases of fossil fuel and renewables use depends crucially on the initial stocks of fossil fuel reserves and capital. We examine how climate policies are affected by growth and development, and also when not the renewable but coal is the effective backstop.

Keywords: fossil fuel, renewables, coal, economic growth, global warming, carbon tax, Green Paradox
JEL codes: D81, H20, Q31, Q38

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Introduction

Climate change is a consequence of the accumulation of CO2 in the atmosphere. A substantial part of this is caused by burning fossil fuel, but increasingly also by the extraction process itself of fossil fuel such as the tar sands. Climate change comes about, to a large extent, due to the accumulation of atmospheric carbon resulting from emissions caused by burning a *finite* stock of fossil fuels. Emissions of greenhouse gases are uniformly mixing, so that it doesn't matter where in the world emissions take place. The world thus faces the challenge of dealing with a global negative externality. Climate change can be mitigated by (i) curbing fossil fuel demand by becoming more energy-efficient, (ii) switching demand from fossil fuels such as coal and tar sands to others such as gas which do less harm from a climate perspective, (iii) substituting fossil fuel for renewables, (iv) making fossil fuel obsolete by locking more fossil fuel in the crust of the earth, (v) sequestrating CO2, and (vi) moving directions of technical progress from dirty to clean or green growth. A credibly announced time path of future carbon taxes suitably differentiated for the carbon content of the different types of fossil fuel can deliver the mitigation measures (i)-(vi). However, if there are network externalities leading to insufficient pipelines for transporting CO2, sequestration subsidies are needed to deliver (v) (Jaakkola, 2012). Also, if markets fail to deliver sufficient green R&D, investment subsidies are necessary to get enough of (vi) (Acemoglu et al., 2012). If climate change is mitigated insufficiently, climate adaptation measures (e.g., dykes) are necessary.

Government failure arises if dirty fossil fuels such as coal or tar sands are subsidized and if renewables such as solar or wind energy are subsidized. Such well intended policies make fossil fuel owners extract their reserves more quickly and induce more rapid burning of fossil fuel and acceleration of global warming. This has been coined the Green Paradox (Sinn, 2008a,b; also see Sinn, 1981, 1982). Although renewables subsidies have an adverse effect on channel (i) (the Green Paradox) and an unclear effect on channels (ii), (v) and (vi), they bring forward the carbon-free age and encourage more reserves to be left untapped if the cost of extracting the last drop of fossil fuel is sufficiently expensive. Renewables subsidies thus reduce cumulative carbon emissions, which may overturn short-run Green Paradox effects. Government failure also arises if national governments are unable to coordinate and realize a global carbon tax, which may result from carbon leakage (a spatial version of the Green Paradox). Since a unilateral carbon tax raises fossil prices at home and depresses them in the non-participating countries via the channel of tax incidence, the lower fossil fuel demand at home is partially offset by higher fossil fuel demand abroad thereby rendering a unilateral carbon tax less productive.

To understand the various guises the Green Paradox can take, we must get to grips with first-best climate policies [3], modeling of the carbon stocks in the crust of the earth and the atmosphere, and the exhaustibility of fossil fuel. We focus at the important role played by backstops: perfect substitutes for fossil fuel, unconstrained by exhaustibility and infinitely elastically supplied at constant cost (cf. Tahvonen, 1997). Fossil fuels are available in limited amounts and their optimal intertemporal use must take account of any adverse effects on global warming. Furthermore, the optimal climate policy should determine the optimal order in which fossil fuels have to be extracted. The Herfindahl rule states that least-cost deposits are extracted first but with climate externalities the social and private cost of the different types of fossil fuels differ and the rule must be modified (Chakravorty et al., 2008).

The Green Paradox is firmly linked to fighting climate change through policies that curb fossil fuel demand and *intend* to flatten[4] the time profile of carbon emissions. Such policies can be counterproductive if they steepen rather than flatten the extraction path of fossil fuel – *despite good intentions*. The paradox occurs if demand-reducing policies become more stringent over time (Sinn, 2008a,b; Hoel, 2011a; Gerlagh, 2011) or if future carbon-free substitutes are subsidized (e.g., van der Ploeg and Withagen, 2012a).

Our review of the Green Paradox starts with pointing out that in designing climate policies one must take account of the supply of non-renewable resources. We thus sketch Hotelling's rule and highlight its consequences. Then we allow for welfare analysis in a global economy with stock-dependent extraction cost, climate change damages and utility deriving directly from using fossil fuel and renewables. We sketch the social optimum and describe the welfare effects of implementing suboptimal policies. A distinction is made between a no-policy scenario and the socially optimal outcome. A *weak* Green Paradox occurs if fossil fuel is pumped up more quickly in anticipation of cheaper renewables and a *strong* Green Paradox if green welfare falls (Gerlagh, 2011). Of course, social welfare not green welfare matters in evaluating climate change policies.

We argue that anticipation of cheaper renewables induces short-run weak Green Paradox effects, but this does not necessarily lead to a strong Green Paradox as green welfare might increase if it is optimal to leave some fossil fuel reserves untapped. The subsidy quickens exhaustion of fossil fuel and always curbs green welfare (strong Green Paradox) if fossil fuel is fully exhausted in finite time. However, cumulative extraction is endogenous with stock-dependent extraction cost. This implies that in order to evaluate

[3] See also Ulph and Ulph (1994) who deal with optimal dynamic taxation of fossil fuels and their detrimental effect on the environment and Sinclair (1994) who argues that with endogenous growth optimal fossil fuel taxes may fall rather than rise over time.

[4] Models of optimal fossil fuel extraction yield decreasing extraction over time. Initial optimal use of the exhaustible resource is smaller than without the externality (Withagen, 1994).

climate policies in terms of social welfare flattening or steepening of the extraction path matters, but how much cumulative carbon emissions are cut compared with the no-policy outcome matters too.

Next, we allow for an upward-sloping supply schedule for renewables. Renewables are still relatively expensive, especially when it comes to costs of increasing capacity, intermittence and repair (especially of offshore wind mills).[5] We argue that with this cost configuration the weak Green Paradox may result from a subsidy on renewables, but not if the backstop is much more expensive than fossil fuel. This may be the case for advanced nuclear which has a mark-up of 70% over conventional fossil fuel (Paltsev et al., 2009).

The next step is to investigate what happens if backstops contribute to global warming. Indeed, coal and shale oil have very high CO2 emissions per unit of energy and are abundant and relatively cheap. Others, such as tar sands, are very bad for global warming and expensive. This raises the issue of optimal ordering of extraction of fossil fuels and its Green Paradox effects. The assumption of fossil fuels and renewables being perfect substitutes in consumption or production is often made to get sharp analytical results. In reality fossil fuels and renewables are imperfect substitutes. We discuss several contributions that aim to capture imperfect substitutability and its consequences for the Green Paradox. We also extend the well-known Ramsey growth model with climate change, fossil fuels and renewables, and argue that Green Paradox effects are weaker for a developing economy. We should take account of policies that do not subsidize renewables directly but that subsidize R&D towards developing cheaper renewable technologies and that can kick-start green innovation. Then one can pose the question whether redirecting technical change towards green growth will enhance or mitigate Green Paradox effects. Before drawing conclusions, we briefly discuss the empirics of the Green Paradox.

