DEPARTMENT OF ECONOMICS
OxCarre
Oxford Centre for the Analysis of Resource Rich Economies

Manor Road Building, Manor Road, Oxford OX1 3UQ
Tel: +44(0)1865 281281 Fax: +44(0)1865 271094
oxcarre@economics.ox.ac.uk www.oxcarre.ox.ac.uk

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Global Warming and the Green Paradox: A Review of Adverse Effects of Climate Policies

Frederick van der Ploeg
OxCarre
&
Cees Withagen*
VU University

***OxCarre External Research Associate**

Direct tel: +44(0) 1865 281281 E-mail: oxcarre@economics.ox.ac.uk

GLOBAL WARMING AND THE GREEN PARADOX:

A REVIEW OF ADVERSE EFFECTS OF CLIMATE POLICIES*

Frederick van der Ploeg, University of Oxford and VU University Amsterdam[1]

Cees Withagen, VU University Amsterdam[2]

Abstract

This article examines the possible adverse effects of well-intended climate policies. A weak Green Paradox arises if the announcement of a future carbon tax or a sufficiently fast rising carbon tax encourages fossil fuel owners to extract reserves more aggressively, thus exacerbating global warming. We argue that such policies may also encourage more fossil fuel to be locked in the crust of the earth, which can offset the adverse effects of the weak Green Paradox. We show that a subsidy on clean renewables has similar weak Green Paradox effects. Green welfare (the complement of environmental damages) drops (i.e., the strong Green Paradox) if the beneficial climate effects of locking up more fossil fuel do not outweigh the short-run weak Green Paradox effects. Neither the weak nor the strong Green Paradox occurs for the first-best Pigouvian carbon tax. We also pay attention to dirty backstops, spatial carbon leakage and green innovation.

Keywords: fossil fuel, renewables, coal, economic growth, global warming, carbon tax, Green Paradox

JEL codes: D81, H20, Q31, Q38

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[1] Department of Economics, Manor Road Building, Oxford OX1 3 UQ, U.K. Support from the BP funded Oxford Centre for the Analysis of Resource Rich Economies is gratefully acknowledged. Also Adjunct Professor at VU University Amsterdam.

[2] Department of Economics, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands. Also Research Professor at CESifo Munich.

INTRODUCTION

Global warming is a consequence of the accumulation of CO_2 in the atmosphere. To a large extent, the accumulation of atmospheric carbon results from manmade emissions caused by burning a *finite* stock of fossil fuels[3]. Because emissions of greenhouse gases mix uniformly throughout the atmosphere, it does not matter *where* the CO_2 emissions take place on the globe. Thus, the world faces the challenge of addressing a *global* negative externality. Since all countries benefit from fighting global change, each country wants to be a free-rider and leave the costs of combating climate change to other countries. This is the main obstacle to a successful climate policy. The other main obstacle is that current generations have to make sacrifices to switch away from using cheap fossil fuel to more expensive renewable energy, but the benefits of these sacrifices in terms of less global warming accrue to generations far in the future, many of them yet unborn. We will see that these spatial and intergenerational obstacles to climate policy will also play a big role in why climate policy may be counterproductive or less successful than what might have been hoped.

The best way to fight global warming is to charge a price for the global warming damages done by burning fossil fuel. This price should be set to the social cost of carbon, which is the present value of all current and future marginal damages done to the economy of burning one ton of carbon today. The carbon price internalizes the global warming externality and can be realized either via a global carbon tax or via a global emissions market. Pricing carbon mitigates global warming in the following ways: (i) curbing fossil fuel demand as it is more attractive to increase energy efficiency; (ii) switching demand from relatively CO_2-intensive fossil fuels such as coal and tar sands to other less CO_2-intensive fossil fuels such as gas, which are less harmful from a climate perspective; (iii) substituting carbon-free renewables for CO_2-intensive fossil fuels; (iv) locking more fossil fuel in the crust of the earth as the price of carbon makes it more costly to explore marginal oil and gas fields; (v) capturing, storing and sequestrating CO_2 as this becomes more attractive as this is a way to avoid having to pay the price for CO_2 emissions; and (vi) moving the direction of technical progress from dirty to clean or green growth. Each of these ways are attractive for private enterprises and households once a price for carbon is implemented, since they cut the bill of CO_2 charges. Pricing carbon thus incentivizes the economy to cause less CO_2 emissions in all these different ways.

A credible announcement of a time path for future carbon taxes that are differentiated according to the carbon content of different types of fossil fuel can achieve the first four mitigation measures. However, if there are network externalities that lead to insufficient pipelines for transporting CO_2, then subsidies will

[3] However, it is increasingly being caused by the fossil fuel extraction process itself as, for example, the tar sands require a lot of energy to get out the oil from the sands.

be needed in addition to the carbon price to capture, store and sequestrate the optimal amount of CO2 (Jaakkola, 2012). In addition, if markets fail to deliver sufficient green R&D due to badly functioning patent markets and large-scale learning-by-doing spill-over effects, investment subsidies will be necessary on top of the price of carbon too (e.g., Acemoglu et al., 2012). Of course, if politicians fail to implement the appropriate price of carbon, climate change will be mitigated insufficiently and then climate adaptation measures (e.g., dykes) are necessary to better cope with the adverse effects of global warming.

One of our contentions is that well-intended climate policies such as a postponed carbon tax or a subsidy on carbon-free alternative for fossil fuel are often counterproductive. Of course, such policies yield worse outcomes than the socially optimal outcome. Moreover, they may even lead to worse outcomes than a no-policy scenario. Before we discuss why climate policies can be counterproductive, it helps to define a *weak* Green Paradox and a *strong* Green Paradox. A *weak* Green Paradox occurs if fossil fuel is extracted more quickly and thus global warming accelerates in the short run in anticipation of a gradual tightening of climate policy (e.g., steeply rising carbon taxes in the coming decades or much cheaper renewables). A *strong* Green Paradox occurs if the present value of the costs of global warming in terms of reduced output, which is the converse of green welfare, falls in anticipation of a gradual tightening of climate policy (Gerlagh, 2011). Social welfare is private welfare (the present discounted value of the utility of consumption) minus green welfare (the present value the cost of global warming). Of course, when evaluating climate policies such as carbon taxes or renewable subsidies, it is *social* welfare rather than green welfare that matters.

Government failure can arise if either dirty fossil fuels (such as coal or tar sands) or renewables (such as solar or wind energy) are subsidized instead of pricing carbon. Such well-intended policies encourage fossil fuel owners to extract their reserves more quickly and cause more rapid burning of fossil fuel and thereby cause an acceleration of global warming. This “failure” is an example of the weak Green Paradox (Sinn, 2008a,b; also see Sinn, 1981, 1982). Government failure can also arise if national governments are unable to coordinate and implement a global carbon tax, which may cause carbon leakage (a “spatial” version of the Green Paradox). The reason for this is that a unilateral carbon tax raises fossil fuel prices at home but depresses them in non-participating countries that do not have carbon taxes as some of the burden of carbon taxes is borne by producers rather than consumers. Fossil fuel prices thus rise in the participating countries but fall in the non-participating countries. In that case, the lower fossil fuel demand at home caused by the carbon tax will be partially offset by higher fossil fuel demand abroad, thus reducing the effectiveness of a unilateral carbon tax.

