COMBATING CLIMATE CHANGE:

POLITICAL ECONOMY OF GREEN PARADOXES

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a. State-of-the-art and objectives

a.1. General introduction

Climate change is generally deemed one of the most urgent and challenging problems mankind has to deal with. It has many fascinating facets and a fruitful analysis requires inputs from almost all disciplines, including physics, sociology, biology, philosophy and, last but not least, economics. The role of economics is important in several respects. Reducing the emissions of greenhouse gases is costly, but it will decrease the damage that is likely to be caused by the accumulation of these gases. Hence there is an economic trade off here. And economists have something to say about this. The benefits and costs of climate policy extend in the far future, implying that we are dealing with a dynamic problem: intra- as well as intergenerational distributional issues come into play, together with spatial considerations, because benefits and costs are typically unevenly distributed over time and space. Moreover, climate change is subject to many uncertainties[1], implying that decisions have to be taken under imperfect knowledge. International environmental agreements are generally deemed necessary to combat climate change when it comes to mitigation. Economics can also contribute to the theory of negotiations and of coalition formation, which is pertinent to international agreements. Climate change is by now a core topic in economics and in political economy. The central aim of this research proposal is to make an innovative contribution to the design of optimal policies to combat climate change.

The motivation for this research proposal stems from the observation that, in spite of the recent failure of attempts to reach an agreement on reducing CO2 emissions in Copenhagen, many policy measures are under consideration by individual governments, or have already been implemented. One may think of the introduction of the European emissions trading system, subsidization of bio-fuels, and solar and wind energy. Increasingly, there are plans to stimulate carbon capture and sequestration but they often face fierce local opposition of citizens. The most obvious policy measure, taxing fossil fuels more heavily to internalise what the influential Stern Review has coined the ‘greatest externality the world has ever seen’, is decidedly unpopular among politicians for fear of the electoral consequences at home, yet it is the first-best policy to attack the problem of global warming. The concept of the Green Paradox, introduced by Sinn (2008a), entails that the emphasis on the demand side or, stated otherwise, the neglect of the supply side of the energy systems, might be counterproductive, in the sense that the supply of fossil fuels, the main source of CO2 emissions, will be brought forward instead of postponed. For example, an anticipated ad valorem tax on extracting carbon enhances present extraction and aggravates global warming, and may therefore be

[1] Including uncertainties regarding the degree of climate change due to human activities and its precise effects.

counterproductive. More importantly, politicians that rely on subsidizing solar or wind energy rather than imposing a (rising) tax on fossil fuels, may inadvertently speed up fossil fuel extraction and thus increase global CO_2 emissions. But such Green Paradoxes are not necessarily cast in stone; for example, if climate policies can be engineered such that there is an incentive to keep fossil fuels in situ.

Our aim is to critically investigate Green Paradoxes, from a theoretical as well as empirical perspective, a national and global perspective, and a normative and political economy perspective. The focus of our proposed research on Green Paradoxes contains various crucial and innovative elements. First, we pay ample attention to backstops; future alternatives for fossil fuels, which may become attractive in the future. We consider a large variety of backstops, both in terms of how much emissions they generate and how expensive or cheap they are to supply, varying from solar and wind to nuclear and the tar sands as well as new hitherto unexplored deeper gas and oil fields. Second, we focus on a broad measure of welfare, not only paying attention to green welfare, but also to the potentially overall welfare effects following from proposed policy measures. Third, in contrast to the current emphasis on perfect competition on the market for non-renewables, we focus on non-competitive global markets for oil and gas (think of OPEC) and how this affects the fight against global warming. Fourth, we will cast part of our analysis in a growth setting, with different types of capital, man-made, human, and natural. Fifth, we focus on political economy issues surrounding the implementation of environmental policies in a world with different jurisdictions, each pursuing their own interest, and surrounding the tough challenge of mustering political support for ambitious climate policy among the electorates of the most heavily polluting countries. Sixth, we will consider the international aspects of realizing effective climate policies, going beyond the standard approach, by considering multi-country, political-economy models of climate change and economic development. Finally, we aim to bring the best empirical evidence to our research in order to make a realistic assessment of the climate policies that will result from our research. The main research question thus reads:

"What is the optimal and politically feasible design of environmental policies with regard to fossil and alternative backstop fuels and technologies to combat (the negative effects) climate change in face of the many economic distortions and other challenges facing governments and the political realities across the globe, both at home and in other countries?"

To highlight our proposed contribution, we briefly sketch the present state of the art. Taking the large uncertainties for granted, for the moment, and taking a global perspective, the central questions addressed in the literature and the approach to their answers can be described as follows. First, what is the optimal and what is the politically feasible development over time of the global economy, taking account of emissions of greenhouse gases, capital investments and consumption patterns over time and space so as to either minimize the cost of obtaining an acceptable level of global temperature, or to maximize social welfare, taking into account the potential damage of climate change? Second, how can the optimum be implemented in a decentralized economy taking account of the most important economic and political distortions? Seminal contributions to the normative approach at an aggregate worldwide level have been made by prominent scholars like Nordhaus (1993) and Stern (2007). Numerous controversies are around and fierce debates have taken place and are still taking place within this more narrow perspective on, for example, the rate of time preference or the discount rate to be used, the way uncertainty should be modelled etcetera (e.g. Nordhaus (2007), Weitzman (2007), Mendelsohn (2008), Weyant (2008), Dietz and Stern (2008), Tol (2009)). Still, broad agreement exists on the necessity to reduce carbon emissions, be it in the medium or already in the short run. Agreement also exists on the necessity of investing in technologies for clean power, by means of renewable energy and other low carbon sources. At the same time carbon capture and storage (CCS) is deemed important, since coal will continue to be one of the main sources of energy in the medium run.

Although most of the analyses are rooted in the well-established theory of optimal economic growth, it is in light of the crucial role played by non-renewables such as oil, gas and coal, somewhat surprising that almost nowhere an integration can be found of growth theory and the theory of non-renewable resources. This could be justified by arguing that conventional oil and gas resources are available to such an extent that either they will not be exhausted in the foreseeable future or by saying that even if all oil and gas would be exhausted, the temperature rise as a consequence of this would only be moderate. However, for coal the latter argument clearly doesn't hold, and the former depends on the horizon one deems appropriate. Moreover, the present project also deals with the optimal timing of transition between non-renewables and from non-renewables to renewables. Finally, it is not only green welfare that matters but total welfare. Hence, we think there is a clear case for taking exhaustibility as a point of departure. The normative approaches to climate policy did not account of second-best issues arising from the numerous economic and political distortions complicating the realization of an effective climate change policy. This observation requires one to leave the realms of homogenous-agent models, which also belongs to the core of the present research programme.

Our research necessarily brings together several sub-disciplines of economics, and, moreover, will use and possibly enrich other disciplines. In order to tackle the problems adequately it is necessary to integrate environmental and resource economics, including the economics of sustainability, on the one hand, and public economics on the other. Even in the simplest setting of the problem, the insights from these approaches are indispensable and their synthesis will be innovative and significant. Given the complexity of the problem statement, the project entails a high risk, but it can have a huge impact on actual policies as well.