For reasons of space we omit two important aspects of the Green Paradox. The first one is imperfect competition on resource markets, which may lead to limit pricing (e.g., Hoel, 1978 and 1983; Salant, 1979; Andrade de Sá et al., 2012) or shed new light on monopoly power on the oil or gas markets for the global climate challenge (e.g., Hassler, et al., 2010). The second has to do with announcement effects and implementation lags of climate policy which can be quite long. For example, the European Union Emissions Trading Scheme was announced in 2001 with a first commitment phase that started 7 years later. It also took a long time for the Kyoto Protocol to enter into force. Such time lags may give rise to the Green Paradox, even without fossil fuel being scarce (Di Maria et al. 2012; Smulders et al., 2012). Such issues are highlighted in the review of the Green Paradox by Di Maria and van der Werf (2012).

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[5] Solar energy is currently 50% more expensive than conventional electricity. Wind energy has the same cost and is (apart from intermittence) competitive. Biomass, CCS coal/gas and advanced natural gas combined cycle have mark-ups of 10%, 60% and 20% (Paltsev et al., 2009). These mark-ups for renewable energy sources are measured from a low base and may fall with a larger market share. Nuclear energy does not emit CO2 and is rather competitive already, possibly due to the neglect of the cost of disposing of nuclear waste.

Hotelling rule with a backstop.

Let the cost of extracting one barrel of fossil fuel be constant and the initial stock of fossil fuel reserves be given. Let there also be a carbon-free backstop which is a perfect substitute for fossil fuel and that can be produced in unlimited amounts at a constant unit cost. This cost exceeds the initial unit extraction cost of fossil fuel, because else fossil fuel would not be used. A competitive energy market requires that demand for energy equals supply of energy. Renewables supply will eventually become profitable if prices of oil and other fossil fuel rise high enough. The Hotelling (1933) rule states that, if supply of fossil fuel is positive, the rent on fossil fuel (i.e., the market price of fossil fuel minus the per unit extraction cost) grows at a rate equal to the (exogenous and constant) interest rate. This rule comes from the arbitrage condition which states that the return on keeping fossil fuel in the ground (the capital gains) must equal the return from taking it out of the ground, selling it and getting a return. Here fossil fuel and renewables are never supplied simultaneously because renewables are supplied at a constant price. Fossil fuel use comes to an end when the price of energy reaches the exogenous backstop cost at some future instant of time. Hence, there is supply of only fossil fuel initially and at some future moment in time the carbon-free backstop takes over. This switch time and the initial energy price follow from two conditions. First, demand and the energy price must be continuous, so that at the transition the energy price must equal the cost of renewables. Second, total fossil fuel extraction up to the switch equals the initial stock.

What is the effect of a specific carbon tax imposed on oil and other fossil fuel producers? Along intervals of time where profit maximization entails positive fossil fuel supply, the after-tax fossil fuel rent must grow at a rate equal to the rate of interest. Hence, if the tax is not prohibitively high, the equilibrium price path is unaffected if the tax rate increases itself at a rate equal to the interest rate. If the tax rate grows faster, the equilibrium price path gets steeper, which implies that (with the same total amount of fossil fuel extracted) there is more extraction initially and less later in the phase with only fossil fuel. Global warming is thus accelerated and green welfare falls (weak and strong Green Paradox). With a growth rate of the carbon tax smaller than the rate of interest, oil extraction and global warming occur less quickly.

What happens if at some instant of time, before the transition, the backstop cost is reduced? To facilitate the argument, let innovation take place at the outset and let new production cost still be larger than the unit extraction cost of fossil fuel. A new equilibrium emerges with a new price path in the phase with only fossil fuel. The new price path will lie below the old one throughout. Indeed, the new price is below the old one at the time of the new transition. Moreover, the two price paths will never cross.[6] Hence, as total extraction still equals initial reserves, the lower cost of renewables brings forward the date of transition

[6] If they would, the Hotelling rule tells us that they coincide forever, which contradicts the fact that they differ at the new transition time.

and thus fossil fuel extraction must increase during the shortened oil-only phase. If the reduction in the backstop cost is not due to ad hoc technical change but due to a time-invariant per unit subsidy, the extraction path steepens without changing cumulative extraction and thus creates a weak Green Paradox.

Several questions suggest themselves from this benchmark analysis of the Green Paradox:

1. When do climate change policies lead to higher initial extraction and CO2 emissions?
2. What kind of policies can depress cumulative CO2 emissions and leave more oil untapped in the crust of the earth?
3. What are the green and overall welfare consequences of climate policies?
4. How should climate policy be designed in order to avoid welfare losses and Green Paradox effects?

We will address these questions in the different frameworks that have been studied in the literature.

Stock-dependent extraction cost and climate damages

So far, all oil is fully extracted unless the carbon tax or the renewables subsidy is prohibitively high. Here we highlight that this is no longer so with stock-dependent extraction costs and convex global warming damages, because then the amount of fossil fuel left untapped can be increased by lowering the cost of renewables. Let damages enter welfare separable from utility from consumption[7], so overall welfare is utility of energy use minus damages from climate change minus expenditures on extraction and production of the backstop. Let emissions be proportional to fossil fuel use and let there be no natural decay of atmospheric CO2.[8] Let per unit extraction costs rise as fewer reserves are left and less accessible wells have to be taken into exploitation (or, at the micro level, as extraction of a single mine becomes more laborious as more is already extracted). We have a positive rate of pure time preference.

The first-best outcome maximizes social welfare taking into account that cumulative fossil fuel extraction cannot exceed initial reserves. If along a period of time renewables are used, their marginal utility should equal their marginal cost. If along a period of time fossil fuel is used, its marginal utility should also equal the marginal social cost of fossil fuel consisting of (i) the marginal cost of extraction, (ii) the scarcity rent which is the present value of all future marginal increases in extraction costs arising from extracting an extra unit of fossil fuel, and (iii) the social cost of CO2 which is the present value of future marginal

[7] Damages from climate change can enter preferences, production technology or both, multiplicatively or additively (e.g., Rezai et al., 2013).

[8] Since 80% of atmospheric carbon has an expected life of 300 years and the remainder of thousands of years, this may not be such a bold assumption and is used in most of the literature on the Green Paradox.

global warming damages resulting from burning an additional unit of fossil fuel.[9] The marginal social costs of fossil fuel are typically not constant, so fossil fuel and renewables will never be used in tandem. Moreover, fossil fuel extraction will come to an end at some future date with either full or partial exhaustion of reserves.