This article, which is part of a symposium on the Green Paradox and Climate Policy Design,[4] seeks to improve our understanding of why well-intended climate policies such as carbon taxes and renewable subsidies might at best be less effective than thought at first blush and at worst may be counterproductive. In order to understand the various forms and implications of potentially misguided climate policies, it helps to have a good benchmark. For this we choose the socially optimal climate policies and the corresponding fossil fuel extraction paths, leading to carbon stocks remaining in the crust of the earth or the complete exhaustion of fossil fuel reserves. We focus here on the key role played by so-called energy backstops, which are perfect substitutes for fossil fuel, are unconstrained by exhaustibility, and are infinitely elastically supplied at constant cost (cf. Tahvonen, 1997). In our context we think of carbon-free backstops such as wind or solar energy which might eventually replace CO2-intensive fossil fuel energy sources such as coal, oil and gas. The world today relies mostly on fossil fuel, which will have to be phased out in the coming decades and replaced by carbon-free backstops in order to tackle the problem of global warming. Even though there are in principle unlimited amounts of fossil fuel, it is too costly to keep on using them all the time as deeper and less accessible reserves have to be explored and as carbon priced they become relatively less competitive compared with the carbon-free backstops. The optimal use of fossil fuel and of carbon-free backstops over time is driven to a large extent by cost developments and any adverse effects fossil fuel use might have on global warming. Furthermore, the optimal climate policy should determine the optimal order in which to extract different types of fossil fuels.[5]

THE HOTELLING RULE AND THE GREEN PARADOX

A crucial concept in the theory of the exploitation of fossil fuel is the Hotelling rule. In this section we define the Hotelling rule and indicate its relevance for the occurrence of Green Paradox effects. To start with, we assume that the cost of extracting one barrel of fossil fuel is constant and the initial stock of fossil fuel reserves is given. We assume there is also 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 of the renewable exceeds the initial unit extraction cost of fossil fuel, because otherwise fossil fuel would never be used. A competitive energy market requires that energy demand and supply are equal in equilibrium. Renewables supply will eventually become profitable if the prices of oil and other fossil fuel rise high enough. The Hotelling (1931) rule states that if the supply of fossil fuel is positive, the rent on fossil fuel

[4] The other articles are Pittel and Sinn (2015) and Jensen, Mohlin, and Sterner (2015), which presents the intuition behind the Green Paradox and discusses climate policy and intertemporal emissions leakage; and Long (2015), which discusses the green paradox in the context of open economies.

[5] The Herfindahl rule states that least-cost deposits should be extracted first. However, with climate externalities, the social and private costs of the different types of fossil fuels differ, and thus the rule must be modified (Chakravorty et al., 2008).

(i.e., the market price of fossil fuel minus the per unit extraction cost) will grow at a rate equal to the (exogenous and constant) interest rate. The Hotelling rule is based on an 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.

Fossil fuel and renewables are never supplied at the same time because renewables are supplied at a constant price. Fossil fuel use will end when the price of energy reaches the exogenous backstop cost at some future moment in time. Hence, initially, only fossil fuel is supplied, and at some future moment in time the carbon-free backstop takes over. The timing of this transition from fossil fuel to renewables as well as the initial energy price follows from two conditions. First, the demand and the energy price must be continuous (i.e., no price jumps). This means that at the time of the transition, the energy price must be equal to the cost of renewables. Second, total fossil fuel extraction up until the transition must equal the initial stock of fossil fuel.

Effect of a Carbon Tax

What is the effect of a carbon tax on oil and other fossil fuel producers? During periods where there is a positive supply of fossil fuel, the after-tax fossil fuel rent will grow at a rate equal to the rate of interest. Thus, if the carbon tax is not prohibitively high, the equilibrium price path will not be affected if the tax rate itself increases at a rate equal to the interest rate. However, if the carbon tax rate grows at a rate higher than the interest rate, the equilibrium price path for fossil fuels will become steeper, which implies that (with the same total amount of fossil fuel extracted) there will be more extraction and thus carbon emissions initially and less extraction and emissions later during the fossil-fuel only phase. This means that global warming will be accelerated and green welfare will fall (i.e., there will be both a weak and a strong Green Paradox). If he carbon tax grows at a rate smaller than the rate of interest, then oil extraction and global warming will occur less quickly.

Effect of a Reduction in the Cost of the Backstop

What happens if at some point before the transition to renewables, the cost of the backstop is reduced? To simplify, we assume that innovation takes place at the outset and that the cost of new renewables production technology will still be higher than the unit extraction cost of fossil fuel. In this case, a new equilibrium will emerge with a new fossil fuel price path in the fossil fuel-only phase, and the new price path for fossil fuel will lie below the old one throughout. Indeed, the new price will be below the old one at the time of the new transition to renewables. Moreover, the two price paths will never cross.[6] This

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

means that, because total fossil fuel extraction still equals initial reserves, the lower cost of renewables will move the date of the transition forward, and thus fossil fuel extraction and carbon emissions will increase during the shortened oil-only phase. If the reduction in the cost of the renewable backstop is due not to technical change but due to a constant per unit subsidy, the extraction path steepens without changing cumulative extraction, thus creating a weak Green Paradox effect.

This discussion of the Hotelling rule and the Green Paradox has been conducted within the context of the simplest analytical framework. We will in the remainder address similar questions in more realistic frameworks. We will also address the following additional issues: when will climate change policies induce higher initial extraction rates of fossil fuel and higher CO2 emission rates?; what kinds of policies can depress cumulative CO2 emissions and leave more oil untapped in the crust of the earth?; what are the green and overall welfare consequences of climate policies?; how should climate policy be designed in order to avoid welfare losses and Green Paradox effects?

DO STOCK-DEPENDENT EXTRACTION COSTS MATTER FOR CLIMATE POLICY?

In our discussion of the Hotelling rule and Green Paradox effects so far, all oil is fully extracted unless the carbon tax or the renewables subsidy is prohibitively high. Here we emphasize that with stock-dependent extraction costs that rise as more fossil fuel has been extracted from the earth and global warming damages that increase with the stock of atmospheric CO2 at an increasing rate, this is no longer the case because the amount of fossil fuel left untapped can be increased by lowering the cost of renewables. To illustrate, let damages enter welfare separately from or independent of the utility from the consumption of energy.[7] This means that overall welfare equals the utility of energy use minus damages from climate change minus expenditures on fossil fuel extraction and production of the backstop. Let us also assume that emissions are proportional to fossil fuel use, there is no natural decay of atmospheric CO2,[8] and per unit extraction costs rise as fewer reserves remain untapped and less accessible wells have to be exploited. Finally, in social welfare a higher weight is given to present generations over future generations (a positive rate of pure time preference).

The First-Best Outcome

The first-best outcome maximizes social welfare under the constraint that cumulative fossil fuel extraction cannot exceed initial reserves. If at some point in time renewable energy is used, its marginal utility should equal its marginal cost. Similarly, if fossil fuel is used, its marginal utility should equal its

[7] Damages from climate change can be multiplicative or additive with production (e.g., Rezai et al., 2012).
[8] Because 80% of atmospheric carbon has an expected life of 300 years and the remaining 20% has an expected life of thousands of years (Golosov et al., 2014), this may not be such a strong assumption.

marginal social cost, which consists of (i) the marginal cost of extraction; (ii) the scarcity rent (i.e., 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 (the present value of future marginal global warming damages resulting from burning an additional unit of fossil fuel).[9] Because the marginal social cost of fossil fuel is typically not constant, fossil fuel and renewables will never be used simultaneously. Moreover, fossil fuel extraction will end at some future date, with either full or partial exhaustion of reserves.

At the time of the transition to renewables, which is the start of the carbon-free era, the scarcity rent of fossil fuel is zero (e.g., Heal, 1976). Thus, in the case of partial exhaustion, the marginal cost of extracting the last unit of fossil fuel plus the social cost of carbon[10] must equal the cost of the renewable energy source.

Fig. 1 illustrates how the amount of unexploited reserves can be determined. The horizontal axis indicates the oil or fossil fuel stock that is left unexploited. The vertical axis indicates the social cost of carbon (i.e., the present-discounted value of marginal global warming damages for each final stock of atmospheric carbon) and the unit production cost of renewables minus the unit extraction cost of oil. The downward-sloping line represents the social cost of carbon. It reflects that the more oil that is left in the ground, the less CO2 is in the atmosphere and the smaller is the social cost of carbon at the time of transition. The upward-sloping line represents the production cost of renewables minus the unit extraction cost of oil. It indicates that oil extraction becomes more costly as less oil is left in the ground. The optimal level of oil left in the ground is found at the point where the two lines cross.