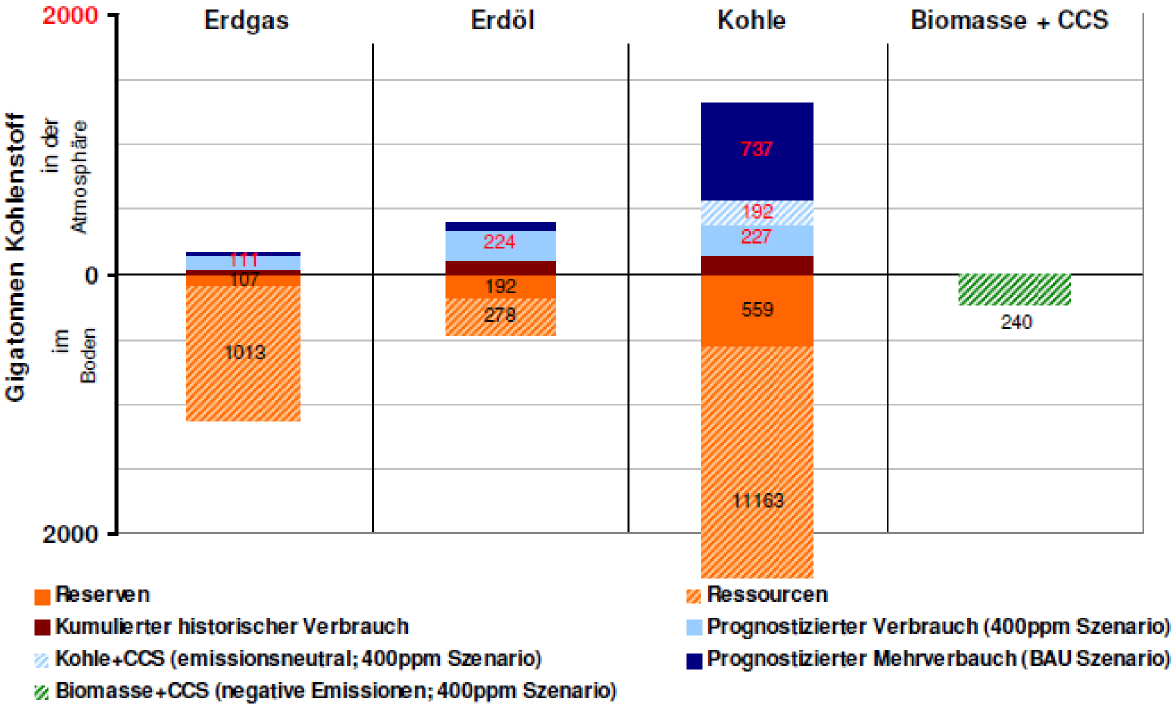
In the sequel we first go into the relevance of conventional energy sources for climate change (a.2) and highlight the importance of including the supply side of fossil fuels as well as backstops in models dealing with climate change (a.3), and briefly relate our proposal to earlier literature (a.4). The normative and more positive research projects composing this research proposal are subsequently outlined in some detail (a.5).

a.2.The relevance of conventional gas, oil and coal reserves for climate change.

In the most well-known Integrated Assessment Models (IAMs) currently used to debate climate policy in the public sphere (Nordhaus (1993, Nordhaus and Yang (1996), Manne et al. (1995), Fankhauser and Tol (2005)) exhaustibility of non-renewable resources and its relevance for the supply side of these resources hardly play a role in the modelling of CO_2 emissions from fossil fuels. The IAMs usually maximize some objective function under a set of constraints. On a global scale the objective function represents social welfare, depending on consumption and the possibly negative direct amenities of climate change, ignoring distributional considerations across time and space and abstracting from economic and political distortions. An alternative to maximizing social welfare is minimizing total discounted costs of obeying an exogenously given upper bound on CO_2 concentrations. The solution yields time paths of emissions, capital accumulation, consumption etc., as well as corresponding shadow prices that can be interpreted as market prices if the economy is pursuing the first-best outcome.

Since emissions of CO_2 come mainly from non-renewable fossil fuels such as oil, gas and coal, one may wonder whether their limited availability sets an upper bound on total emissions and therefore whether this leads to the conclusion that climate change, in as far as caused by the burning of fossil fuels, will in the end only be small. Campbell and Laherre (1998) argue in favour of this position, whereas Odell (1999) stresses that there will always be discoveries of cheap new resources. More moderate views are taken by others. Some agreement seems to exist. The first finding is that it is feasible to meet moderate stabilization targets of CO_2 with the given resources of conventional oil, gas and coal. For example, Grubb (2001) puts forward that reaching 450ppm CO_2 in 2100 would require three times the amount of total reserves of oil and gas (and also more than the resource base of these fossil fuels). Hence, conventional oil and gas will be exhausted and coal will make a large contribution without getting exhausted. If the aim were to have 400ppm CO_2, conventional oil and gas reserves would suffice. But with 600ppm Grubb concludes that all proven fossil fuel reserves are needed. Hence, the main problem arises with increased use of coal and unconventional deposits such as tar sands and oil shales. The findings of Edenhofer and Kalkuhl (2009) are similar, although the results concerning exhaustion do not coincide. This is illustrated in their figure 1 below.

The brown areas in the figure give the CO_2 that has been emitted over the past. Under the scenario where CO_2-equivalent levels are stabilized at 400 parts per million (compatible with the objective of efficiently limiting the increase in global temperature to a maximum of 2 degrees centigrade over pre-industrial levels) estimated energy consumption until 2100 will be 227, 224 and 111 Gigatons of carbon for coal, oil and gas, respectively. An amount of 192 Gigaton coal will be emission neutral. In the business as usual scenario estimated additional consumption will hit 737 Gigaton for coal, but almost none for gas and oil and coal. Biomass and CCS will lead to negative CO_2 emissions. Under-the-ground reserves imply the following potential further future CO_2 emissions: for gas, oil and coal reserves (probable and proven resources and reserves for gas, respectively, amount to 1013 and 1027 Gigaton; oil 278 and 192 Gigaton of carbon; and 11,163 and 559 for coal. In the business as usual scenario we see the claim by Grubb confirmed; namely, substantially more coal use. Sinn (2008a) argues that burning the reserves of coal, oil and methane is likely to lead to a concentration level of 1220ppm, which is generally deemed too high for an acceptable temperature rise. Stern (2006, p. 212) says that that without climate policy demand for fossil fuels will grow but not in such a way that increased scarcity will drive up prices to a large extent. If the demand for oil is always met, however, CO_2 concentration will increase considerably. We see that in several scenarios some of the conventional fossil fuels will become exhausted whereas others do not, in particular coal. All in all it seems premature too neglect exhaustibility beforehand. The consequences of this observation will be discussed next.



a.3. The supply side of fossil fuels and backstops

If along some program a non-renewable resource gets exhausted, whereas another one does not, that latter has a zero shadow price, and the former has a positive shadow prices. An addition to the stock of the former would not be valuable along the program in the sense of adding to the success of the programme. On the contrary, adding something to the stock of the depleted resource would have a value. Therefore the price of the exhausted resource contains a rent component. This implies that, if policy would lead to a fall of fossil fuel prices (e.g. through subsidization of a backstop technology), supply of the resource could increase initially. This is what Stern (2006) alludes to when advocating "carbon capture and storage" by saying that "there is a danger that fossil fuel prices could fall in response to the strengthening of climate change policy, undermining its effectiveness". CCS will "help guard against this risk" (o.c., 213). This is one reason why we are convinced of the necessity to explicitly model the supply side of fossil fuels in climate models and take exhaustibility into account. The following comes to mind: ".. the 'pure' mining problem must be coupled with the 'pure' pollution problem and questions like these become relevant: which should we run out first, air to breathe or fossil fuels to pollute the air we breathe?" (d'Arge and Kogiku (1973), p. 68). Another reason is that in the design of optimal climate policy one could neglect the exhaustibility of fossil fuels by arguing that they are abundant until the far future, as is the case for coal or oil from tar sands, but this may lead to the failure of climate policy. In the absence of renewable resources such as solar or wind energy, some fossil fuels such as oil and gas are essentially available in limited amounts and their optimal intertemporal use needs to be determined in conjunction with any adverse effects this may have on global warming. The optimal policy of extracting such fossil fuels and combating climate change should take into account the order in which the fuels are to be extracted. In doing so, differences in extraction costs for the various sources of energy as well as differences in the contributions the resources make to climate change play a role. With the availability of renewable backstops these problems persist. In addition, the timing, order and speed of extraction in conjunction with the introduction of the backstop are crucial for future welfare. Finally, one could argue that exhaustibility is not relevant when it comes to climate related damages. However, what counts in environmental policy is not only the social environmental damage of accumulated emissions but also other welfare components matter.

