Green and Grey Paradoxes

prof. dr. C.A. Withagen

Faculteit der Economische Wetenschappen en Bedrijfskunde
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Green and Grey Paradoxes¹.

1. Introduction.
It is a golden age for environmental economics and environmental economists, you would think.

- Cities in China are heavily polluted. The population suffers severely from smog.
- Some beaches are completely ruined by waste.
- African rebels poach, and finance their wars with selling ivory.
- Solar energy is gaining momentum in many places. The tipping point has reached as solar is now as cheap to produce at less than 6 $c/kWh as energy from oil.
- Climate change is occurring. Consequences in terms of droughts, massive migration flows and conflict are well documented.

On all these topic environmental economists have something to say. For example, does it make sense to destroy or to hinder the trade in illegal ivory by supplying the market with an enormous amount of legal ivory? What is the best instrument to fight waste disposal in public places: Persuasion, fines? Should solar energy be subsidized or is it better to tax carbon emissions? Why is it so difficult to reach agreements on global warming, whereas everybody might benefit? Environmental economists have answers to such questions. And, let me proudly say that they agree more among themselves than many economists from other fields. But does this lead to better policies in the real world? On the one hand, I am not so optimistic in view of what is happening now in practice. On the other hand, we can observe that gradually policy makers implement measures that were recommended by us already long time ago. A prominent example is the EU system of tradable permits, forty years after Herman Daly proposed such a system. We also see that cost-benefit analyses are becoming more common, although it is not always clear policy makers are willing to act on such studies. And, with the Netherlands chairing the EU, our Minister of Infrastructure and the Environment is now finally advocating an EU-wide uniform

¹ Department of Spatial Economics, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam. Email: cwithagen@feweb.vu.nl. I would like to thank Erik Ansink, Antoine d’Autume, Gerard van der Meijden, Rick van der Ploeg, and Katheline Schubert for helpful comments and suggestions. Financial support from FP7-IDEAS-ERC Grant No. 269788 is gratefully acknowledged.
carbon tax (one hundred years after the British economist Arthur Cecil Pigou). Nevertheless there is still a lot of work to be done. What I will do in this valedictory lecture is to mention three topics that I would like to address after my retirement. This is my Grey Paradox: A grey man talking about his research agenda after retirement. One of the main topics is the Green Paradox. This explains the title of this lecture.

I will first talk about negotiations on climate change. Then I will deal with the question whether a uniform carbon price, as advocated by our Minister, is optimal for fighting global warming. Finally, I will address the low price of oil. The topics are all related to climate change. For those of you who are not familiar with the causes of climate change I will briefly outline the essence of this phenomenon. A crucial role is played by greenhouse gases such as

- carbon dioxide (CO$_2$).
- methane.
- nitrous oxide.
- fluorinated gases.

These gases are called greenhouse gases because when they are in the Earth's atmosphere they function as the glass of a greenhouse. They trap the sun's heat and stop it from leaking back into space. This then leads to global warming. Many of these gases occur naturally, but accumulation of greenhouse gases is partly also anthropogenic, man-made. CO$_2$ accounts for 64% of man-made global warming. Emissions are rising due to

- burning of fossil fuels like oil, gas and coal.
- deforestation.
- livestock farming (cows produce methane).
- use of fertilizers.

Global warming is a fact. The current global average temperature is 0.85°C above the temperature some hundred years ago. The international community finds that an increase of 2°C

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2 See her interview in Volkskrant, February 12, 2016.
3 See e.g. [http://www.eea.europa.eu/media/audiovisuals/are-we-ready-for-climate-change/view](http://www.eea.europa.eu/media/audiovisuals/are-we-ready-for-climate-change/view)
compared to the temperature in pre-industrial times is the maximum we should allow for. During the recent summit in Paris some (especially threatened island states) have argued that 1.5°C is more appropriate.