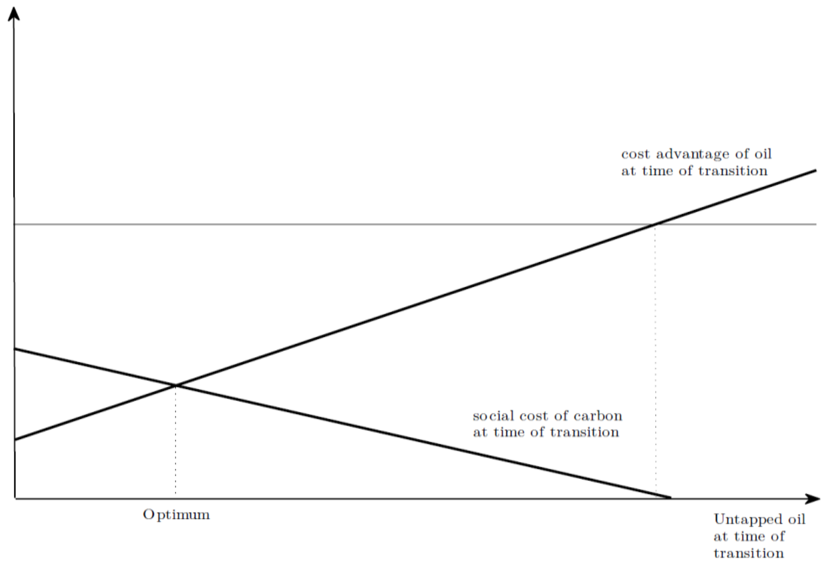
Variation of crucial parameters leads to the following results. First, a lower rate of pure time preference increases the social cost of carbon and shifts out the downward-sloping curve, so that more oil will be left in the ground. A more patient society thus pursues a more ambitious climate policy and leaves more fossil fuel untapped in the earth. Second, if extraction becomes more expensive for every oil stock, the upward-sloping curve shifts down and thus more oil is locked in the ground (possibly everything). Third, an exogenous drop in the cost of renewables also shifts down the upward-sloping line, which leads to more oil being left untapped and thus less total accumulation of atmospheric CO2. Hence, a strong Green Paradox (i.e., an increase in the total discounted damages from climate change) does not necessarily occur. However, if oil is fully depleted (the upward sloping curve is above the downward sloping curve

[9] The literature on integrated assessment models provides estimates of the social cost of carbon (e.g., Nordhaus, 2007, 2011). These estimates 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 and have yielded similar estimates (e.g., Golosov et al., 2014).

[10] At the start of the carbon-free era this is the marginal global warming damage from the constant stock of atmospheric carbon that results from burning the last unit of fossil fuel, divided by the rate of pure time preference.

already initially) and the reduction in the cost of renewables is only marginal, then oil is still fully depleted. Moreover the transition to renewables will place earlier because of the cheaper renewables.

Figure 1: Determining the stock of oil to be left untapped



Source: Van der Ploeg and Withagen (2012a)

In this case there is a strong Green Paradox (i.e., green welfare unambiguously deteriorates), but overall welfare increases, since the economy benefits from the lower renewables cost. If the cost of renewables is close to its lower bound (below which no oil will be extracted), then the social cost of carbon will be small. If the cost of renewables is close to its upper bound (above which all oil is extracted), then the cost of carbon will be high. This suggests that for renewable costs that are between these lower and upper bounds climate damages will increase

Implementation of the social optimum: the Pigouvian carbon tax.

The Pigouvian carbon tax is defined as a tax on emissions which is equal to the optimal social cost of carbon, i.e., the present value of the damages resulting from burning an extra ton of carbon. Such a tax forces the market to internalize all climate damages from burning carbon. The social optimum can thus be achieved in the market economy if the carbon tax is indeed set to the Pigouvian carbon tax. The optimal carbon tax always grows at a rate that is lower than the rate of pure time preference.[11] Thus, in this case,

[11] Here both damages and the carbon tax are expressed in terms of utility. If we wish to have damages and taxes expressed in monetary terms, then we need to divide them by the marginal utility of consumption. Supplementary Material A analyses the regimes that can occur with optimal carbon taxes in a model of growth and development.

the Green Paradox does not arise. However, if political factors prevent the carbon tax from being set optimally, there are several possible outcomes.

If it is optimal to fully exhaust the oil stock and the carbon tax also leads to full exhaustion, total CO2 accumulation will not be affected. Alternatively, if the carbon tax increases rapidly but starts from a low level, there will be more carbon emissions initially and the transition to renewables will take place earlier, implying an acceleration of global warming relative to the first-best outcome. However, the transition will take place later if the carbon tax increases more gradually. Another possibility is that the suboptimal carbon tax will lead to more oil being left in the ground than in the first-best case. However, generally, one can argue that a carbon tax that does not deviate very much from the first best improves welfare relative to the no-policy scenario.

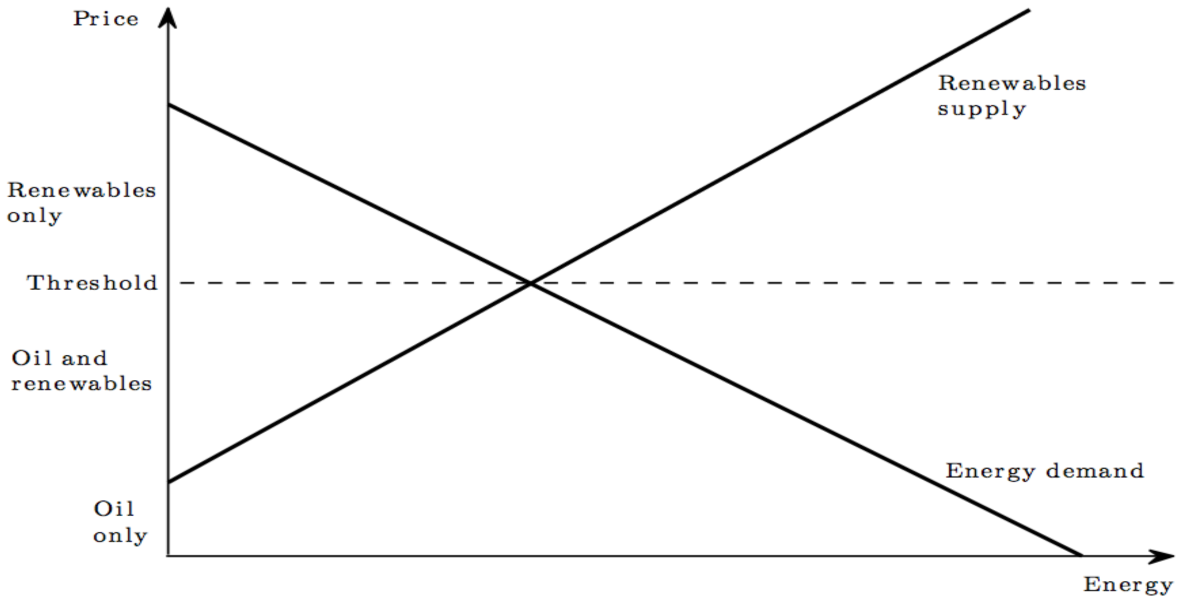
Another option is to subsidize renewables *without* taxing carbon as politicians often prefer the carrot to the stick. If the subsidy is large enough, oil reserves are not fully exhausted even if reserves are fully exhausted in the no-policy scenario. There is then a weak Green Paradox as higher oil extraction rates occur during the oil-only phase. The renewable subsidy shortens the oil-only phase, so that more oil is left in the ground than without the subsidy, and thus carbon emissions will be lower. Hence, although the renewables subsidy accelerates global warming in the short run, ultimately there is less global warming. Whether there will be a strong Green Paradox 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 (i.e., the renewables cost more than extracting the last drop of oil), social welfare would be increased by marginally *taxing* renewables in order to spread oil supply more evenly over time.