We explicitly consider exhaustibility of some fossil fuels, but also look at backstops. Backstops are defined as renewable resources that are perfect or imperfect substitutes for fossil fuel and are not constrained by exhaustibility. Our special interest in the role of backstops is motivated by the fact that subsidizing backstops may have negative detrimental climate effects and therefore be part of Sinn's 'Green Paradox' that has received a lot of attention in the press and recently also has been scrutinized more rigorously (e.g., Hoel (2008) and Gerlagh (2009)). Remarkably, however, Sinn (2008a) only pays minor attention to backstops. He argues that "public policies that would limit the overall extraction and exempt part of the stock in situ permanently from extraction to mitigate the problem of global warming seem hardly defendable" (Sinn, 2008a, p. 376). If stimulating backstops is aimed at reducing the total amount of fossil fuels extracted then he argues that this is impossible, the more so since backstops are generally imperfect substitutes for conventional sources at best. It is our aim to critically review such arguments. In particular we think there are some cases for subsidizing backstops, and other cases for taxing them, and it is necessary to identify the conditions under which each of these possibilities occurs given the huge subsidies given to solar and wind energy in some parts of Europe. Moreover, we are not only interested in the consequences of such policies for climate change, but take a much broader welfare perspective

a.4 Setting the stage.

A first normative attempt to integrate climate change and non-renewable resource economics into an intertemporal optimizing model was made by Withagen (1994), who shows that initial use of the exhaustible resource should be smaller than without the climate externality. In the same context Ulph and Ulph (1994) deal with optimal (dynamic) taxation of fossil fuels and their detrimental effect on the environment, and Sinclair (1994) argues that with endogenous growth optimal fossil fuel taxes may fall rather than rise over time. Withagen (1994) provides the simplest setting in which Green Paradoxes can be understood. He considers an economy that is endowed with a non-renewable resource, say oil, that can be extracted at no cost. Oil is the only source of welfare, but at the same time the use of oil causes the accumulation of CO2, that constitutes a negative externality on the economy's welfare. The stock of CO2 decays slowly and exogenously over time. The problem the economy faces is to determine an extraction path for oil over an infinite time horizon. Crucial is the form of the social welfare function. As usual, a pure rate of time preference, possibly equal or close to zero, is employed. Moreover, marginal utility of the consumption of oil is assumed to be unbounded for low levels of consumption, and marginal damage of a low CO2 stock is assumed to be low, but goes to infinity if the stock of CO2 goes to infinity. This, together with concavity of the utility function and convexity of the damage function implies that eventually all oil reserves will be depleted. The result is that, compared to the case without the externality, extraction of oil occurs more slowly: initially the extraction rate is smaller, but, in view of the fact that the oil stock will be depleted, the extraction rate must be higher eventually. After characterizing the socially optimal path, the question arises how it can be implemented in a decentralized economy. Clearly, without government interference the first-best will not prevail in a decentralized economy because the suppliers of oil neglect the externality when taking their extraction decisions. In the absence of the externality the Hotelling rule holds. This rule says that, if oil can be extracted at no cost, the price should increase at a rate equal to the interest rate. Indeed, the oil stock can be considered a capital asset, on which the return must be equal to the return on capital, the interest rate. In the case at hand, the interest rate is related to the rate of time preference and the growth rate of consumption. Moreover, the initial market price can be determined by using the condition that all oil will be fully depleted eventually. With the externality, oil producers should internalize the damage. Hence, the oil price should be corrected for marginal damage. This yields a new price path, where the price goes to infinity as time goes to infinity.

Suppose next that consumption not only comes from the non-renewable resource but also from a renewable resource, the latter at some cost per unit of consumption. Hence, a backstop technology is available and produces a perfect substitute for the conventional energy source. Moreover, assume the backstop technology is clean, meaning it does not add to the stock of CO2. Without externalities, it is optimal to first deplete the non-renewable resource and then use only the backstop technology. Moreover, a decentralized economy, without any other economic or political distortions other than the global warming externality, will behave this way. However, with the climate externality (assuming initial pollution is not too severe) initially only the non-renewable resource will be used. Thereafter the backstop and the non-renewable will be used simultaneously indefinitely. Consumption will always be smaller than in the optimum without the externality (see Hoel and Kverndokk (1996)). In the decentralized economy a CO2 emission tax is needed to implement the social optimum. The resource owners need to be persuaded to slow down extraction.

The essential feature of the Green Paradox is the potential welfare loss of a seemingly beneficial improvement of the conditions under which the economy operates, in casu a decrease in the cost of providing the backstop technology. Clearly, from a social welfare perspective an exogenous decrease in the cost will be welcomed, because it makes substitution less cumbersome. However, if one were to look at a decentralized economy, where a CO2 tax is difficult to impose, matters can turn out wrongly, and even an adverse counterproductive result may be obtained. Now confronted with a lower upper bound on the oil price, mining firms will start to extract at a higher rate. This is so because they want to extract all oil they possess, since they can extract at no cost, which can only be done by setting a lower price until the backstop price is reached. If the backstop price is lower than before, the oil price will then also be lower than before and supply will be higher. The resource stock is going to be exhausted earlier than before. Two welfare effects arise. The lower oil price enhances consumption, which adds to welfare, but the faster extraction also leads to more accumulation of CO2, which is detrimental to welfare. It is difficult to say beforehand what effect is dominant. If the decrease of the backstop price is brought about by a subsidy, then the subsidy goes at the costs of another allocation of funds, so that the welfare prospect is less optimistic.

So far, our discussion has focused at how to combat climate change in an ideal world in which the only market failure is that economic agents fail to internalize the most important externality facing the globe today, namely the global warming externality. The real world is a much murkier place where there are other tax distortions, resource and other markets are characterized by imperfect competition and do not always clear instantaneously, and governments face the challenge of supplying or facilitating the universal supply of other public goods (such as schools, health care and pensions), looking after an acceptable income distribution and having to cope with other intra-generational issues such as greying of the populations. Furthermore, as the Stern Review makes very clear, countries are in different stages of development and are affected differently by global warming. The challenge is to come up with climate policies that are supported by citizens throughout the globe, and that minimize the damage done the world economy and prospects for sustainable development.

a.5. A detailed description of the research projects

We start from the basic structure outlined above and extend it into several directions that are deemed relevant for the general research question. In the sequel we sketch our ambitious research agenda for this project.

- Firstly, a distinction needs to be made between several types of backstop technologies and the transitions from fossil fuels to these new energy sources. The project concerns the costs and the relative degree to which the backstops are more or less polluting than conventional energy sources.
- Second, we need to think more deeply about the way climate change is incorporated in the model and the criterion for optimality. Should we employ the usual utilitarian objective or the egalitarian objective, that might do more justice to intergenerational equity? What is the most appropriate rate of discount to use for assessing climate damages that may not occur for another century and how is this affected by intrinsic uncertainties surrounding climate change? Contrary to most Green Paradox studies, we will pay only attention to changes in green welfare (related to damage from climate change), but also to the private components of social welfare.
- Third, the market structure plays a crucial role for the outcome of the economic process. This obviously also holds here. No doubt the oil market cannot be characterized as a competitive market. And it will turn out that for the policy advice that could result from our analysis the market structure is crucial. This has to do with the sensitivity of the order of extraction of several resources to the prevailing market structure. Special attention needs to be paid to the role of OPEC and the emerging gas cartel and how they will react to a growing tax on hydrocarbon fuels. Since these cartels own many assets in the OECD, they do not only obtain monopoly power from setting world oil prices but also may have a big impacts on assets prices in the OECD.
- Fourth, the work done so far hardly deals with the accumulation of man-made capital by means of investments and human (innovative capital) through research and development. This is another

novelty in the proposed agenda. In particular, we will consider side payments in the form of climate change adaptation (water defences, etcetera) that are needed to get support from developing economies for a more ambitious climate policy.