Climate change affects everybody in all countries. For some countries, like Canada, climate change is a blessing, at least when the temperature increase is modest. For others, like Guinea-Bissau, it is detrimental for welfare, in a broad sense. In the long run the effect will be negative on the whole. The accumulation of greenhouse gases constitutes a so-called negative externality. According to Baumol and Oates (1988) "An externality is present whenever some individual's (say A's) utility or production relationships include real (that is, nonmonetary) variables, whose values are chosen by others (persons, corporations, governments) without particular attention to the effects on A's welfare." Externalities, whether positive or negative, are distortive. Adam Smith’s invisible hand, unfettered markets lead to efficiency, no longer holds. Applying the notion of externalities to climate change, emissions of greenhouse gases are not intended to cause climate change, but they do. Moreover, the market does not provide incentives by itself to restrict emissions of greenhouse gases. Greenhouse gases are uniformly mixing throughout the atmosphere, meaning that for global warming it is immaterial where emissions take place. Whether emissions originate from a coal-fired power plant in Australia or from methane from farting and burping Dutch cows in Friesland, does not matter. So, man-made greenhouse gases constitute a global externality. It is important to note that benefits from reductions depend on total reductions, whereas the cost of reductions is borne by individual countries.

2. **International climate agreements**

A fairly simple way to illustrate the distortive effect of greenhouse gas emissions and the need for international agreements is by means of a game with only two regions, North and South. Each of the regions has two options: to reduce emissions or not to reduce emissions. Reduction of emissions is beneficial to both countries because there is less accumulation of CO₂, which leads to less global warming. The cost of emissions reduction is borne by the individual regions. These costs consist, for example, of the loss of consumption opportunities because resources have to be used to reduce emissions instead of producing consumption goods. The differences between benefits and costs, to each of the regions, are called payoffs and can be represented by

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the numbers in the matrix given below. We assume that payoffs can all be expressed in money terms. Hence, (3,3) means that if both North and South reduce emissions, the payoff to each of them is 3, in some monetary unit. But if North reduces and South does not, then the payoff to North is -2 and to South it is 5.

![Payoff matrix for the simple climate game](image)

**Figure 1.** Payoff matrix for the simple climate game.

In a stylized way, for two regions that have to take a once and for all decision simultaneously, the problem can be considered as a game. Most of you will recognize the so called prisoners’ dilemma. In the case at hand, the dominant strategy for both players is not to reduce emissions. Given that South does not reduce, it is best for North not to reduce as well. If South reduces, it is best for North not to reduce. Hence, North will not reduce emissions, irrespective of what South does, and the other way around.\(^5\) This is the reason why it is so difficult to reach an international agreement on taking climate actions: Every region attempts to free-ride on other countries. Another reason is that current generations have to make sacrifices to reduce global warming for the benefit of future, possibly richer generations.

A modification of the assumptions may offer a less pessimistic perspective. If the game is played multiple but *finite* times, nothing changes. However, if the game is played for an *infinite* period of times, the ‘best’ outcome, where both North and South reduce emissions, can be reached as an equilibrium if the rate at which future payoffs are discounted, is small enough. This works as follows. The regions agree on playing both the reduce strategy, until one of them deviates. And from that moment in time on they are back in the original ‘no reduction’ equilibrium. Hence, the

\(^5\) Other payoff configurations are possible, with other types of equilibria, but there is some consensus that the prisoners’ dilemma setting represents climate change issues fairly well.
region that deviates, gains 5 compared to 3, during one period of time. But then it gets only 0 from that moment on. Hence, if the deviating region does not value future payoffs much less than present ones, this works. Another way of putting this is that future punishments when deviating from an international cooperative agreement are felt more if the future is discounted less heavily and therefore it is easier to sustain international cooperation.

Another way out is to link issues. One might couple environmental issues to trade issues, such as maintaining or reducing barriers to trade, or one links making sacrifices today with better pension rights in the future. It can be shown that this might also widen the window for better outcomes.