Van der Ploeg (2013) gives some numerical illustrations of a simple model with a dinky-toy calibration to get an idea of how much fossil fuel to lock up and what carbon taxes to set, paying attention to both optimal carbon taxes and second-best climate policies that have adverse Green Paradox effects (see also Supplementary Material B).

UPWARD-SLOPING SUPPLY CURVE FOR RENEWABLES

The well-known McKinsey Greenhouse Gas Abatement Cost Curve (McKinsey and Company, 2009) which provides the marginal abatement costs of a large variety of mitigation options. It suggests that, as the price of energy increases, more and more fossil fuel substitutes become competitive. This means that with an increasing marginal cost of renewables, the “generic” optimal sequence of fuel use is to first have only fossil fuel use, then a phase with simultaneous use of fossil fuel and renewables, and a final phase with only renewable energy (van der Ploeg and Withagen, 2012a). The first phase only exists if fossil fuel is sufficiently abundant. The third phase collapses if the second phase (i.e., simultaneous use) never ends.[12] Next we address the working of a subsidy on renewables in the market economy.

Figure 2: Upward sloping supply of renewables



For this purpose, fig. 2 illustrates the case of a quadratic function for the production costs of renewables, which gives rise to supply of renewable energy which is a linear increasing function of its price, and a quadratic utility function, which gives rise to demand for energy which is linear decreasing function of the price of energy. As long as the price of fossil fuel is low, such that energy demand exceeds the supply of renewables, part of demand (the area between the two lines in the left part of the figure) will be met by fossil fuel (known as the residual demand for oil or fossil fuel). There is thus a threshold price (the intersection point of the demand and supply curves) above which demand for fossil fuel is zero.

It is convenient to make a distinction between the case where the extraction costs do not depend on the remaining stock of fossil fuel reserves and the case where they do depend on the remaining stock. In the first case, and with linear demand for energy, a fixed and permanent specific subsidy per unit of renewables produced, there will be full exhaustion of fossil fuel within finite time and a higher subsidy typically leads to later exhaustion of all reserves. Effectively, all fossil fuel is burnt but more conservative use is made of it which obviously helps to mitigate global warming. This result has also been found by Grafton et al. (2012) who consider an ad valorem subsidy. Two effects play a role. The subsidy increases

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[12] If we assume that the marginal cost of renewables is linear, we can identify the parameter values that give rise to these outcomes. There will also be a simple inequality for identifying the full or partial depletion of oil.

supply of renewables and, if the price path would be unchanged, depresses demand for fossil fuel. But that would lead to fossil fuel being left in the ground at the time renewables fully take over. With constant per unit extraction cost, this cannot be optimal. Hence, the price path must change such that prices become smaller, which leads to more demand for fossil fuel. However, the effect that depresses fossil fuel demand dominates. Hence, in this case no Green Paradox effect occurs. Grafton et al. (2012) also show that with other demand functions a subsidy may cause faster exhaustion of all fossil fuel reserves. In the case of stock-dependent extraction costs, both Van der Ploeg and Withagen (2012a) and Grafton et al. (2012) show that full exhaustion of reserves may be delayed but may also may take place faster. There is also the possibility of exhaustion of fossil fuel not taking place within finite time, but only asymptotically and where some fossil fuel is left unexploited. This may go together with an initial phase with only fossil fuel use. A subsidy on renewables will then lead to faster phasing in of renewables and to more fossil fuel left in the ground ad infinitum. But still initial fossil fuel use goes up, so that there is a weak Green Paradox effect. Green welfare may still increase, due to less overall extraction and thus less cumulative carbon emissions.

DIRTY BACKSTOPS AND THE GREEN PARADOX

Some substitutes for oil and natural gas are dirty and abundant and might also function as 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, but coal has higher emissions per unit of energy burnt. It is of interest to see what role such dirty backstops play for possible Green Paradox effects. To illustrate this role, we assume that coal has a constant marginal cost of production, whereas extraction cost of oil increases as the stock of oil reserves diminishes. The most empirically relevant case occurs when the marginal utility of energy is high enough to warrant energy use (oil or coal) forever. Moreover, suppose 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. This means that it is optimal to start off with using only oil. But since burning coal emits more per unit of energy, the social cost of coal grows faster than the social cost of oil and thus the transition to simultaneous use of oil and coal in the production process will have to take place at some point in time. It can then be shown that the social optimum must have an initial phase with oil use only, a second phase with simultaneous use of oil and coal, and possibly a final phase with use of coal only. If simultaneous use of oil coal goes on forever, then still some oil will be left indefinitely (van der Ploeg and Withagen, 2012b).[13]

In the no-policy scenario there will never be simultaneous use of oil and coal. More specifically, if the extraction of oil is relatively expensive, only coal will be used. Otherwise, the no-policy scenario will entail first using only oil and then using only coal. If coal is subsidized, there is an incentive to keep more oil in the ground, but the initial use of oil will increase (weak Green Paradox). In this case, coal is also phased in more quickly. Thus, a coal subsidy is a bad policy from a climate perspective. In the social optimum a lower cost of coal in the social optimum (e.g., caused by technological progress) leads to more oil use initially and a longer period of using only oil, which means that the simultaneous phase starts later. However, this phase lasts for a shorter period of time because oil is phased out earlier. It may then happen that the long-run atmospheric CO2 concentration decreases considerably, implying that green and total welfare increase considerably. Hence, a subsidy on a dirty backstop in a market economy may have detrimental effects, whereas a lower cost of the dirty backstop in the optimizing economy has positive welfare effects.

What happens if both clean but costly renewables and dirty but cheap coal are introduced? The social optimum is to first have only oil use, then a phase with simultaneous use of oil and coal, then a phase with only coal, and finally, a phase with only renewables. With this social optimum, a lower cost of renewables results in an earlier phasing out of coal, which curbs global warming. In a market economy, however, a subsidy on renewables will have no effect at all as long as the market price of renewables stays above the market price of coal. If, however, renewables are subsidized so that their price is slightly below the cost of coal, there will be an overall gain in welfare as long as the renewables price is not too high relative to the price of coal. Otherwise, the subsidy for renewable energy must be very high, which would give rise to large distortions in the economy so that the gains from the subsidy in green welfare are offset by these distortions.

Another potential policy instrument in the market economy is a high tax on coal or a moratorium on coal extraction, both of which would cause a significant delay in the phasing out of oil even though the phasing out would still occur faster than in the optimal economy. From a social perspective, it is better to rely on oil for a longer time and to delay the use of coal, which after all emits much more carbon per unit of energy. Thus, a prohibitively high coal tax or a moratorium on coal appears to be a very effective tool for combating climate change. In fact, in a series of numerical simulations, Van der Ploeg and Withagen

[13] The final phase may not occur if asymptotically the oil stock is only partially exhausted during the phase of simultaneous use.

(2012b) show that a coal tax performs much better than a subsidy, in terms of both combating climate change and improving overall social welfare.

IMPACT OF SUBSTITUTABILITY OF ENERGY SOURCES ON THE GREEN PARADOX

So far, we have discussed the Green Paradox in frameworks where fossil fuel and renewable energies are perfect substitutes but to be more realistic this assumption needs to be relaxed too. Due to problems of intermittence wind energy will never be a perfect substitute in production for oil, coal or gas. Similar issues arise for solar energy, which can be a reasonably good substitute for coal in electricity generation but not necessarily in other parts of the economy. Renewable energy is still at best a complement to traditional forms of fossil fuel and our arguments need to reflect this. Long (2014) therefore allows for *imperfect* substitutability of fossil fuels and renewables in the utility function.[14] He finds that there is a first phase with simultaneous use of oil and renewables. Once 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. At the moment of transition from oil to renewables, the price of oil is determined by the requirement that consumption is continuous and is not allowed to jump at any point of time.