At the time of transition to the carbon-free era, the scarcity rent of fossil fuel (ii) is zero (e.g., Heal, 1976) and thus with partial exhaustion the marginal cost of extracting the last unit of fossil fuel plus the social cost of carbon (the marginal global warming damage for the from then on constant stock of atmospheric carbon resulting from burning the last unit of fossil fuel divided by the rate of pure time preference) must equal the cost of the renewable. This transition condition implies that the optimal stock of untapped fossil fuel increases as the cost of renewables falls, the carbon tax rises and society weighs the welfare of future generations more strongly (lower rate of pure time preferences). Indeed, an important objective of carbon taxation and subsidizing renewables is to lock up more oil, gas and oil in the crust of the earth to prevent the atmospheric carbon stock and the global mean temperature rising. However, if global warming damages are linear or not convex enough and extraction costs do not become very large as full exhaustion approaches, this transition condition cannot hold as oil remains fairly cheap and full exhaustion of reserves will prevail.[10] The only lever for climate policy is then how fast or slow global warming takes place, because the cumulative stock of CO2 emissions is constant.

Fig. 1 illustrates the case of partial exhaustion of fossil fuel (say, oil for short). On the horizontal axis is the oil stock left unexploited. The downward-sloping line represents the social cost of carbon (i.e., the present-discounted value of marginal global warming damages for each final stock of atmospheric carbon). The more oil is left in the ground, the smaller is the social cost of carbon at the time of transition. The upward-sloping line represents the production cost of renewables minus unit extraction cost of oil. It indicates that oil extraction gets dearer if less oil is left in the ground. The optimum is found at the point where the curves cross. A lower rate of pure time preference boosts the social cost of carbon and shifts out the downward-sloping locus, so more oil will be left in situ. Making extraction more expensive for every oil stock shifts down the upward-sloping locus and locks more oil in the ground.

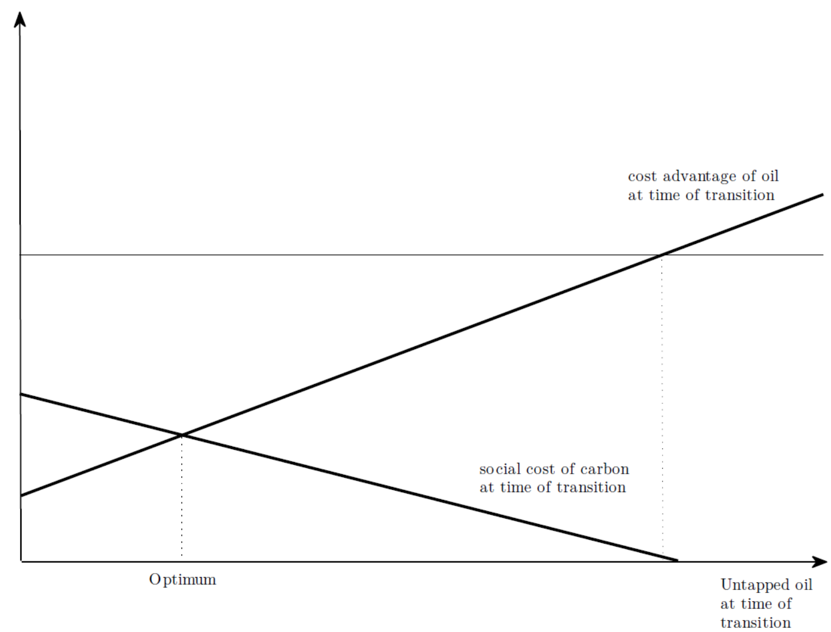
An exogenous decrease of the cost of renewables also shifts down this locus and leads to more oil left untapped and thus less global warming. This offsets the acceleration of global warming arising from

[9] The literature on integrated assessment models provides estimates of the social cost of carbon (e.g., Nordhaus, 2007, 2011) which have also been used, albeit with a lower discount rate, to obtain higher estimates of the social cost of carbon in the Stern Review (2007). More recently, simplified discrete-time Green Ramsey models of growth and climate change have been used to estimate the social cost of carbon too which manage to yield similar estimates (e.g., Golosov et al., 2013).

[10] If the social cost of oil is so high that the marginal extraction cost plus the social cost of carbon is higher than the marginal production cost of renewable, already at the outset, oil is never used.

short-run weak Green Paradox effects, so a strong Green Paradox need not necessarily occur. However, if oil is fully depleted and the reduction is marginal, oil is still fully depleted and transition takes place at an earlier stage. There is now a strong Green Paradox (green welfare unambiguously deteriorates), but overall welfare increases. If the renewables cost is close to its lower bound, below which no oil is extracted at all, the social cost of carbon is small, and with the cost close to its upper bound, above which all oil is extracted, the cost of carbon will be high. We conjecture that for values between these lower and upper bounds green damages increase. This observation is helpful in evaluating cost decreases due to a subsidy.

Figure 1: Determining the stock of oil to be locked in the earth



A Pigouvian market forces the market to internalize climate damages. The social optimum can be replicated in the market economy if this tax is set to the social cost of carbon with marginal damages evaluated at the optimal values. The optimal carbon tax always grows at a rate smaller than the rate of pure time preference[11], so the Green Paradox does not arise. If political reasons prevent the carbon tax being set optimally, several outcomes are possible. If it is optimal to fully exhaust the oil stock and the tax also leads to full exhaustion, total CO2 accumulation is unaffected. With a tax that increases fast but starts

[11] Damages are in terms of utility here, and so is the carbon tax. If we wish to have damages and taxes in money terms, we need to divide by marginal utility of consumption. If the marginal utility is constant, it does not matter.

from a low level, more emissions will result initially and the transition will take place earlier. There will thus be acceleration of global warming compared to the first-best. With a carbon tax that increases more gradually the result is reversed. It could also be that the suboptimal carbon tax leads to more oil to be left in the ground than in the first-best. But, in general one can say that a carbon tax that deviates not too much from the first best improves welfare compared to laissez-faire.

An alternative is to subidize renewables without taxing carbon. If the subsidy is large enough, oil reserves will not be fully exhausted even if reserves are fully exhausted in the no-policy scenario. In that case, there is a short-run Green Paradox effect with higher oil extraction rates during the oil-only phase. This phase is shorter as a consequence of the subsidy and more oil will be left *in situ* and thus less carbon will stay in the atmosphere. Although global warming is accelerated in the short run by the renewables subsidy, global warming is ultimately less. Whether a strong Green Paradox appears depends, among other things, on the weight attached to present damages relative to future damages. If atmospheric CO2 is severely damaging and the backstop is very expensive (the renewables cost more than extracting the last drop of oil), social welfare is increased by marginally *taxing* renewables in order to spread oil supply more evenly over time.