The example shown before was meant only to illustrate the fundamental problem of free-riding. In reality negotiations take part among many countries. In the Conference of Parties in Paris last December, 195 countries were involved. Over the past 25 years we have witnessed the failure of many of these conferences. Economists have developed theories to explain these failures.6

A central concept is that of a coalition. A coalition is a group of countries that reach an agreement on CO₂ reduction. The coalition takes the emissions by non-participating countries as given and finds the optimal level of emissions (or emissions reduction) by its members, so as to maximize the sum of their net payoffs.7 A coalition is stable, if no outsider wants to become part of the coalition (external stability), and no coalition member wants to become a free-rider (internal stability). This sounds simple but we have to realize that there are many alternative assumptions that can be made. For example, what happens if one country leaves the coalition? Do all other members stay in the coalition? Do all other members leave? Will free-riders enter coalition?8 The usual assumption is that everything stays unaltered, except for this one country entering or leaving the coalition. A rather negative finding with identical countries is that stable coalitions are small, so that mitigation is not substantial and the gains in total welfare are small. With countries that differ, stable coalitions might be large but also then the overall gain is rather small. This is called the ‘paradox of cooperation’ (Barrett, 1994). In the wording of Finus and McGinty (2015): "Either stable coalitions are small or even if they are large, then the gap between the aggregate payoff in the grand coalition (social optimum or full cooperation) and all

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6 See e.g., Barrett (2003).
7 For the moment we work in a static context. This allows us to restrict ourselves to cost and benefits of the flow of emissions, rather than taking into account the stock of accumulated emissions.
8 There exist alternative stability concepts. See e.g., Chander and Tulkens (1993) and De Zeeuw (2008).
There have been many attempts to develop mechanisms that allow for larger and more successful coalitions. One of them is due to William Nordhaus (2015), one of the leading climate change economists. One other attempt is made by Erik Ansink and myself (2016). I will briefly discuss them in turn.

Nordhaus’s idea goes back to linking climate and trade. He introduces the notion of a Climate Club. This is a coalition of countries that agrees on a carbon price, or tax, of, say, 25$ per tonne of CO_2. This is a rough approximation of the global social cost of carbon, the increase of global damages as a consequence of one ton extra CO_2 emissions. The national social cost of CO_2 is the additional damage to a country as a consequence of one extra ton of CO_2 emissions. The difference between the two is the external social cost of CO_2. One can calculate the emissions of a region in case of full cooperation, minus the emissions when there is no cooperation at all. This yields the externality caused by a country that does not participate in the agreement. But not taking part in the agreement also brings along a cost for that country in the sense that there the Climate Club imposes a uniform import tariff, amounting to 2% on all imports from non-participants. The loss can be calculated under the assumption of all other countries participating, or just one country participating. The main finding is that this approach works quite well in a static model with 15 regions, calibrated with respect to damages and abatement costs. It is shown that trade sanctions are essential for having a successful new approach. A big problem, of which Nordhaus is aware, is that international trade laws need amendment. This might be justified if the benefits in terms of climate change outweigh the costs.

Erik Ansink and I have developed an alternative approach where there are not only coalition members and free-riders, but also supporters and joiners to the coalition. The idea is to get some virtual spiral of “zwaan-kleef-aan’ (Golden Goose) effects. For the sake of exposition we start from a small stable pre-existing coalition. Under fairly standard assumptions, such a coalition has 3 members, irrespective of the total number of countries involved. Let us take this total

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9 Karp and Simon (2013) argue that this conclusion rests on the assumptions with regard to costs and benefits of emissions reduction. See also Hovi et al. (2015) for a survey of less pessimistic views.
number equal to 50, for illustrative purposes. So, originally there are 47 outsiders, or free-riders. The coalition maximizes its total welfare, taking emissions of the free-riders as given. We assume equal benefit and cost functions for all countries. To have different countries is something for later.\(^\text{10}\) Next we introduce supporters and joiners. A country is called a supporter if it is not part of a coalition, but gives money to a coalition. The money is used by the coalition to distribute it among its members, who hence get a higher payoff. This may attract other countries to join the coalition (Golden Goose). Those countries were free-riders originally, and are willing to join the coalition because their profits are higher than when they stay free-rider. The free-rider that enters is called a joiner because he becomes part of the coalition and is committed to emissions reductions, just like all other members of the coalition.