A higher degree of substitutability may occur due to the advent of technical change and has two effects. First, higher substitutability lowers the price of energy prevailing at the transition and, depending on the date at which the transition from oil to renewable energy takes place, will cause lower oil prices along the entire path toward the transition, resulting in 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 between oil and renewable energy is sufficiently high for the first effect to dominate in which case there will be a weak Green Paradox effect.

Michielsen (2014) allows for imperfect substitutability between oil and renewable energy in a two-period economy with finite oil reserves, abundant dirty coal, and a carbon-free renewable. In this case, a carbon tax that is levied in period two and that is announced at the beginning of period one will result in different oil and coal prices in the second period, with the substitutability between oil and coal playing a crucial role in periods one and two. He illustrates this result for the case of zero extraction cost of oil and constant unit production cost of coal. Furthermore, total oil demand over time is restricted by the available stock of oil reserves, and the demand functions for oil and coal in the two periods are iso-elastic

[14] This study has a utility function which depends in a linear way on income and contains a separate parameter that measures substitutability, ignores decay of atmospheric CO2, has a constant unit extraction cost of fossil fuel, and a unit production cost of renewables.

(i.e., a one percentage increase in the price leads to a fixed percentage fall in demand independent of at which price one starts) and depend on both the market price of oil and the market price of coal. 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. Because this significantly depresses demand for coal in period one, Michielsen (2014) can establish that the weak Green Paradox effect does not arise.[15] Conversely, technical change might lead to more substitutability in the future in which case a Green Paradox effect is more likely to occur.

Di Maria et al. (2014a) have argued that the literature on the Green Paradox emphasizes the supply side of fossil fuel markets and accounts for marginal extraction costs, but largely ignores demand side issues, such as oil being used mainly for transportation and coal being used mainly for electricity generation. These issues might have important implications for the *magnitude* of the Green Paradox. For example, electricity demand is not very responsive to price changes, which means that large price changes are needed to lead to a significant increase in the demand for coal. In that case, a future carbon tax does not boost carbon emissions very much in the short run.

CARBON LEAKAGE AND THE GREEN PARADOX

So far most of our discussion has been directed at the intertemporal effects of climate policies. Here we focus on the combination of intertemporal and spatial effects of climate policy in a multi-country setting, and, more particularly, on the effects of unilateral climate policy on carbon emissions elsewhere in the world economy. So, we address the question what happens if countries' unilateral efforts to curb CO2 emissions with a carbon tax cause before-tax oil prices to decline, thereby causing CO2 emissions to increase elsewhere in the world. In this sense, carbon leakage is a *spatial* version of the weak Green Paradox.

Hoel (2011a) analyzes global warming in a two-country context. His main aim is to show that with countries implementing different climate policies the effects of a change in policies might differ essentially from the case with identical countries (or a single economy). He assumes that 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 in consumption, and preferences are identical in the two countries. The two countries impose a constant, possibly different, non-optimal carbon tax and a constant renewables subsidy. A change in taxes implies a change in the

[15] He applies similar reasoning to the case of low substitutability between oil and renewable energy in the first period and high substitutability in the future and gets comparable results for situations with a carbon-free backstop.

initial oil price and in the country-specific moment at which renewables take over from oil. The analysis stresses the effects of such changes in taxes on welfare, and highlights the crucial role of price elasticities of demand and asymmetries across countries. If initially the countries have identical carbon taxes that are below the Pigouvian level, a multilateral increase in the carbon tax boosts welfare, as expected. But with large differences in initial carbon taxes, a high marginal cost of climate change and inelastic demand, , total welfare in both countries falls if the country with the lowest carbon tax increases this tax. In addition, if carbon taxes are equal, a lower cost of renewables, due to e.g., technical change, will typically increase global warming damages. However, if there are large differences in carbon taxes and inelastic demand, a lower renewables cost might lower climate damages. Hoel (2011a) also finds that if carbon taxes are equal across countries (and set below the Pigouvian carbon tax), subsidizing renewable energy reduces welfare in both countries. This latter result is a consequence of oil being fully exhausted in his model. Concluding, in this two-country setting the effects of policy changes depend on the initial policy in place. Ryszka and Withagen (2014) follow up on Hoel (2011a) by allowing heterogeneity across countries, not only in policies, but also in terms of extraction costs, renewables costs and preferences. They show that a unilateral increase in the carbon tax (on oil users) in the country with the highest extraction cost oil, may result in a Green Paradox effect, but this is unlikely to happen as typically, the period over which the imported cheap oil is used, is prolonged.

Eichner and Pethig (2011) focus on 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 CO2 permits, a country with no climate policy which does not abate CO2, and a country that exports fossil fuel which is used in the two other countries to produce consumer goods. Preferences are identical across countries and homothetic (so that the ratio of current and future consumption of final goods depends on the interest only). In each period, demand for fossil fuel equals supply and the world market for the consumer good is in equilibrium. If the amount of CO2 emission permits issued by the abating country in period one is binding and there is no permit trading in period two, they find that tightening the supply of permits in period one may boost overall carbon emissions in period one. The reason for this Green Paradox effect is as follows. The first-period fossil fuel price drops because otherwise there would be less overall demand for fossil fuel in the first period and, therefore, more demand for fossil fuel in the second period. So, present final output would decrease relative to future final output. Hotelling's rule then stipulates that in order to have an equilibrium on the fossil fuel market, the interest rate needs to decrease. But then the ratio of present and future consumption will increase, so that a contradiction is obtained. Hence, if the present price of fossil fuel drops considerably, we might get a Green Paradox effect due to increased fossil fuel demand from the region without the climate policy. Using a similar model (which allows for stock-dependent extraction cost), Schopf and Ritter (2012) reach similar conclusions, and find that a strong Green Paradox effect may arise if the beneficial effect of a reduction in cumulative carbon emissions is relatively small compared with the adverse effect of short-run increases in carbon emissions.

Van der Meijden et al. (2015) use a two-period general equilibrium model with an oil-importing country and an oil-producing country, allowing for non-homothetic preferences. They analyze the interaction between a future carbon tax levied by the oil-importing country and the world rate of interest. They show that typically the interest rate will change, which will have an effect on demand for final goods in the future relative to the present because the relative price changes. But there will also be an income effect because the interest rate affects the 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, which will strengthen or weaken the Green Paradox. Van der Meijden et al. (2015) find that with sufficient asymmetries in preferences, the weak Green Paradox can even be reversed. However, if preferences are homothetic and identical for the oil-importing and oil-exporting countries then it can be established that a future carbon tax always leads to a drop in the world interest rate. In that case, capital market repercussions thus lead to an attenuation of the weak Green Paradox effect.

Michielsen (2014) uses previously estimated price elasticities of demand to assess the impact of an anticipated future carbon tax on oil and coal.[16] He finds that this tax makes oil relatively cheaper than coal, thus boosting oil use, but it also boosts energy prices overall, thus curbing demand. The intertemporal carbon leakage is less than 3%. For reductions in the cost of renewables leakage is moderate as well: about 7-8% for bioenergy and 5% for renewable electricity.

Fischer and Salant (2012, 2014) distinguish five major categories of oil with different extraction costs and emission coefficients. They consider reductions of the cost of backstops, emission taxes, a blend mandate, improvements of energy efficiency, and carbon capture and sequestration and find that all of them lead to intertemporal leakage. With carbon taxes leakage is smaller than with backstop cost reductions, for low carbon taxes, but no longer so for high carbon taxes. Hence, the ordering of leakage rates of different policies, depend on the stringency of the policy at hand. A general conclusion is that leakage becomes smaller, regardless of the type of policy, the more stringent the policy is.