- Fifth, after deriving the optimal outcome in an ideal world where the only challenge is how to internalize the global warming externality, we need to focus at the important political challenges of how to do this in a world where many countries have poor citizens who may be most hurt by climate policies, yet politicians in democracies need their support to implement an ambitious climate policies. Furthermore, we need to consider the different interests of developing and developed economies and how this affects the chances of coming up with a successful climate policy at the global level. Special care needs to be taken of emerging economies with fast-growing population growth rates such as China and India. To tackle these issues, we need to face issues of optimal income distribution and economic development head on.
- Sixth, climate change is a global problem, but it has different impacts on different jurisdictions, that have different means and objectives of conducting environmental policy. Oil still comes for a large part from the Middle East, the main negative damages of climate change are found in Oceania, and the Western hemisphere has the technology to combat climate change. Hence, determining a global optimum is interesting per se, but the implementation cannot neglect the uneven distribution of means and effects.

The six projects of our research programme are directed at these six issues, which all follow from our core research question. Before discussing each of the projects in some detail, we highlight that our analysis will be rooted in sound economic theory, but will then be calibrated and/or estimated to the best empirical data we have. Furthermore, we stress that our six projects are strongly interrelated and that a final product of our research effort will be a variety of normative and politically feasible (positive) simulation models of how climate policies should and can be conducted in the real world. We hope these different perspectives on what ought and what might be feasible will illuminate the debate on climate policies, and will help to get climate policy out of the gridlock it often appears to be in.

Project 1: Transitions to non-fossil-fuel backstops, sequestration and energy-saving technologies

The literature on Green Paradoxes and backstops thus far focuses on the transition from energy from a non-renewable resource to a clean perfect substitute that can, at a certain cost, be produced in unlimited amounts over time, not constrained by a limited resource. The conventional sources of energy are oil and gas and for the backstops one has in mind solar, wind and advanced nuclear. Usually, the optimal path consists of a phase where only the non-renewable is used (possibly until full depletion) followed by a final phase where only the backstop is used. Two famous rules from resource economics determine this outcome. The first is the Hotelling rule (Hotelling, 1931). If extraction costs do not depend of the remaining stock it says that as long as a mine is active (meaning supplying oil), the net price, consisting of the market price minus the extraction costs, should rise at a rate equal to the interest rate. The reason for this is that if the net price would rise at a lower rate, the mine owner has an incentive to extract in the present rather than in the future, which would violate demand matching supply, and the other way around. For the case of extraction costs not depending on the remaining stock, the rule becomes somewhat more complicated. The second rule is the Herfindahl rule (Herfindahl, 1967)). It applies to the case of multiple non-renewable resources, such as oil, gas and coal, with extraction costs that can unambiguously be ordered. It says that, the cheaper resource will be depleted before the more expensive one is taken into exploitation. Moreover, this is optimal from a social welfare point of view if there are no externalities, such as the greenhouse effect. Hence, in the case at hand, the cheaper oil is extracted before the expensive solar energy is taken into production. Two features are missing in the Green Paradox literature.

First of all, there are important exceptions to the Herfindahl rule, that should be investigated in the context of the Green Paradox. Van der Ploeg and Withagen (2010) show that with stock dependent extraction costs it will not necessarily be the case that the conventional stock is depleted before the backstop takes over. Kemp and Long (1980b) also provide a sufficient condition, with non-linear extraction costs, for an ordering of exploitation that does not conform to the Herfindahl rule. Several authors put forward that capacity constraints on the extraction of the fossil fuel may lead to a reversal of the Herfindahl rule. For example, Amigues et al. (1998) introduce a capacity constraint on a backstop technology. An important contribution was also made by Chakravorty and Krulce (1994). They argue that two non-renewables may be imperfect substitutes, say oil and coal. Extraction can be used for two purposes, electricity generation and transportation. In order to use coal for transport additional expenses are needed. Under some mild assumptions it is shown that the optimum consists of three phases. Phase 1 in which all demand is only met by oil. Phase 2 in which only coal is used for electricity, but where coal is still not used for transportation. And a final phase 3 where coal is used for both purposes. At the beginning of this phase the oil stock is depleted. So, in phase 2 both resource stocks are under exploitation. Im et al. (2006) add a backstop technology and show that there exist conditions under which coal is extracted discontinuously. In a first phase only oil is extracted for both purposes. Then oil is used for transportation and coal for electricity. While oil is still used for transportation the backstop technology takes over for electricity and this will remain the case. However, coal is used for transportation even after it is no longer used for electricity. Eventually only the backstop is used for both purposes. These results obtained hold for competitive economies where environmental damage was not taken into account. If damage is playing a role, the order of use may change again. Also, it is worthwhile to consider multiple non-renewables. In any case, we conclude that a further investigation into potential violations of the Herfindahl rule is relevant for the Green Paradox.

Second, next to clean but expensive backstops, there are dirty backstops. Indeed, for analytical tractability reasons one could treat tar sands and coal as being available in unlimited amounts, at least to start with. When it comes to emissions and the costs of the backstops, what counts is their position relative to the conventional sources like oil and gas. This leads to the crude taxonomy given in table 1. The table only provides a crude classification because of the possibility that extraction costs of fossil fuel are stock dependent, implying that whether they are expensive or cheap depends on how much of them is left in the ground.

Table 1: Alternative energy sources to conventional oil and gas

Backstop	Expensive	Cheap
Zero CO2 emissions	Solar/wind/advanced nuclear	Nuclear
Cleaner	CCS coal	Bio-fuels
Bit dirty		Coal
Very dirty	Tar sands	

Solar and wind energy are clean and expensive backstops. These resources by themselves make no contribution to the accumulation of greenhouse gases. However, a lot of energy might be needed to produce them. These backstops are expensive, possibly not when it comes to the marginal production costs once capacity is installed. But surely it is expensive to increase capacity, there are costs to do with intermittence and especially offshore windmills are very costly to repair. Wind energy is estimated to be at least three times as expensive as 'grey' electricity. However, a recent study suggests that, as far as the electricity industry is concerned, the costs of renewable sources of energy have fallen quite a bit: solar energy is currently 50% more expensive than conventional electricity, wind energy has the same cost and is (apart from the problem of intermittence) competitive, and biomass, CCS coal/gas and advanced natural gas combined cycle have mark-ups of 10%, 60% and 20%, respectively (Paltsev et al., 2009). These mark-ups for renewable energy sources are measured from a very low base and may not be so impressive when they account for a much larger market share. At the other end of the spectrum of energy sources that do not emit CO2, we place nuclear energy, which is deemed to be rather competitive already, possibly due to the neglect of the cost to be incurred after the plants become obsolete. The third category consists of carbon sequestration of electricity-generating industries, which is more expensive than using conventional oil or gas but has lower CO2 emissions. Bio-fuels are relative clean and cheap, although their opportunity costs in terms of land use, and food prices, might be high. This is not taken into account in Grafton et al. (2010). Another category consists of heavily polluting and expensive backstops. We treat the tar sands as such, because their reserves are orders of magnitude larger than the existing conventional oil and gas reserves. Although burning oil from tar sands yields the same emissions as burning conventional oil, a lot of energy is used in producing oil from tar sands and therefore CO2 emissions are at least 50% higher and in some cases perhaps even 3 to 5 times higher than those of conventional oil. They also adversely affect the livelihood of indigenous communities via large-scale leakage of toxic waste in groundwater and destruction of ancient forests larger than the size of England. Finally, we consider coal which is heavily polluting (electricity from coal-fired plants are 30% higher than oil-fired plants), but cheap to exploit (depending on location and soil characteristics). Also, the process of making coal liquid so that it can be a substitute for oil in transportation takes a lot of energy. Coal can be considered as a backstop, since to all intents and purposes the supply of coal lasts indefinitely as may be seen from figure 1. However, strictly speaking coal is a non-renewable resource.