Cumulative emissions and the global climate challenge

Climate scientists are more concerned about cumulative CO2 emissions than the time paths of emissions. They may therefore be less concerned about temporary increases in emissions rather than the cumulative stock of emissions and fossil fuel use. Indeed, the change in global peak temperature depends principally on cumulative past carbon emissions (Allen et al., 2009; Solomon et al., 2009). To get a feel for the numbers, remember that half of emitted carbon returns to the surface of the earth and the oceans quickly and the other half stays in the atmosphere forever or hundreds of years. The initial stock of atmospheric carbon is roughly 0.5 TtC (trillion tons of carbon) and current fossil fuel reserves are 3 TtC. Cumulative emissions are then 2 TtC minus half of what is left of fossil fuel in the crust of the earth. To reflect that extraction becomes more costly as fewer reserves are left, let extraction costs be the inverse of the existing stock of fossil fuel. With production cost of renewables half higher than the current market price of oil, a price elasticity of energy demand of 0.85, an interest rate and rate of time preference of 1 percent per year (assuming quasi-linear preferences and a constant marginal utility of money) and ignoring decay of atmospheric carbon, we calculate the first-best optimal carbon tax and how much oil should be locked in the earth and compare these with the no-policy scenario (van der Ploeg, 2013).

In the no-policy scenario the market leaves 0.67 TtC of reserves untapped at the time of transition to the carbon-free era where the scarcity rent is zero. Extraction cost has then risen to the price of renewables (1/0.67 = 1.5 times the initial market price). Cumulative carbon emissions are 2 – 0.5 × 0.67 = 1.67 TtC, which corresponds to too much global warming. With a linear marginal damage function (and slope 0.04) the social cost of carbon is also linear in the amount of untapped fossil fuel. The social optimum at the time of transition must thus leave much more, 2 TtC, in situ, since now the extraction cost plus the social cost of carbon must equal the cost of renewables. The social optimum thus leads to only 1 TtC of carbon in the atmosphere and ultimately to less global warming than the no-policy scenario. In fact, as can be seen from fig. 2, this first-best policy leads throughout to lower carbon emissions.

Figure 2: Effects of renewables subsidy and optimal carbon tax

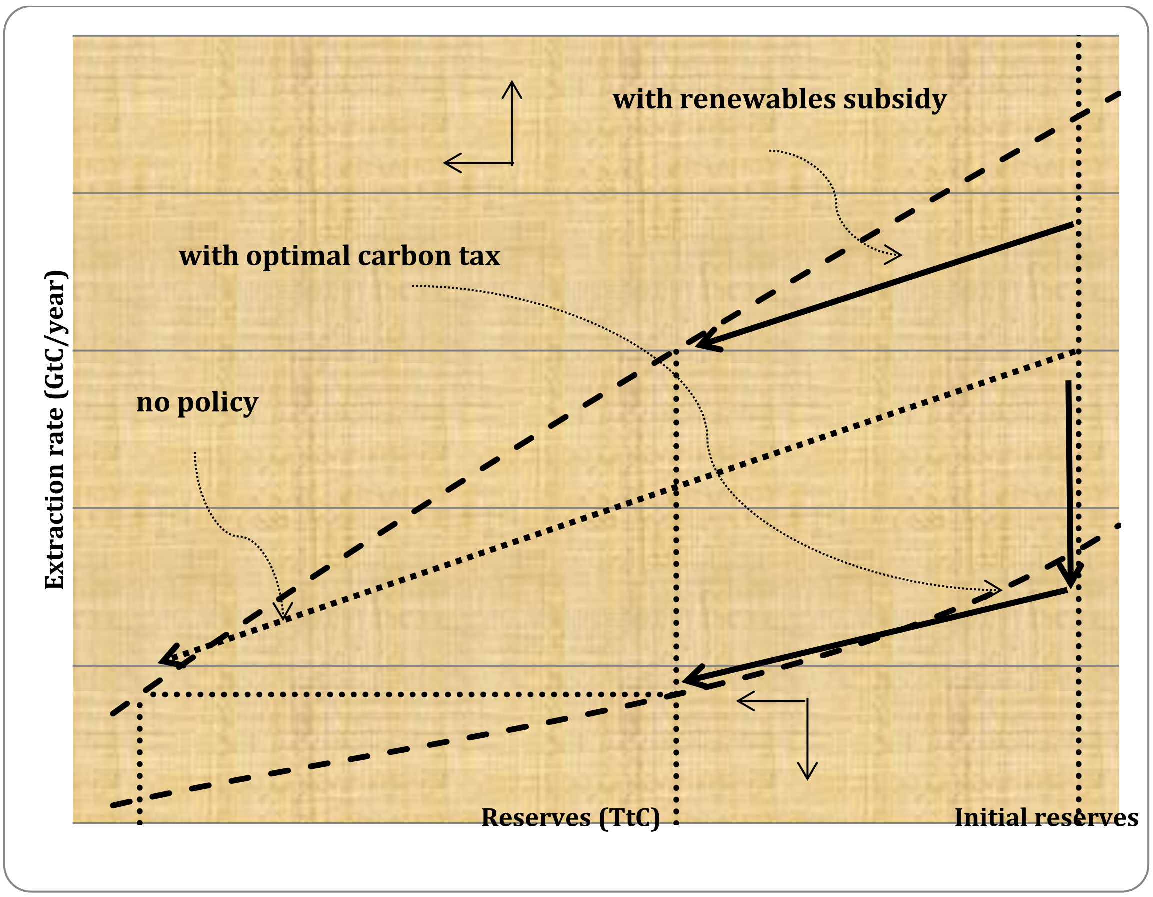
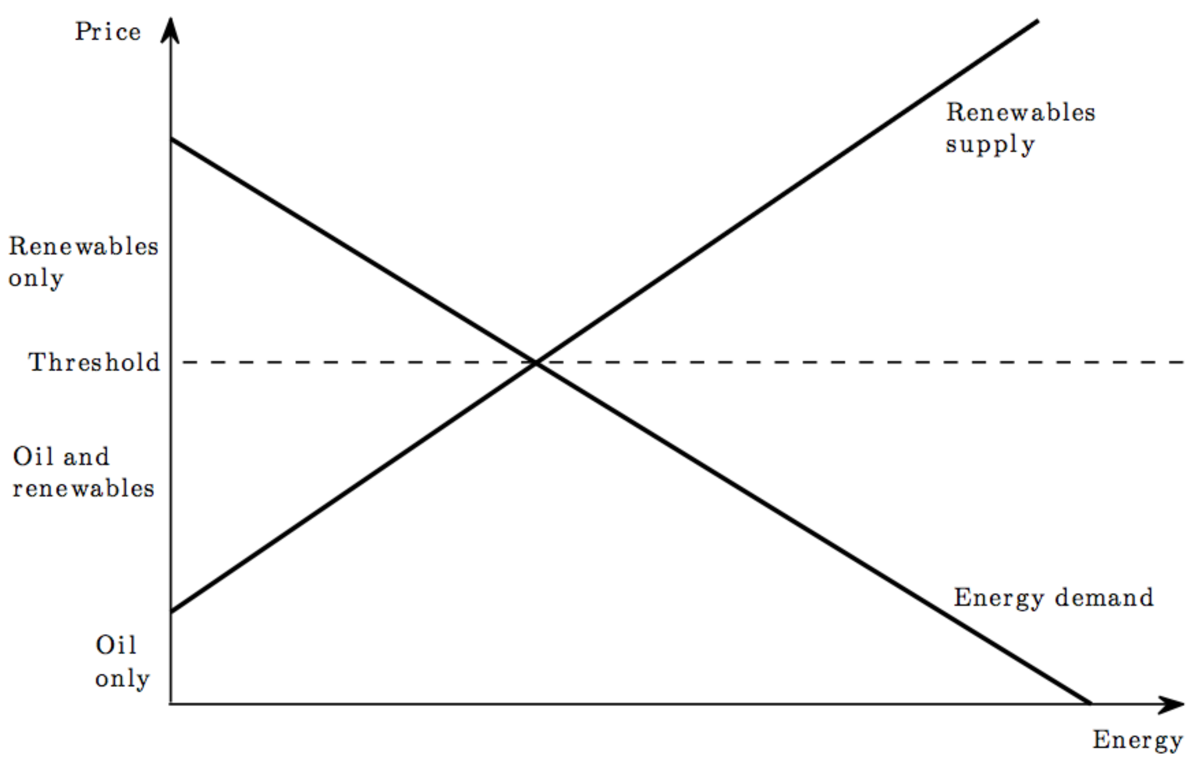