GREEN INNOVATION AND THE GREEN PARADOX

The direction of growth and development is crucial to understand climate policy. One must not rely on exogenous technological developments but on endogenous growth, since a crucial aspect of climate policy is to boost green innovation. Otherwise, one might have to rely too much on slowing down the rate

[16] He uses a calibrated two-period model that includes scarce and dirty oil and abundant and dirtier coal.

of economic growth to curb global warming. We will discuss first the impact of breakthrough technologies for renewable energy and then proceed to discuss directed technical change which amounts to developing technologies to kick-start green innovation.

Effect of a Breakthrough Technology for Renewable Energy

Strand (2007) considers the effect of the sudden arrival of a breakthrough backstop technology that will at some yet uncertain moment of time render oil worthless. In such situations the oil profit margin grows at the market rate of interest plus the (exogenous) probability that oil becomes obsolete. Using linear demand functions, a marginal drop in the cost of the existing backstop brings forward the expected moment of time when oil extraction ceases. Furthermore, it also increases total expected extraction of fossil fuel and thus increases total cumulative carbon emissions. The higher the probability that the new technology will arrive, the faster oil extraction will take place. This is akin to the Green Paradox effect.

Van der Ploeg (2012) also examines the effects of a pending breakthrough in renewable energy, but allows for monopolistic resource owners to invest in the exploration of new fossil fuel reserves. In this case, what matters for efficiency is not *whether* a carbon-free substitute will arrive, but rather what matters is the uncertainty about *when* the breakthrough substitute will arrive on the market. In this scenario, reserves are depleted too rapidly before the carbon-free substitute has come to the market. Subsidizing R&D to accelerate the introduction of breakthrough renewable technologies will also accelerate oil extraction before the breakthrough occurs which is a manifestation of the weak Green Paradox. However, more oil will be left in the ground because investment in exploration will be lower. This latter effect curbs cumulative CO2 emissions and thus reduces global warming.

Winter (2013) also studies the impact of a breakthrough technology for renewable energy, but allows for stock-dependent extraction cost of fossil fuel, which has an effect that is similar to endogenous exploration investment. He finds that prior to the arrival of the breakthrough technology there is more oil extraction than when there is no possibility of innovation. If innovation is possible but does not occur before oil extraction stops, oil extraction is always higher and oil extraction ceases earlier. If the breakthrough discovery is made before oil extraction stops, oil extraction is also higher, but it stops earlier and more of the oil reserves remains untapped. Global warming will be curbed if the fall in cumulative emissions outweighs the short-run increase in emissions that is due to the accelerated oil extraction resulting from the fear of oil reserves possibly being made obsolete at some future moment in time. In that case the weak Green Paradox is merely a short-run nuisance. Winter (2013) warns that there is a danger that the increased carbon emissions resulting from short-run weak Green Paradox effects might unleash positive feedback effects in the CO2 cycle (e.g., release of methane from ocean floors). To the extent that these feedback effects are irreversible, the welfare effects of subsidizing breakthrough, carbon-free energy sources are potentially disastrous.

Strategic Interactions: Keeping Out Renewable Energy

So far, we have ignored any conflicting interests in the formulation of climate policy. However, strategic interactions between oil exporters (who must decide how fast to extract their finite reserves in the face of the risk that if they wait too long their reserves may become economically obsolete due to the arrival of abundant carbon-free substitutes) and oil importers (who are trying to reduce their oil dependence by investing in the development of alternatives) may be important in the real world. Gerlagh and Liski (2011) therefore examine the strategic interaction between the sellers and buyers of oil and find that fossil fuel producers try to delay the introduction of the renewable energy substitute by supplying more oil to the market and lowering the oil price. This way the incentives to develop the perfect substitute for fossil fuel are weakened, especially if the required investments are costly and take time to develop. Effectively, buyers are compensated for postponing the introduction of the renewable energy substitute.

Jaakkola (2012) argues convincingly that it pays to invest in carbon-free energy substitutes while the economy still relies on oil because this curbs the development costs of the substitute.[17] Although initially oil prices are determined by the Hotelling rule, eventually they are driven by the carbon-free energy substitute, which is becoming cheaper all the time. Thus, the supply of oil falls before it is forced up by competition from the renewable energy substitute. A gradually improving carbon-free substitute forces the monopolist to sell more oil, temporarily increasing carbon emissions, before oil is driven out of the market (i.e., a weak Green Paradox). If oil extraction becomes more expensive as oil reserves are depleted, oil importers will switch to clean fuels once oil is priced out of the market. As a result of technological developments in the production of renewable energy oil becomes more quickly obsolete and thus more oil is locked up in the ground and cumulative carbon emissions are curbed. This latter effect can reverse the effect of the higher short-term damages that are associated with the weak Green Paradox and thus avoid the strong Green Paradox. An interesting conclusion of this analysis is that the development of the clean substitute will slow if global warming becomes more acute because further development of the carbon-free substitute for oil will trigger more oil extraction and this is highly undesirable if global warming has already reached unacceptable proportions.

[17] 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 (2014).

Directed Technical Change and Kick-Starting Green Innovation

The direction of technical change is endogenous and can be shaped by the right type of R&D. Subsidizing green R&D is a crucial supplement to pricing carbon in this view. Green R&D can thus kick-start green innovation away from more conventional directions of economic growth that rely heavily on traditional fossil fuels. Although the literature on subsidizing R&D for green technologies and directed technical change (e.g., Acemoglu et al., 2012; André and Smulders, 2012; Hassler et al., 2011) typically does not refer explicitly to the Green Paradox, a recent study by Van der Meijden (2014) does refer to the Green Paradox. He investigates the determinants of endogenous growth in a setting, where final good are produced with intermediate goods and energy. He assumes that energy is generated by oil and renewable energy which are imperfect substitutes; production of intermediate goods requires only labor; labor is also used for producing renewable energy and creation of new intermediate goods; and knowledge accumulated in the R&D sector spills over to the productivity of oil and renewable energy. Van der Meijden (2014) shows that the availability of renewable energy boosts initial oil use and carbon emissions which corresponds to a weak Green Paradox. If an invention increases the substitutability between oil and renewable energy, the initial oil supply and carbon emissions are reduced so that there is no weak Green Paradox effect. The reason is that with higher substitutability, although the supply of energy is predominantly oil, it is spread more evenly over time. Furthermore, higher substitutability leads to more growth, which boosts future demand for energy and demand for fossil fuel. Thus, we find that climate policy can be counterproductive in the short run due to the presence of renewable energy despite such policy boosting growth.

It should be realized, however, as has been argued by Hoel (2011b), that a credible high future carbon tax does not necessarily imply more oil use today, nor does it necessarily trigger additional investments in renewable technology.[18] He assumes that once the investment is made, renewable energy is available without cost. This means that total energy use in production in period one consists of oil, but part of the initial investment in the renewable energy yields energy in period one. In the second period, energy use consists of oil and energy from the rest of the initially installed renewable energy capacity. This is the reason why Hoel (2011b) is able to show that a high future carbon tax does not boost investments in renewable technology and is yet another example of why climate policy is less productive than what might have thought at first blush.

[18] Hoel (2011b) assumes that a final good is produced with oil and renewables, which are perfect substitutes; production and extraction take place over two periods; oil use is taxed in both periods; and production of renewable energy requires an upfront investment in the first period that has a marginal cost that rises with investment.

Following Acemoglu et al. (2012), Daubanes et al. (2012) also investigate the role of directed technical change. They find that a *gradual* increase in subsidies for the development of green inputs does not lead to a Green Paradox. Rather, they find that the initial use of oil is lower and spread more evenly over time, suggesting that that gradual phasing in of renewable subsidies can avoid Green Paradox effects.

CONCLUSIONS

Well-intended climate policies can have adverse consequences. There are three main reasons for this. The first is carbon leakage which 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. The second is the weak Green Paradox which occurs when credibly announcing a future carbon tax or a too rapidly rising carbon tax as this quickens fossil fuel extraction and accelerates global warming. However, this does not necessarily lead to a strong Green Paradox because green welfare might increase if it is optimal to leave more fossil fuel reserves untapped. The third is subsidizing renewables as these also speed up extraction of fossil fuel and accelerate 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.