It is worthwhile to proceed in the following directions. First, it may be of interest to allow for imperfect substitution in the demand for the non-renewable and the backstop energy source. This may arise from concerns with security of energy supplies, diversification and/or intermittence of backstops such as wind and solar energy and will lead to the simultaneous use of both the non-renewable and the backstop. Second, it is important to investigate what happens if there are various types of backstop available at the same time. If it is possible to rank them, e.g., clean but competitive (nuclear), clean and expensive (wind, solar, advanced nuclear) and dirty and expensive (tar sands), it is best to go for the cleanest and cheapest backstop. However, with dirty and cheap backstops, matters are more complicated especially if we allow for upward-sloping supply schedules of the backstop.

Summarizing, this new avenue will extend the analysis to more types of backstops, more types of fossil fuels and takes into account potential violations of the Herfindahl rule, in the social optimum as well as in the competitive economy. The methodology employed in deriving the first-best optimum is optimal control theory over an infinite horizon. Ample use will be made of the transversality conditions. We will empirically investigate the costs and the emission intensity of the various backstops compared with conventional fossil fuels. We will also scrutinize Green Paradoxes when backstops constitute imperfect rather than perfect substitutes for fossil fuels. And we will formally analyze the economics of carbon capture and sequestration, especially whether the market will supply an efficient network of pipes and carbon sinks. These extensions present major generalizations of the earlier literature on climate change policy and add to the empirical relevance, but the analysis is still firmly normative and focuses on only one market failure (i.e., the one arising from the global warming externality).

Project 2: Sensitivity of climate policies to alternative concepts of social welfare

One important step in answering the research question is the design of a benchmark program in order to evaluate economic policies. Since climate change is dynamic by nature the criterion needs to be dynamic as well, meaning that it should allow us to compare programs over time. There are good reasons to opt for an infinite horizon because it captures the long run and because any finite horizon would be arbitrary. Total welfare from a program can be conceptualized in at least two ways, utilitarian and egalitarian. In both cases total welfare is a function of instantaneous welfare, consisting of instantaneous utility from consumption of final goods and instantaneous disutility from CO2 concentrations. The former is usually modelled by a standard utility function. The latter can be modelled in at least three ways. One way is direct by including it in the instantaneous utility function (with a negative sign). The second way is indirect through introducing a negative externality in the set of technological opportunities. Climate change has a detrimental effect on agriculture for example. Both approaches have their merits and they will most likely lead to the same qualitative results. If one allows for separability of the instantaneous welfare function, as is usual, then it is also possible to decompose the welfare effects of environmental policies into ‘grey’ welfare changes due to changes in consumption and ‘green’ welfare changes from climate change. This will add to the present practice of looking only at green welfare aspects. A third way is to perform a welfare analysis subject to a given constraint on CO2 concentrations (see e.g. Chakravorty et al., 2008). One may argue that this upper bound should follow from some optimization and depends on the specification of disutility of accumulated CO2 emissions. However, this approach turns out to make the problem technically more tractable.

After determining instantaneous welfare at each instant of time, one has to set the stage for intertemporal welfare comparisons. We will have to consider carefully the implications of population growth and the demographic transition which many developing economies are still going through, and investigate how this impacts optimal climate policies. In a utilitarian framework total welfare then consists of the integral of instantaneous utilities, possibly weighted by a discount rate. With a positive discount rate future generations' utility receives a smaller weight and in the absence of technological progress this may lead to ethically undesirable outcomes (see however Diamond et al., 1964). Nevertheless, this is the most common approach, also in climate economics. Alternatively one may opt for an egalitarian welfare function, which can be made operational by maximizing the instantaneous utility of the generation that is worst off. This criterion is closer to the notion of sustainability according to the well-known Brundtland definition. Moreover, taking this perspective also necessitates going into the question of the existence of an optimum, which is non-trivial in the presence of non-renewable resources.

Both approaches will be practiced in the research project. Looking at egalitarian or Rawlsian (maxi-min) welfare, and comparing it with utilitarian welfare is, in the framework of Green Paradoxes, innovative. We will study how different concerns about intra-generational and inter-generational equity, both within sovereign states and across sovereign states, affect the shape of optimal climate policies. Most importantly, the questions are how or even whether to discount the future. The Stern Review has, following the classic work of Frank Ramsey, decided to use a very low discount rate, which biases the results in favour of very ambitious climate policies. We will also take the view that the large uncertainties, both traditional and Knightian, surrounding climate change will affect the social discount rate that one should use. We will pay ample attention to how uncertainty might bias towards or away from myopic decision making. These different perspectives have hitherto been unexplored in the literature on Green Paradoxes. Although this project is theoretical in nature and will benefit from extensive discussions with moral philosophers; we will use numerical exercises and simple calibration to get a feel for how climate change policies are affected by the different perspectives on social welfare.

Project 3: Effects of non-competitive markets for backstop and sequestration on optimal climate policies and Green Paradoxes

The literature on Green Paradoxes is mostly concerned with competitive markets for fossil fuels, but given the importance of OPEC and the emerging global gas cartel it is essential to study imperfect competition. In the context of Green Paradoxes Van der Ploeg and Withagen (2010) already discuss a monopoly for the oil market. With a linear demand schedule and in the absence of a backstop, a monopolist postpones depletion of oil reserves compared with perfect competition, a well known result. Hence, a monopolistic market structure is beneficial for climate change, because emissions take place later than under perfect competition. In this sense, greens and business protectionists are 'unlikely bedfellows'. With a backstop technology the phenomenon of limit pricing occurs: the extraction schedule has two phases. One where the price is increasing, and strictly below the backstop price, and one where the monopolist sets the price marginally below the backstop price, thereby for some time outcompeting the backstop (Hoel, 1978). Van der Ploeg and Withagen (o.c.) show that with stock dependent extraction costs, limit pricing still prevails. Moreover, a Green Paradox may hold: a lowering of the backstop price will enhance early extraction of the monopolist, but not necessarily so. A comprehensive welfare assessment of subsidizing the backstop, taking full account of the sensitivity of the optimal sequencing of extraction of the various available fuel reserves to the prevailing market structure, is a key objective of this project. Imperfect competition not only prevails on the market for fossil fuels, but possibly also on market for renewable energy. When it comes to, say, windmills big players will dominate the market. Also, when it comes to nurturing a grown-up market for carbon-free backstops and to having a suitable network of pipes and sinks for sequestration, natural monopolies may be needed which need to be looked at in our analysis.