Fig. 2 also shows what happens with a second-best policy which subsidizes renewables by 60 percent. This incentivizes the market to also leave 2 TtC of carbon untapped in the crust of the earth and thus limits cumulative carbon emissions to 1 TtC. Short-run carbon emissions are higher than in the no-policy scenario, which reflects the weak Green Paradox. Since carbon emissions are higher and more carbon is left in the ground, the renewables subsidy manages to shorten the carbon era unambiguously. Whether green welfare falls or increases (i.e., whether there is a strong Green Paradox or not) depends on whether the adverse effect of short-run acceleration of global warming outweighs the beneficial effects of less cumulative emissions and an earlier start of the carbon-free era.

Upward-sloping supply schedule of renewables

The McKinsey Greenhouse Gas Abatement Cost Curve suggests that, as the price of energy increases, more and more fossil fuel substitutes become competitive. With increasing marginal cost of renewables the generic optimal sequence of fuel use is to have first only oil use, then a phase with simultaneous use, and a final phase with only renewables (van der Ploeg and Withagen, 2012a). The first phase is degenerate unless oil becomes very abundant. The third phase can be degenerate if the phase with simultaneous use never comes to an end.[12] For an illustration see Fig. 3.

Figure 3: Upward sloping supply of renewables



[12] With linear marginal cost of renewables we can identify the parameter values for which these outcomes are found. There exists also a simple inequality to identify full or partial depletion of oil.

Demand for energy decreases and renewables supply increases with the energy price. As long as the price is low, such that energy demand is larger than supply of renewables, part of demand (between the two lines in the figure) should be met by oil. This part is called residual demand for oil. There is a threshold price above which demand for oil is zero. If it is larger than the marginal cost of extracting the last drop of oil plus the social cost of carbon associated with fully exhausting all oil reserves, full exhaustion occurs within finite time. With a quadratic cost function a lower renewables cost follows from a lower slope of the marginal cost curve. For the regime with asymptotic exhaustion there are two possibilities. If renewables kick in at the outset, extraction of oil is unaffected, but asymptotically more oil is left in situ and thus the stock of atmospheric carbon is lower. If oil kicks in initially, then initially there will be more oil use and asymptotically more oil is left in situ as in the Green Paradox scenario already discussed.[13]

Grafton et al. (2012) consider a competitive economy with fossil fuels and renewables (bio-fuels), both perfect substitutes. They have linear energy demand function and a linear supply function for bio-fuels, as in Fig. 3. Their paper identifies two effects of an ad valorem subsidy. First, the supply function of bio-fuel rotates clockwise (as the subsidy is ad valorem) which entails, for each given price, a decrease in fossil fuel demand. Second, exhaustibility of fossil fuel implies that the initial energy price must fall, which enhances oil supply in case of constant marginal extraction cost. The sign of the effect on total emissions is ambiguous. Grafton et al. therefore consider several special cases. With linear demand, a linear supply function of the renewable, and constant marginal extraction cost an increase of the bio-fuel subsidy leads to later exhaustion of oil reserves and less oil supply throughout. With other demand schedules a weak Green Paradox may arise, particularly for a low supply elasticity of renewables. With stock-dependent extraction costs, linear demand and full exhaustion over time, a higher subsidy will cause a delay in exhaustion. The Green Paradox does not hold in this case.

Dirty backstops

Some substitutes for oil are dirty and abundant and can also be considered backstops. For example, coal is dirty and available in large amounts at a low cost. Global warming depends on the emissions from burning oil and coal, where coal has a higher emission coefficient. Let coal have a constant marginal cost of production. The most relevant case occurs if the marginal utility of energy is high enough to warrant oil or coal use forever, the production cost of coal plus the social cost of carbon for coal exceeds the initial extraction cost of oil plus the social cost of carbon for oil so that it is not optimal to use only coal,

[13] For the regime where exhaustion takes place in finite time, a lower backstop cost postpones exhaustion of oil if the backstop kicks in immediately. If there is an initial phase with only oil, oil extraction is lower initially, renewables are introduced more quickly but fossil fuels are exhausted more quickly as well.

and the social cost of coal grows faster than the social cost of oil so that the transition to simultaneous use must take place at some point in time. It can then be shown that the social optimum has an initial phase with oil use only, then a phase with simultaneous use of oil and coal, and a final phase with use of coal only (van der Ploeg and Withagen, 2012b).[14]

It is easy to see that in the absence of climate policy the market never has simultaneous use. If extraction of oil is expensive, only coal will be used. Otherwise the no-policy sequence is to first use only oil and then only coal. Subsidizing coal provides an incentive to the market for keeping more oil in the ground, but the initial use of oil increases (weak Green Paradox). Also coal is phased in more quickly. A coal subsidy is thus a bad policy from a climate perspective (strong Green Paradox). In contrast, a lower cost of coal in the social optimum leads to more oil use initially and a longer period of using only oil so that the simultaneous phase starts later. However, it lasts for a shorter period of time, because oil is phased out earlier. In the numerical simulations the long-run atmospheric CO2 concentration decreases considerably.

What happens if clean renewables are introduced aside coal? Under mild additional conditions the social optimum is to have first only oil use, then a phase with simultaneous use of oil and coal, subsequently only coal is used, and finally, only renewables are used. In this social optimum a lower cost of renewables leads coal to be phased out earlier. For the market economy, however, a subsidy on renewables obviously does not matter at all as long as the market price of renewables is above the market price of coal. If renewables are subsidized so that their price is marginally below the cost of coal, an overall welfare gain results if the renewables price is not too high as the loss due to the distortions from the subsidy is compensated by the gain in green welfare. An alternative policy instrument is a prohibitive tax on coal or a moratorium on coal which leads the market to delay the phasing out of oil considerably even though abandoning oil occurs still quicker than in the first best. After all, from a social perspective it is better to rely for longer on oil and delay the use of coal which emits much more carbon per unit of energy. This prohibitive coal tax is very successful in combating climate change. In a series of numerical simulations it performs much better than the subsidy, also in terms of overall social welfare.