We highlighted that coal and shale oil have very high CO2 emissions per unit of energy and are abundant and relatively cheap. If oil and gas are phased out in favor of such backstops, this accelerates global warming. Other backstops, such as the tar sands, are both very bad for global warming and expensive. Such dirty backstops should not be used if one wishes to attain the target of a maximum of 2 degrees Celsius global warming. In fact, there is a lot to be said for a moratorium of coal.

Although an examination of the potential counterproductive nature of climate policies is important, this should not distract researchers and policy makers from other important climate issues such as the possibility that the global economy still has made precious little progress in becoming less reliant on cheap, CO2-intensive coal. A moratorium on coal may be crucial in the fight against global warming. It is crucial then 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 exacerbates 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 because this may render climate policy less effective too. This calls for a general equilibrium approach to the Green Paradox in a multi-country context.

Green Paradox effects highlight the short-run costs of second-best policies. However, further research is needed in order to assess the empirical magnitude of these effects and the associated welfare consequences. To test the weak Green Paradox effect one needs to identify a policy and see whether or not it leads to more extraction in the short run. Ideally, one then has mine of well level data on the Hotelling rent before and after the policy but such data are hard to get. One rare study finds that the announcement effects of the 1990 Clean Air Act Amendments (CAAA) has led to large drops in the price of high sulfur program up to the implementation of the Acid Rain Program in 1995 but this has not led to increased production of coal-fired plants (Di Maria et al., 2012, 2014a, 2014b).[19] Hence, the empirical evidence on the Green Paradox is at best mixed. The challenge for future research is to provide sound micro evidence on the counterproductive nature of certain climate policies.

We have neglected two important aspects of the Green Paradox. The first is imperfect competition in resource markets, which may lead dominant fossil fuel producers to price fossil fuel just below the price of renewables to keep them out and maintain and reinforce their monopoly power on the fossil fuel market (e.g., Hoel, 1978 and 1983; Salant, 1979; Andrade de Sá et al., 2012). This might also shed light on the role of monopoly power in oil or gas markets and its implications for addressing the global climate challenge (e.g., Hassler et al., 2010). The second concerns the announcement effects and the potentially long implementation lags of climate policy.[20] Such time lags may cause the Green Paradox to arise, even without fossil fuel scarcity (Di Maria et al. 2012; Smulders et al., 2012). See Di Maria and van der Werf (2012) for a discussion of these issues.

[19] The CAAA entails a future limit on sulfur dioxide emissions, which signals to coal mine owners that it becomes more difficult in the future to sell high sulfur coal. Production might not have increased because power plants were regulated in the period under consideration and already producing at full capacity.

[20] For example, the European Union Emissions Trading Scheme was announced in 2001, but the first commitment phase did not start until 7 years later. It also took a long time for the Kyoto Protocol to enter into force.

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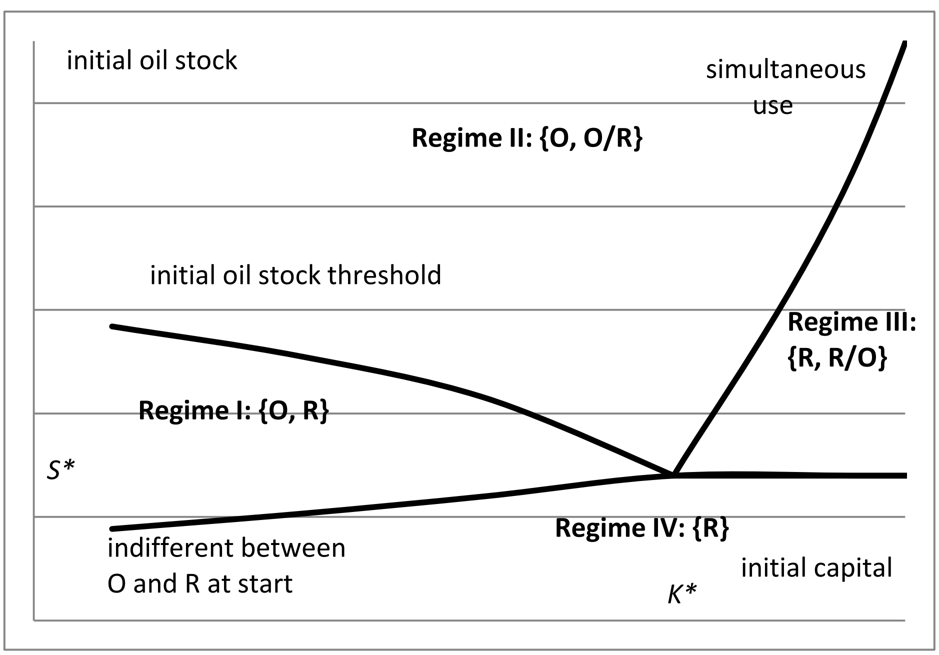
SUPPLEMENTARY MATERIAL

A. Tradeoffs between growth and climate objectives

We now consider the relationship between climate policies and the stage of development of an economy within the context of a model of growth and development. The model used is a so-called a green Ramsey growth model. It has capital, labor and energy in the economy's production function. The central idea is that developed economies may attach larger weight to detrimental effects of climate change than economies in an early stage of development, since the latter have lower consumption levels and thus higher marginal utilities of consumption and prefer to boost material consumption rather than combat global warming. These issues are addressed in Van der Ploeg and Withagen (2014). Output is used for extracting oil, producing renewable energy, gross investments in capital and, finally, consumption. The optimal path of capital accumulation and the use of renewable energy and fossil fuel is the result of dynamic maximization of social welfare. They establish that for the green Ramsey growth model there potentially four qualitatively different regimes for the socially optimal paths. These regimes are depicted in fig. SM1, with the initial stock of capital on the horizontal axis and the initial stock of oil reserves on the vertical axis. Different regimes correspond to different combinations of these two initial stocks. In fig. SM1 we let K^* denote the capital stock to which the economy would converge if only renewable energy is available.

Figure SM1: Four regimes of the Green Ramsey model



Region I corresponds to an initial capital stock smaller than the carbon-free steady state and intermediate values of the resource stock. If the economy starts from any point in this region, it can be proved that it is optimal to start with only oil. This oil-only phase is indicated by the letter O in fig. SM1. Further, at some future moment in time oil extraction will cease and from that moment onwards only renewable energy is used forever. This phase is indicated by R. The economy converges to the carbon-free steady state.

Region II corresponds to an initial situation where the economy is relatively well endowed with fossil fuel and not too rich in capital. It is then optimal to start using only oil and for capital to overshoot the carbon-free steady-state capital stock. Eventually, renewable energy and oil are used simultaneously which is indicated by O/R in fig. SM1. The carbon-free steady state is reached in the long run.

Region III corresponds to initial situations where both capital and the resource are initially abundant. In that case, only renewable energy is used in the first phase, but eventually the economy switches to simultaneous use of oil and renewable energy. Intuitively, moving from region II to region III 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. This means that, from a social perspective, it is no longer attractive to start off using oil and thus the economy will start off using only renewable energy. Finally, if the economy starts in region IV, with a fairly low oil stock, oil will never be used. Intuitively, this is because if initially oil is very scarce and oil extraction is expensive, renewable energy is more attractive despite a relatively low social cost of carbon.

It is interesting to note that under the no-policy scenario, the market economy has only two regimes: either oil is initially scarce and oil extraction expensive, so that it is attractive to use renewable energy throughout; or if oil is initially less scarce, the economy starts off with an oil-only phase and then transitions to a final phase where only renewable energy is used.