Even more challenging is to consider the case of oligopoly and in particular the case of cartel-versus-fringe. Although much work has been done on this decades ago, only recent developments, in which the PI was directly involved, allow for incorporating these market structures in investigations regarding climate change and backstop technologies. However, still much innovative work has to be done. A full account of oligopoly with an arbitrary number of players, linear demand and two types of constant marginal extraction costs, low and high, can be found in Benchekroun et al. (2009), who amply use the theory of differential games. It is important to consider cost differentials because they prevail in reality and turn out to be relevant for the order of extraction. Benchekroun et al. consider the open-loop Nash equilibrium. In this equilibrium the extraction paths are determined at the outset of the game, say at instant of time 0 and they are functions of time only (and not conditional at each instant of time on the then existing stocks). As is common in these games, every player takes the extraction (path) of every other player as given when determining its own optimal extraction path. One of the remarkable outcomes is that the order of extraction will not obey Herfindahl's rule, if the cost advantage of the low cost mines is only moderate and their aggregate stock is large. This result may have serious consequences for the Green Paradox. If the low cost mines can be identified with coal then initially we might have simultaneous extraction of oil and coal, and only coal thereafter. This is bad from a welfare perspective, in the absence of externalities. However, it might be good from a social welfare perspective if externalities prevail. The case of oligopoly with the presence of a backstop technology has not yet been explored. If it would lead to results similar to those derived earlier then this is definitely a relevant issue when it comes to climate change. In such a case we wouldn't need stock effects in extraction costs in order to ascertain (or refute) the idea of Green Paradox. In addition, it even becomes more exciting if we would allow for stock effects. However, it cannot be hoped that an analytical approach will lead to clear results. A numerical approach is in order in that case. Nevertheless it seems worthwhile to explore this too.

In addition to the previous setting of oligopoly, the cartel-versus-fringe model may offer new insights and is relevant to the oil market. There is a large number of price taking mining firms called the fringe, mostly extracting high cost fossil fuels, and one coherent dominant firm, called the cartel. The PI has been important in analysing this market structure as well. For the case of the open-loop Nash equilibrium (Benchekroun et al. (2010), the closed-loop Nash equilibrium (Benchekroun and Withagen, 2009), the open-loop Stackelberg equilibrium (Groot et al., 2000) and the closed-loop Stackelberg equilibrium (Groot et al., 2003). For plausible parameter values the open-loop Stackelberg equilibrium does not satisfy the condition of subgame perfectness, which is a reason to reject it as an equilibrium candidate. However, the closed loop Stackelberg equilibrium is hard to find. Groot et al. (2003) were the first to do so. Their result can be very helpful in the research proposal at hand. The market for fossil fuels can indeed best be characterized by a cartel (OPEC) versus a large group of price takers, with OPEC acting as a dominant player. What is needed in order to investigate the role of this equilibrium concept in the context of Green Paradoxes, is an extension so as to include a backstop technology, which hasn't been captured so far, even for the case of a linear demand function. In first instance we should try to do without stock dependent extraction cost, but maybe numerical exercises can be made in due course.

Project 4: Capital accumulation, R&D, education, health, sovereign wealth and design of sustainable climate policies

In the absence of externalities such as climate change, economics has been enriched with the theory of non-renewable resources finding its origin in Hotelling (1931), whereas in the seventies of the last century seminal contributions were made by e.g., Dasgupta and Heal (1974, 1979), Stiglitz (1974), Koopmans (1974), and Solow (1974). This literature deals with sustainability and optimality of economic development in the presence of non-renewable resources. A typical way of investigating non-renewable resources in conjunction with social welfare is to have at least two capital goods: the resource stock and a stock of man-made capital. The so called Dasgupta-Heal-Solow-Stiglitz (DHHS) model has become a standard vehicle in dealing with this. The economy is endowed with oil, serving as an input in the production of a final commodity that can be allocated to consumption as well as to the accumulation of man-made capital. Man-made capital is also a production factor, together with labour. Hence, oil no longer appears as a direct consumption commodity but as a factor of production. A lot of work has been done in the area. The model is an ideal instrument to tackle questions such as: What is the optimal extraction rate of oil in view of a utilitarian welfare criterion? Does there exist an optimal program such that a constant positive level of consumption (per capita) can be maintained by transforming exhaustible oil or gas reserves into ever-lasting productive assets such as infrastructure, capital goods, human capital, health and sovereign wealth? Another rule, the Hartwick rule, emerges from the latter question: to have a constant rate of consumption the economy has to invest all revenues from oil in accumulation of man-made capital (e.g., Asheim et al., 2003).

An early extension to include environmental aspects was performed by Van der Ploeg and Withagen (1991). Their approach can fruitfully be employed in this project. Green Paradoxes have until now only been studied under the assumption that oil is delivering utility in a direct way. Its demand schedule is taken as given. This is of course hard to justify. If oil is a factor of production demand for it should follow from welfare or profit maximization. Therefore it is innovative and relevant to extend the DHSS model so as to incorporate damage from accumulated CO2 emissions, backstop technologies, and energy as an input in the aggregate production process. This is a far from easy task. It implies extending the DHSS model with one additional state variable, whereas already two state variables pose serious mathematical problems. Nevertheless, important questions need to be answered, such as how the Hartwick rule should be modified in this new framework, how substitutability between types of energy plays a role, and what kind of policies can be recommended. One step further is to introduce technical change brought about by investments in knowledge and to see this affects about the rate of labour-augmenting technical progress, as is usual in the modern theory of endogenous growth emanating from Lucas (1988), and energy-saving technical progress. This will build on the pioneering work of Bovenberg and Smulders (1995).

Previous literature on this topic includes Tahvonen and Salo (2001), Tsur and Zemel (2005) and Jouvet and Schumacher (2010). Common to these papers are a utilitarian welfare function, not including environmental damage, one non-renewable resource (to be extracted for free or at some cost), three inputs in national production: man-made capital, oil and the backstop, and the allocation of total production to consumption, investments in man-made capital, extraction and input into the backstop technology (or its development, Tsur and Zemel, 2005). The problem then is to determine the optimal allocation of output to these activities. One possible outcome (Jouvet and Schumacher, 2010) is that the optimal depletion of the non-renewable resource may be non-monotonic, meaning that it could be that extraction is high initially, decreases over time and increases, until full exhaustion is reached. The reason for this behaviour is that initially time preference plays an important role, but then the economy wants to build a large stock of capital for the moment the transition to the backstop takes place. It is challenging to investigate the optimal programme if climate change comes into the picture, and to be deal with environmental policy in the corresponding decentralized market economy.

This project constitutes another major innovation to the prevailing normative approach to formulating optimal climate policies. Under the heading of this project we will not only study optimal mitigation of global warming, but also the optimal adaptation to global warming (e.g., investing in water defences). It obviously is closed linked to project 1, which abstract from accumulation of capital and sovereign wealth, and project 2 on how to make the best inter- and intra-generational welfare judgements; for example, if R&D and accumulation of sustainable forms of wealth will make future generations wealthier and will thus affect our judgement on intergenerational equity and consequently the temporal sequencing of optimal climate policies.

Project 5: Political economy of climate policies, redistribution and other public goods

Projects 1-4 are concerned with the characterization of optimal climate policies in a world where there is no need to worry about whether and, if so, how such policies can be implemented in the real world. In the real world politicians face many challenges than the optimally mitigating or adapting to climate change. They face problems today, such as combating unemployment and poverty, striving for an acceptable distribution of income among their citizens or funding adequate health care and education, and problems in the far future, such as funding social security and dealing with the consequences of global warming. A proper analysis of climate policies can therefore not be done without rigorous intra- and intertemporal trade-offs between each of these problems and dealing with an effective climate change policies. To do this properly, we will make use of the best that public finance has to offer and will consider the optimal setting of a detailed menu of non-CO2 and CO2 taxes as well as the supply of the various public goods. The role of the marginal cost of funds, both today and in the future, will be important in this second-best analysis of climate policies, since it captures not only the direct cost of public goods varying from schools and hospitals to climate mitigation projects but also the indirect costs arising from higher distortionary taxes that have to be levied to finance these public goods and the resulting drops in labour supply, capital accumulation and the tax base. The various ‘double dividend’ conundrums that have been investigated by Bovenberg and van der Ploeg (1994) and others will come in useful in this respect. The resulting public finance framework will in its most advance form correspond to a dynamic extension of the Pigou-Ramsey-Mirrlees framework, since it will deal with global warming externalities (Pigou), the task of optimally financing public goods by taxing activities more that are less elastic (Ramsey) and optimally redistributing incomes from rich to poor in an incentive compatible manner (Mirrlees). To the extent that we are able to do this taking fully account of endogenous capital accumulation, we will make use of the recently developed Ramsey-Mirrlees theory of dynamic taxation and economic growth developed by Golosov et al. (2007) and Kocherlakota (2010).