Substitutability between energy sources

The studies on the Green Paradox surveyed so far suppose that fossil fuels and renewables are perfect substitutes in production or consumption. Long (2013) allows for imperfect substitutability of fossil fuel and renewables in the utility function, which depends in a linear way on income and contains a separate

[14] The final phase may not appear if the oil stock is asymptotically only partially exhausted along the phase with simultaneous use.

parameter that measures substitutability, ignores decay of atmospheric CO2, and has constant unit extraction cost of fossil fuel and unit production cost of renewables. The equilibrium has a first phase with simultaneous use. After oil is fully exhausted, only renewables are used. In the renewables-only phase the price and the quantity of renewables follow from equating demand and supply. The price of oil at the moment of transition follows from the requirement that consumption is continuous. A higher degree of substitutability then has two effects. First, higher substitutability lowers the price prevailing at the transition and, given the transition date, causes lower oil prices along the entire path towards the transition and hence higher oil demand. Second, for given oil prices, a higher degree of substitutability also curbs oil demand (after taking into account renewables demand). Long (2013) identifies cases where the degree of substitutability is sufficiently high for the first effect to dominate and a weak Green Paradox to occur. He also offers an example where a higher subsidy on renewables renders a weak Green Paradox less likely in the sense that the critical level of substitutability between the two energy sources is higher.

Michielsen (2011) allows for imperfect substitutability within the context of a two-period model with finite oil reserves, abundant dirty coal and a carbon-free renewable. A carbon tax for period two, announced at the outset of period one, thus gives rise to different oil and coal prices in the second period with a crucial role for the substitutability between oil and coal in periods one and two. This can be illustrated for the case of zero extraction cost of oil and constant unit production cost of coal. The Hotelling rule states that the return on keeping an extra unit of oil in the ground must equal the return of taking it out of the ground. Total demand over time for oil is restricted by the available stock of oil reserves. The demand functions for oil and coal in the two periods are isoelastic and depend on both the market price of oil and the market price of coal. The own price elasticities are constant over time, but cross price elasticities can vary over time. A small future cross price elasticity compared to the present cross price elasticity indicates low substitutability and implies that a future carbon tax leads to a higher future oil price and a lower oil price today. This significantly depresses demand for coal in period one, so that the weak Green Paradox does not arise. A similar reasoning applies for low substitutability in the first period and high substitutability in the future. Comparable results hold in a model with the clean backstop.

Di Maria et al. (2013) argue that the literature on the Green Paradox emphasizes the supply side of fossil fuel markets and accounts for marginal extraction costs, but has largely neglected demand side issues such as oil being mainly used for transportation and coal for electricity generation. This might be important for the magnitude of the Green Paradox. For example, electricity demand is not very responsive to price changes, so that large change in the price is needed to observe a significant increase in the demand for coal.

Space, trade and capital markets: carbon leakage and the Green Paradox

Carbon leakage occurs if the unilateral efforts of countries to curb CO2 emissions with a carbon tax depress before-tax oil prices and thereby boost CO2 emissions elsewhere in the world. It is thus a spatial version of the weak Green Paradox. Hoel (2011a) analyzes global warming in a two-country context. The representative consumer in each country derives utility from the use of energy, oil extraction is costless, renewables are available at constant unit cost, oil and renewables are perfect substitutes and preferences are identical for the two countries. With a constant, possibly different non-optimal taxes per unit of oil (justified by linear marginal global warming damages) in each country and a constant renewables subsidy and a common constant rate of interest, the equilibrium follows from maximizing utility and from the world market oil prices following the Hotelling rule.

A change in taxes implies a change in the initial oil price and in the country-specific moment where renewables take over from oil. Hoel (2011a) stresses the effects of such changes in taxes on welfare: price elasticities of demand and asymmetries across countries are crucial. If countries have identical carbon taxes below the Pigouvian level, a multilateral increase of the carbon tax boosts welfare. Interestingly, with high marginal cost of climate change, inelastic demand and large differences in taxes, total welfare in both countries falls if the country with the lowest carbon tax increases this tax. Also, with equal carbon taxes, a lower cost of renewables typically boosts climate cost. However, with large differences in carbon taxes and inelastic demand, a lower cost might lower climate cost. Another result is that with equal taxes not higher than the Pigouvian tax, subsidizing renewables reduces welfare in both countries which is a consequence of oil being fully exhausted in the model.

Eichner and Pethig (2011) highlight carbon leakage and the Green Paradox in a two-period model with three (groups of) countries: a CO2-abating country which uses a system of tradable permits, a non-abating country with no climate policy, and a country that exports a fossil fuel which is used in the two other countries to produce consumer goods. In each period demand for fossil fuel equals supply and the world market for the consumer good is in equilibrium. All firms maximize profits. If the amount of permits issued by the abating country in period one is binding and there is no permit trading in period two, tightening the supply of permits may boost overall emissions in period one (defined as a Green Paradox). Demand for fossil fuel falls due to the drop in permits in the abating country. If the price of the future consumer commodity is unaffected, the world market price of fossil fuel is lower and triggers more demand by the non-abating country. This is insufficient to generate the Green Paradox. For that the future price of the consumer good must fall sufficiently, which requires that fossil fuel demand is sufficiently elastic. Also, if emission caps are binding in both periods, tightening the future emission cap triggers a Green Paradox if the elasticity of intertemporal substitution is large enough. Schopf and Ritter (2012) reach similar conclusions in a similar model which allows for extraction cost and find that a strong Green Paradox may arise.

Eichner and Pethig (2011) highlight the importance of a general equilibrium approach and price elasticities of demand to assess the consequences of unilateral policy measures and the Green Paradox, but no crucial role is played by the interest rate. Van der Meijden et al. (2013) study a two-period general equilibrium model with an oil-importing country and an oil-producing country and analyze the role of a future carbon tax levied by the oil-importing country. Typically, the interest rate will change. This has an effect on demand for final goods in the future relative to the present, since the relative price changes. But there is also an income effect since the interest rate affects income of the oil exporter through Hotelling's rule. Depending on the preferences of the agents in the model the interest rate may increase or decrease, giving rise to reinforcement or attenuation of the Green Paradox. With sufficient asymmetries in preferences the weak Green Paradox can even be reversed.