As in our earlier frameworks, in the market economy the first-best optimum can be realized by imposing a carbon tax that is set equal to the optimal social cost of carbon. Here the marginal benefits of oil and renewable energy are expressed in consumer goods rather than in utility terms, so the carbon tax may decrease (even without the decay of atmospheric CO2) if consumption is decreasing (as occurs in regime II, which has abundant oil). The Green Paradox will prevail in this case, since a subsidy for renewable energy increases the initial use of oil. However, if the subsidy is used in an economy that is in its early stages of development and still has to grow, the negative effect on welfare will only be modest. This is because the developing economy has a relatively high marginal utility of consumption, attaches less value to global warming damages, and thus has a low social cost of carbon.

The conclusion one may draw from this analysis is that the welfare consequences of Green Paradox will be less severe in developing economies than in mature economies.

Reference

Ploeg, F. van der, and Withagen, C. (2014): "Growth, renewables and the optimal carbon tax", *International Economic Review* 55, 283-311.

B. Cumulative emissions and the global climate challenge

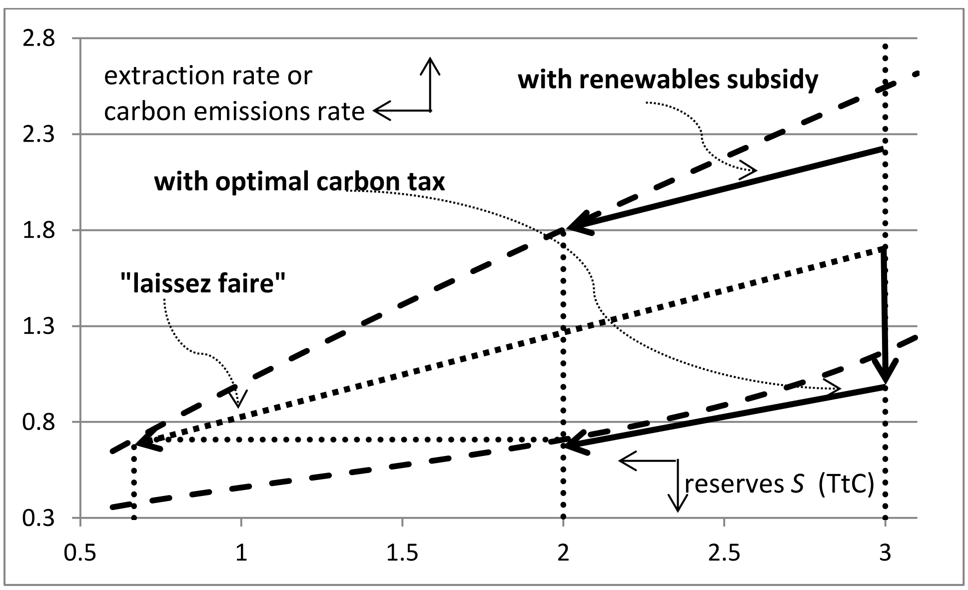
The Green Paradox effect highlights the adverse effects of increased short-run carbon emissions but it is important to realize that carbon taxes locks up more fossil fuel in the ground. Climate scientists are indeed more concerned about *cumulative* CO2 emissions than the time path of emissions as these are what principally affect the change in global peak temperature (Allen et al., 2009; Solomon et al., 2009). Thus, temporary increases in emissions may be less of an issue than the cumulative stock of emissions and fossil fuel use. To get a rough idea of magnitudes that are involved and the principles at stake, we now make some specific assumptions and calculate the social cost of carbon and the stock of untapped fossil fuel. We will abstract from growth and development, and refer for this to the Supplementary Material.

Let us suppose that half of emitted carbon returns to the surface of the earth and the oceans quickly but the other half stays in the atmosphere forever or for hundreds of years. The stock of atmospheric carbon is currently roughly 0.5 TtC (trillion tons of carbon). Let us suppose a benchmark estimate of current fossil fuel reserves of 3 TtC. If all fossil fuel is burnt, then cumulative emissions are the initial 0.5 TtC plus the 1.5 TtC from burning fossil fuel. If only a part of fossil fuel is burnt, cumulative emissions are 2 TtC minus half of the amount of fossil fuel that is left in the crust of the earth. To reflect the fact that extraction becomes more costly as reserves decline, we make the specific functional form assumption that fossil fuel extraction costs are equal to the inverse of the existing stock of fossil fuel. Let us also suppose for the sake of argument that the production cost of renewables is 50 percent higher than the current market price of oil, that the price elasticity of energy demand is 0.85, that the interest rate and rate of time preference are 1 percent per year, and that marginal global warming damages are proportional to the stock of atmospheric carbon with a slope coefficient of 0.04. With these back-on-the-envelope assumptions we can calculate the optimal carbon tax and how much oil should be left in the earth, and compare these with those in 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 renewables (where the scarcity rent is zero), because the extraction cost (1/0.67) then has exactly risen to the cost of renewable energy, both in terms of the initial market price (1.5). This means that cumulative carbon emissions are 2 TtC minus half of what is left of fossil fuel reserves (0.5 × 0.67), which is 1.67 TtC. Since cumulative carbon emissions corresponding to 2 degrees Celsius of global warming are 1 TtC and 2 degrees Celsius is what is judged by climate scientists to be an upper limit before global warming becomes acceptable (Allen et al., 2009), the no-policy scenario has much more cumulative emissions and thus leads to unacceptable levels of global warming. Given that marginal global warming damages are linear in the stock of atmospheric carbon, the optimal social cost of carbon which is the present value of these marginal damages is linear in this stock too and thus linear in the amount of untapped fossil fuel.

In the social optimum society charges a carbon tax which is equal to the social cost carbon. The fossil fuel extraction cost plus the social cost of carbon must thus equal the cost of renewable energy at the time of transition to the carbon-free era. Thus, the social optimum at the time of transition will leave much more fossil fuel in the ground, in fact, 2 TtC, than in the no-policy scenario. The social optimum leads to a total amount of only 1 TtC of carbon in the atmosphere (i.e., 2 TtC − 0.5 × 2 TtC) and ultimately leads to less global warming than under the no-policy scenario. The social optimum manages to limit global warming to 2 degrees Celsius whilst the no-policy scenario leads to 4-5 degrees Celsius of global warming.

Figure SM2: Effects of renewables subsidy and optimal carbon tax on carbon emissions



Source: Van der Ploeg (2013).

As can be seen from comparing the lower solid arrow denoted ‘with optimal carbon tax’ with the dotted arrow denoted “laissez faire” in fig. SM2, this first-best policy of charging emissions at a tax equal to the social cost of carbon consistently leads to lower extraction rates (on the vertical axis) and thus lower carbon emissions compared with the no-policy scenario at each point of time. Here the arrows point in the direction of time as the economy starts off in both cases with initial reserves of 3 TtC. Note that the socially optimal policy with the carbon tax switches much more quickly to the carbon-free era than the no-policy scenario. Of course, the reason is that the latter fails to internalize the costs of global warming.

Fig. SM2 also shows that a second-best policy corresponding to a subsidy for using renewable energy of 60 percent and indicated by the upper solid arrow incentivizes the market to leave 2 TtC of carbon untapped, thus limiting cumulative carbon emissions to 1 TtC. In this case, short-run carbon emissions are higher than in the no-policy scenario, indicating the adverse effects on global warming of a weak Green Paradox. Because with such a renewable subsidy carbon emissions are higher and more carbon is left in the ground than under the no-policy scenario (namely, 2 TtC instead of 0.67 TtC), the renewables subsidy unambiguously shortens the phase where only fossil fuel is used and thus brings forward the carbon-free era. Whether green welfare falls or increases (i.e., whether or not there is a strong Green Paradox) depends on whether the adverse effect of a short-run acceleration of global warming outweighs the beneficial effects of less cumulative emissions and an earlier start to the renewables-only (i.e., carbon-free) era. The assumption of there being only form of renewable energy is unrealistic as in practice other types of renewable energy become competitive as the price of energy rises.

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