We will also take account of the various hold-up and credibility problems that may occur when decisions are made about long-term investment programmes. The other major innovation of this research project is to consider the political economy of realizing a serious climate policy. This is important, since rising carbon taxes are often considered to be infeasible. We will therefore look at the design of climate policies that may not be fully optimal, but can be expected to get sufficient support in cabinet and parliament to be carried through. We will also pay attention to what kind of political systems (first-past-the-post, presidential, autocratic with and without longsighted electorates, etcetera) are more likely to lead to climate policies that can work.

Project 6: International aspects of realizing effective climate policies

Project 6 also departs from projects 1-4 in the sense that it is concerned with how to realize effective climate policies in a work where different sovereign states are in different stages of economic development, have wide variations in population growth rates, have differing degrees of CO_2 emissions, are very differently affected by global warming, and have very different political and cultural traditions. Given the truly global nature of climate change, it will be a Herculean task to come to agreement on a global climate policy that has the support of all countries. Important work by Barrett (2003) on how to design global climate change treaties has been followed by many others (including our co-author De Zeeuw), but is fair to say that this literature deals almost exclusively on the use of game theory to look at winning coalitions for climate mitigation including side payments in the form of climate adaptation whilst ignoring the intricate intra- and intertemporal economic and political trade-offs highlighted under projects 1-5. We will therefore attempt to extend this literature by setting the analysis of international climate treaties within a full-scale multi-country, political-economic, dynamic model of climate change and economic development. Only by facing the problem of multiple jurisdictions will we come up with politically feasible climate policies. Under the heading of this project we will also discuss *credible* climate policies. An example is the case for an independent bank for CO_2 emission permits, which is needed to overcome problems of political temptation.

This final project thus deals with the important feature that developed and developing countries are affected by climate change in different ways. Some countries suffer severely, others may even benefit from a moderate increase of temperatures. Moreover, countries find themselves in different stages of economic development and governance. And their production possibilities as well as abatement technologies differ. Finally, the distribution of endowments such as oil is rather uneven across the world. These observations pose several serious problems. It becomes tremendously difficult to define sustainability on the world scale. This holds as well for a utilitarian optimum. Weights must be given to the welfare of individual states, which are inevitably open to critique since they are arbitrary. Probably the best thing one can do is to have all countries acting in their own interest, thereby yielding some kind of intertemporal or temporary equilibrium. In a stylized setting one may start with a distinction between one oil rich, capital poor region and one oil poor and capital rich region that trade. The oil poor region implements policies to make itself less dependent on oil, possibly for political reasons but also in view of cost considerations and environmental damage. The policy may involve a subsidy on a backstop or a tax on oil. So, what is needed is to gain insight in the working of several independent sovereign jurisdictions. The outcome of the game is not going to be Pareto inefficient and the question arises whether improvements of this outcome are feasible. This is the field of modern political economy as masterly summarized by Persson and Tabellini (2000), and in particular the fields of coalition formation and fiscal federalism. One would have to take account of how effective global climate policies can be realized when economies are democracies whilst others are autocracies.

It also deals with the issue of credibility or time consistency of environmental policy, since actions need to extend into the far future and government cannot tie the hands of successive governments many decades away. One simple example is that a subsidy on a backstop can be announced at the outset of time, and will do its work. However, as soon as conventional oil would be exhausted, there is no need anymore for the subsidy. Hence, we have a time consistency problem here. A similar problem may arise in the context of climate change. Policies are needed to accumulate knowledge but once the desired level of knowledge is achieved, no further policies are needed. Another example concerns climate itself. Coalitions of countries are called externally stable is no country wants to join the coalition, the coalition is internally stable if not country want to leave the coalition. However, the decision to be part of a coalition is not a once and for all decision; it will depend on the state of the world, in particular the stock of CO_2. If the stock changes, the inclination to be part of a coalition may change. A further aspect of environmental policy is that subsidizing the development of knowledge may give rise to positive spillovers, which constitute a positive externality. However, individual jurisdictions may find it in their interest not to share the newly developed knowledge.

The international context also asks for an anlysis of carbon leakage and ways to sustain international cooperation (see Hoel, 2008; Eichner and Pethig, 2009).

Finally, we should like to point out that an over-arching theme linking all six projects is that we will do our utmost best to calibrate or estimate the models that we put forward. Towards the end of the project, this will lead to an integrated, calibrated detailed model of climate change which can play an important role in policy discussions in Europe and elsewhere in the world.

b. Methodology

The issue of methodology has already been addressed in the presentation of the projects. Here follows a brief summary. From a methodological point of view the research proposal will combine various advanced theoretical methods, in particular methods for dynamic optimization and differential games. The supply of non-renewable resources takes place in a world with imperfect competition. Moreover, supply needs to be cast in a dynamic setting. This clearly calls for differential game theory, and involves a critical evaluation of adequate and appropriate equilibrium concepts, such as open-loop versus closed loop, Stackelberg versus Nash-Cournot and Cournot versus Bertrand (in case of imperfect substitutability). Here also the notions of dynamic consistency, credibility or subgame perfectness are to be involved. These features not only appear in characterizing the market structure for non-renewables but also for the policy recommendations that follow from the analysis, in particular when dealing with issues surrounding fiscal federalism. Ample use will also be made of optimal control theory over an infinite horizon. This technique is by now standard in economics. However, we will deal with multiple state variables, such as man-made capital, accumulated CO2 and non-renewable resources. This makes the use of optimal control theory challenging, in particular since in view of the exhaustibility of non-renewables, not allowing for a steady state analysis cannot be performed. From economics, a large variety of theories will be invoked: intertemporal general equilibrium, public economics, environmental and resource economics, economics of innovation, theory of the core, theory of the second-best. We will make use of the most advanced developments in international economics, development economics, macroeconomics (modern growth theory), public finance and political economy. The optimal and political feasible climate policies will be derived by calibrating and simulating intertemporal, game-theoretic models with the aid of the computer programme MATLAB. The estimation of the necessary parameters, where they are not obtained from earlier climate change studies, will be obtained with the aid of the computer programme STATA and other econometric programmes when necessary. 'We will collaborate closely with environmental institutes in the Netherlands such as the IVM and RIVM, the Intergovernmental Panel on Climate Change, and internationally renowned scholars such as Professor Ottmar Edenhofer and his team in Potsdam, Lord Nicholas Stern and his team in London, and Richard Tol to obtain the best available climate science data necessary to calibrate and estimate our models for policy purposes.

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c. Organization

Withagen is the principal investigator, located at VU University. Van der Ploeg is the co-investigator, located at the University of Oxford, and also affiliated with the VU University Amsterdam. This implies that is will be easy to communicate, not only by means of modern electronic techniques but also in person. One post-doc and three PhDs will be located at VU University Amsterdam and one post-doc and one PhD at the University of Oxford. Each post-doc will directly supervise two PhD students. It should be stressed that the principal and the co-principal investigators are both involved in all projects, and that all PhD students and post-docs will benefit from the research environments in both Amsterdam and Oxford.