Tradeoff between growth and climate objectives

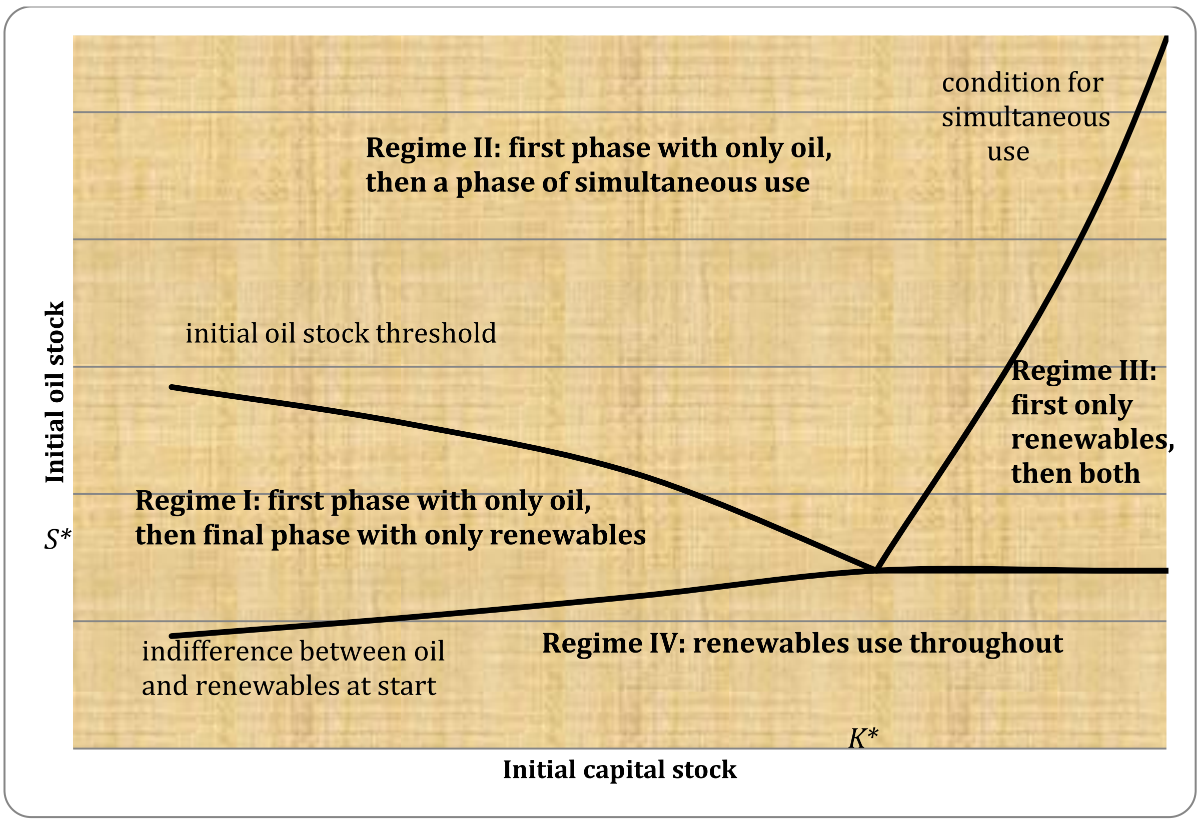
Van der Ploeg and Withagen (2012c) identify within the context of a green Ramsey model another channel by which the occurrence of a Green Paradox may be less harmful. This is illustrated in a green Ramsey growth model with capital and energy in the economy's production function. Output is produced with capital, labor and energy. It is used for extracting oil, producing renewables, gross investments and consumption. With capital in general equilibrium the analysis is more complicated. As shown in fig. 4, we can delineate four qualitatively different regimes for the social optimum depending on the initial oil shock shown on the vertical axis and the initial capital stock shown on the horizontal axis. (The initial atmospheric CO2 stock is fixed.)

If the economy is initially in region I, it is optimal to start with only oil and at a future moment of time extraction ceases and renewables are used forever from that moment on: the economy converges to the carbon-free steady state indicated by (S^*, K^*). If the economy is in region II initially with relatively abundant oil, it is optimal to start using only oil and overshoot the carbon-free steady-state capital stock. Eventually, renewables and oil are used alongside each other and the carbon-free steady state is reached asymptotically. In region III there is use of the renewable only in a first phase, but eventually the economy will switch to simultaneous use. Intuitively, moving from region II to region III corresponds to a horizontal rightward shift which implies a higher initial capital stock and thus a higher rate of consumption, a lower marginal utility of consumption and a higher social cost of carbon. Hence, it is no longer attractive from a social perspective to start using oil and therefore the economy sets off using only the renewable. Finally, with a start in region IV the economy will never use oil. Intuitively, if oil is initially very scarce and oil extraction is expensive, the renewable is more attractive than oil despite a relatively low social cost of carbon.

In the no-policy scenario the market economy only has two regimes: if oil is initially scarce, oil extraction is expensive and it is attractive to use renewables throughout; if oil is initially less scarce, the economy starts off with a phase where only oil is used and then transitions to a final phase where only the renewable is used.

The first-best optimum can be realized in the market economy by imposing a specific carbon tax reflecting the social cost of carbon. Now the marginal benefits of oil and renewable use are expressed in consumer goods rather than in utility terms, so the carbon tax may decrease (even without decay of atmospheric CO2) if consumption is decreasing as occurs in regime II with abundant oil. The Green Paradox prevails in this setting: a renewables subsidy increases the initial use of oil. However, if the subsidy is given in an economy that is in its early stages of development and still has to grow, the negative effect on welfare is only moderate: the developing economy has relatively high marginal utility of consumption, attaches less value to climate damages and thus has a low social cost of carbon.

Figure 4: Four regimes of the Green Ramsey model



R&D Development and uncertainty

Strand (2007) considers the sudden arrival of a breakthrough backstop that will render oil worthless, where the arrival date is Poisson distributed. The oil profit margin grows at the market rate of interest plus the (exogenous) probability that oil becomes obsolete. With linear demand functions a marginal drop in the cost of the existing backstop cuts the expected moment of time where extraction of oil ceases. It also increases total expected extraction. The more likely it gets that the new technology presents itself, the faster oil extraction will take place. This effect is reinforced if it is known that the breakthrough will at the earliest only arrive after a given instant of time.

Van der Ploeg (2012) allows monopolistic resource owners to invest in exploration of new reserves. Not the arrival of a carbon-free substitute, but uncertainty about the timing of this substitute coming on stream matters for efficiency. Before the carbon-free substitute has come to market, reserves are depleted too rapidly. Subsidizing R&D to speed up the introduction of breakthrough renewables also speeds up oil extraction before the breakthrough (weak Green Paradox), but more oil is left in situ as exploration investment is lower. This latter effect curbs cumulative CO_2 emissions and attenuates global warming.

Winter (2013) allows for stock-dependent extraction cost of fossil fuel, which has a similar effect as endogenous exploration investment. Prior to the breakthrough, oil extraction is then higher than without the possibility of innovation. If innovation is possible but does not occur before oil extraction stops, oil extraction is always higher and abandoning oil extraction takes place earlier. If the discovery is made before that moment, extraction is higher as well, but it stops earlier, and more oil is left untapped. The net effect on global warming is negative if the drop in cumulative emissions dominates the short-run increases in emissions in which case the weak Green Paradox is merely a short-run nuisance. With positive feedbacks in the CO_2 cycle (e.g., release of methane from ocean floors) higher temperatures can come about in spite of innovation.

Strategic interactions between oil exporters who decide how fast to extract their finite reserves whilst realizing that if they wait too long their reserves may become economically obsolete due to the advent of carbon-free, abundant substitutes and oil importers trying to wean themselves away from their oil addiction by investing in the development of alternatives matters. Gerlagh and Liski (2011) consider strategic interaction between the seller and buyers of oil. Buyers can invest in a perfect substitute but it takes money and time to implement it. Sellers benefit if the arrival of the renewable is postponed and achieve this by increasing their supply over time and lowering the oil price. Effectively, buyers are compensated for postponing the introduction of the renewable.

It pays to invest in substitutes before they are used and the economy still relies on oil, since this curbs development costs of the substitute (Jaakkola, 2012).[15] Although initially oil prices are determined by the Hotelling rule, they are eventually driven by the substitute which is getting cheaper all the time. The supply of oil thus falls before it is forced up by competition from the substitute. A gradually improving substitute forces the monopolist to sell more, temporarily aggravating emissions, before being driven out of the market (weak Green Paradox). If oil extraction becomes more expensive as reserves are depleted, importers switch towards clean fuels once oil is priced out of the market. Technological development locks up more oil and curbs cumulative carbon emissions. This latter effect can reverse the effect of higher short-term damages associated with the weak Green Paradox and avoid the strong Green Paradox. Furthermore, development of the clean substitute slows down if climate change becomes acute as further development triggers more oil extraction.

The literature on subsidizing R&D in green technologies and directed technical change (e.g., Acemoglu et al. 2012; André and Smulders, 2012; Hassler et al., 2011) seldom refers to the Green Paradox. However, van der Meijden (2013) studies endogenous growth where a final good is produced with intermediates and energy. Energy is generated by means of oil and renewables, oil and renewables are imperfect substitutes, production of intermediates requires only labor, labor is also used for producing renewables and creation of new intermediates, and knowledge accumulated in the R&D sector spills over to productivity of oil and renewables. As usual, availability of renewables boosts initial oil use (weak Green Paradox). If an invention increases the substitutability between oil and the renewable, initial oil supply is curbed (no weak Green Paradox) as with higher substitutability supply of energy is predominantly oil and spread more evenly over time. Furthermore, higher substitutability leads to more growth which boosts future demand for energy and demand for fossil fuel.

Hoel (2011b) shows that a credible high future carbon tax does not necessarily imply more oil use today, nor needs to trigger additional investments in the technology for renewable. A final good is produced with oil and renewables. They are perfect substitutes. Production and extraction take place over two periods. Oil use is taxed in both periods. Renewable use requires an upfront investment in the first period that has a convex cost. Once the investment is made, renewables are available without cost, but only in part. So, total energy use in production in period one consists of oil whereas part of the initial investment is productive and yields renewable energy. Energy use in the second period consists of oil and energy from the rest of the initially installed capacity. These parts are exogenous Oil extraction costs depend on the remaining stock of oil reserves.

[15] Jaakkola (2012) extends Hoel's (1978) model of a limit-pricing monopolist to a dynamic game and complements earlier work on strategic interactions and climate by Liski and Tahvonen (2004) and Wirl (2012).

Daubanes et al. (2012) base themselves on Acemoglu et al. (2012) to investigate the role of directed technical change. They find that a gradual increase in the subsidies to the development of green inputs does not lead to a Green Paradox. Instead, initial use of oil is reduced and spread more evenly over time.

Dearth of empirical evidence for the Green Paradox

There are almost no studies which test the Green Paradox. Di Maria et al. (2012) find evidence for abundance and ordering effects for the announcement of the 1990 Clean Air Act Amendments. These results relate to substitution of different types of coal, but as coal is abundant the results are of less significance for testing the Green Paradox. For that we need studies on oil or natural gas. Michielsen (2011) uses previously estimated price elasticities of demand to assess the impact of an anticipated future carbon tax within a calibrated two-period model with a scarce and dirty oil and abundant and dirtier coal. Such a tax makes oil relatively cheaper than coal and thus boosts oil use, but also boosts energy prices and curbs demand. Intertemporal carbon leakage, defined as the increase in present emissions over the decrease in future emissions, varies from -22 percent to +13 percent and is thus of no or minor concern. Fischer and Salant (2012) calibrate a model that includes five major categories of oil with different extraction costs and emission coefficients. They focus at supply responses and consider several climate change policies. They find that, compared to a carbon tax, conservation policies such as improving energy efficiency or clean fuel blend mandates yield higher intertemporal leakage whilst subsidizing clean backstops yield lower intertemporal leakage.

Concluding remarks

Well-intended climate policies can have adverse consequences. Carbon leakage occurs if a carbon tax induces countries that do not levy a carbon tax to consume more fossil fuel and renders climate policy less effective. Credibly announcing a future carbon tax or a too rapidly rising carbon tax quickens fossil fuel extraction and accelerates global warming (weak Green Paradox). Subsidizing renewables also speeds up extraction and accelerates global warming. Such policies depress future prices by more than current prices, thus cutting into the expected capital appreciation of fossil fuel reserves. Owners of these reserves avert this by accelerating extraction and putting sales revenue into investments in the capital markets, thus obtaining higher yields. Such policies thus operate as an announced expropriation which provokes owners to accelerate extraction of their reserves and exacerbate global warming.

If extraction becomes more costly as less accessible fields are explored, the stock of fossil fuel to be left untapped follows from the condition that the cost of extracting the last unit of fossil fuel including the social cost of carbon equals the cost of the renewable. A renewables subsidy then not only brings forward the carbon-free era but also encourages the market to leave more fossil fuel untapped. Global warming is then ultimately mitigated despite short-run Green Paradox effects. A renewables R&D subsidy makes it less attractive to explore new reserves in which case the resulting reduction in cumulative CO2 emissions offsets short-run increases in emissions as well.

The booming interest in Green Paradox effects should not distract attention away from other important climate issues. If not solar or wind but cheap coal is the relevant backstop, global warming is much more difficult to fight. One should then try to slow down oil and gas extraction to limit coal use or postpone reintroduction of coal. Similarly, one should limit use of tar sands which also harms global warming very much. Another challenge is how to get an international climate deal, since developing countries have less incentive to pursue an ambitious climate policy in view of the basic needs of their citizens. More understanding is needed of the strategic interactions between oil and gas exporters and the various importers on the other hand, because this may render climate policy less effective too. This calls for a general equilibrium multi-country approach to the Green Paradox.

Green Paradox effects highlight the short-run costs of second-best policies. There is an urgent need for a proper empirical assessment of the potential welfare costs of such effects, both econometric and using properly calibrated integrated assessment models with a realistic model of the carbon cycle, specification of global warming damages, different energy sources varying from coal, oil and gas to the recent surge in unconventional energy such as shale gas, strategic interactions between jurisdictions, and explicit attention for the development of renewable energy. Only then will we fully understand the wider implications of the Green Paradox.

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