The six projects consider different aspects of our core research question. It should be clear however that all projects are closely linked to each other. -Through co-operation and co-ordination we will reach cross-fertilization of the six projects. In addition to bilateral meetings and exchanges, we will have two joint workshops per year in which all team members present their work (especially their work in progress) and to discuss ideas. Hence there will be ample opportunities of the post-docs and PhD students to exchange views. Part of the exchange of views and supervision will take place at the prestigious Tinbergen Institute, of which both PI’s are fellows, and which is located near VU University and Schiphol Airport.

d Research environment

a. PI's Host institution

VU University Amsterdam is a well-established research university and among the best in The Netherlands. Its scale of 2000 fte scientific staff and over 20,000 students is large enough to host all major disciplines but small enough to allow for synergetic interaction among scientists. The university is well equipped with the latest information and communication technologies, research labs and a modern library with access to all major journals and to numerous research data. The university's reputation is excellent and while there are numerous ways of measuring this, I just mention the number of over 100 FP7 projects, 6 ERC starting grants and 4 ERC advanced grants.

The *Faculty of Economics and Business Administration* is the university's largest Faculty, hosting 12 research programs, 4 undergraduate teaching programs and 8 graduate teaching programs. The Faculty ranks among the best economics and business Faculties in the country and several research groups are considered to be world class by consecutive assessment committees. In collaboration with the Erasmus University of Rotterdam and the University of Amsterdam, the Faculty has founded the prestigious Tinbergen Institute. This joint research school gathers the best researchers in economics from the three universities and runs an MPhil program, next to hosting the PhD students from the collaborating universities. Tinbergen Institute as such is usually not ranked separately from the three universities participating in it. However, if it would be ranked based on the publications of its fellows (professors), it would invariably end up near the very top of Europe and in the top-20 worldwide.

The *Department of Spatial Economics*, where this research will be based, is with 60 staff members probably the largest concentration of economists worldwide, in this combination of fields (environmental, urban, transport). The research group holds leading positions within each of these fields at the international level, as reflected in its strong publication records in the main journals in the field, the large number of citations, memberships of editorial boards, and involvement in international organizations and associations.

The department has been very successful in obtaining large grants and has proven, in collaboration with the Faculty and the University, to be an excellent site for hosting large projects that result from these grants. A good example is Peter Nijkamp's Spinoza grant, which led to the establishment of the highly successful "Masterpoint" at the Department in 1997, in which some 15 faculty members and PhD-students studied a variety of topics from spatial economics, and Erik Verhoef's Advanced ERC grant, awarded last year, that will lead to a programme in which 4 PhDs and 2 post-docs are involved. Other projects of significant size that were recently undertaken at the department resulted from their success in various recent Dutch research programmes. The professional world-class research atmosphere, the size, and the experience of the department undoubtedly helped in managing this inflow seamlessly and turning these projects into successes.

The following features may characterise the strong and highly productive research culture within the department:

- Ambition: Staff members feel that they are part of a strong research group and that their publication activities should be in agreement with this. They are stimulated to formulate their ambitions.
- Collaboration: Staff members collaborate in various combinations; no barriers exist between the subfields of spatial, transport and environmental economics. Also collaboration with foreign visitors is stimulated.
- Knowledge sharing: The department has its own lunch seminars and lunch discussion groups in which recent advances in the field are discussed among junior and senior staff members.
- International atmosphere: The research group hosts staff-members from about 10 countries.

The department has traditionally combined a strong internal structure with an outward-looking attitude, which has resulted in a high number of strategic and structural national and international collaborations. It has a structural strong relationship with the Institute for Environmental Studies, also located at VU University, which is a leading applied research institute. Senior researchers and PhD students of the research group are affiliated to the Tinbergen Institute. Also structural cooperation takes place with colleagues at the universities in Utrecht, Delft, Groningen, Tilburg, Eindhoven and Wageningen, in the context of a series of NWO (Netherlands Organisation for Scientific Research) funded programmes. The department has strategic collaboration with a number of important players in the Netherlands, among whom the CPB (Netherlands Bureau for Economic Policy Analysis), the Netherlands Environmental Assessment Agency, the Ministry of the Environment and the Ministry of Transport. At the international level, structural or highly regular collaboration takes place among others via European research projects in consortia with partners like University of Leuven, University College London, University of Bologna, George Mason University, University of California at Irvine, McGill University, University of Chicago, University of Oxford, University of Toulouse, etc.

In sum, the Department, the Faculty, and the University seem perfectly fit to host an ERC Advanced Grant project. They offer an international top research oriented environment, they are very experienced in hosting prestigious research projects of this type and scale, and they have a supporting department with world-leading specialists in environmental, transport and spatial economics of an internationally unique quality and size, embedded in a national and international network of researchers that would create the ideal circumstances for the project to become a great success.

b. CI's Host Institution

Oxford's *Department of Economics*, is part of the Division of Social Sciences of the University of Oxford. It is one of Europe's leading research departments and its members include some of the world's most distinguished academic economists whose research has made major recent contributions to modern economic analysis. The current faculty includes 14 Fellows of the British Academy and 13 Fellows of the Econometric Society. With 78.5 full-time equivalent researchers, Oxford Economics was by far the largest group of economists submitted to the 2008 Research Assessment Exercise conducted jointly by the UK higher Education Funding Councils. Within this large group, 95 percent of all research activities were classified as internationally excellent in terms of originality, significance and rigour (3* or better), with 40 percent of activities regarded as world leading (4*).

In the Department, research activity is focused within smaller, specialized, research groups. Research groups are flexible entities reflecting the evolving research interests of the members of the Department rather than formal administrative units. Every member of the Department belongs to at least one research group, many to several. Groups share the objectives of promoting and supporting high-quality research, and of providing an active and supportive research environment for faculty and research students in their field. The Department, through its research groups organizes an extensive programme of seminars and workshops throughout the academic year, with both internal and distinguished external visitors.

In partnership with the Department, the Colleges of the University underpin Oxford Economics. The co-PI is an associate member of Nuffield College, which is dedicated to research in the social sciences with a fellowship made up of researchers drawn from economics, politics, sociology and statistics. Part postgraduate college, part research institute, it provides its permanent fellows, postdoctoral and postgraduate researchers, and project-based researchers with high quality infrastructure. The co-PI is also a Senior Research Fellow of New College. Its fellows count most members of the Oxford Centre for the Analysis of Resource Rich Economies (Oxcarre) including its Director Professor Tony Venables (one of the world's top experts on international trade and very much interested in joining research on the economics of climate policy), but also well-known environmental economists such as Professor Dieter Helm and Dr. Cameron Hepburn (witness their 2009 book with OUP entitled The Economics and Politics of Climate Change) as well as engineers, philosophers and natural scientists working on climate change. The co-PI is the Co-Director of Oxcarre where the research for this proposal will be conducted. It is a friendly but highly competitive and international research centre on environmental and resource economics, which interacts with some of the best theoretical and applied economists in Europe as it is based in the Department of Economics.

Oxcarre has well-known series of Research Papers and Policy Papers, hosts regular seminars and brown bag lunches, has lots of short-and long-term visits of international experts on environmental and resource economics, organizes various conferences each year, and is actively engaged with the policy making communities in developing countries but also with the IMF, the World Bank, the Asian Development Bank and the African Development Bank.

The post-docs and research students working at Oxford and the Free University will benefit from the large number of official and brown-bag seminars, extensive data and computer software, and the excellent research environment offered by Oxcarre and the Department of Economics, but also from the wealth of relevant research experience available in New College and Nuffield College and the knowledge of climate change assembled in the Smith School. All these institutions provide a truly unique and diverse research environment for those interested in studying the economics and the political economy of climate change, as can be witnessed from the many scholars that are inquiring to come and visit and work with us on environmental and resource economics.