The important question is whether the new structure is stable. This is a bit more complicated than in the case where there are no supporters or joiners. Let us first consider the members of the new coalition. For the coalition to be stable, such countries should not want to become free-riders, nor supporters. If they are considering leaving the coalition, they need to have an idea about what happens if they actually defect. Many variants are possible. We assume that if a coalition member contemplates becoming a free-rider, the coalition does not collapse. All members except this country stay members, and the number of supporters, as well as their contribution to the coalition, remains unaltered. If they consider becoming a supporter we assume that all original supporters remain supporters, so that the number of supporters increases by one. Moreover, the number of coalition members decreases by one, because one old member leaves, but there are more supporters now, so that there might also be more joiners. We assume that the transfers and the corresponding joiners are such that a member of the coalition prefers to stay in the coalition.

We have to consider as well the possibility of free-riders becoming a coalition member or free-riders becoming a supporter. This is also part of the analysis of stability. We assume that a free-rider considering becoming a coalition member, assumes that all coalition members stay coalition member and that neither the number of supporters nor their contribution to the coalition changes. This implies that the total contribution is now divided among a larger number of coalition members. A free-rider may become a supporter. For this we need again to make assumptions. We cannot assume now that the number of coalition members stays unaltered, because there will be one more supporter. We suppose that the new joiners and new

\(^{10}\) See Finus and McGinty (2015).
contributions are such that the agent is indifferent between staying a supporter and becoming a free rider. Finally, we need to make sure that supporters do not want to join the coalition, nor desire to become free riders.

What we are able to show is that under mild conditions there exists a stable coalition. This coalition is larger than the ‘old’ one, and makes a major contribution to reducing emissions. This is our ‘zwaan-kleef-aan’ (Golden Goose) result. We also show that there are multiple equilibria, as in the figure below.

![Figure 2. Payoffs as a function of number of joiners.](image-url)

Moreover, we observe that larger coalitions are better for everybody so that the game evolves from a prisoners’ dilemma to a coordination game.

There is much to be done in this field. First of all we want to get a better insight in the conditions that make the approach work. Our assumptions are not always satisfied and in some cases no equilibrium exists. This occurs for example for very steeply increasing cost functions. We also would like to find out how the recipe works in a model with calibrated values for different countries with different benefits and costs. So, the next step we want to make is to assess the
extent to which our approach would be able to close the gap between current levels of cooperation and those required to reach a global optimum.

3. A uniform carbon tax?

Standard economic theory prescribes a uniform carbon tax. Also in applied work the optimality of a uniform carbon tax is uncontroversial. For example, Nordhaus (2015) in his article on Climate Clubs proposes a carbon tax of $25 per ton of CO₂ among the members of the climate coalition. In policy circles the idea of a uniform carbon tax is put forward as well. The Minister of Infrastructure and the Environment in the Netherlands, which is now chairing the European Union, is in favor of a uniform carbon tax and believes this is a magnificent idea. The underlying reasoning is simple. Greenhouse gases are uniformly mixing and constitute a global externality. An additional unit of CO₂ emissions, wherever on the planet emitted, leads to additional accumulation of the CO₂ stock and to additional global warming. These effects of additional emissions are not limited to today but extend over the far future. This leads us to the definition of the social cost of carbon, which is the total discounted¹¹ net marginal damages aggregated over time and space (countries), evaluated at the optimum over the entire future. Suppose we know the optimal path of CO₂ emissions and we want to implement it in a decentralized way, by setting a carbon tax. Then consumers and producers should internalize the externality and, hence, the carbon tax should equal the social cost of carbon. This will also induce firms worldwide to reduce emissions to the optimal level, at minimal cost, by abatement. The revenues accrue to the world policy maker, who can redistribute them to individual consumers and producers in a lump-sum way, to achieve the optimal allocation of welfare. This is the standard story, which supposes that all market failures are addressed too. For example, any learning by doing or other externalities in the development of green R&D might require a subsidy, for otherwise markets will not achieve an efficient outcome.

However, crucial elements are lacking in this approach. In a simplified framework for the world economy there is a set of countries, each with its own sovereign consumers and producers, and a government. Producers maximize their profit, consumers maximize their welfare. For the sake of exposition, we assume that all commodities in all countries are produced at the same cost. In

¹¹ Discounting is a delicate issue in climate change economics. I will not touch on discounting here in detail, but just point out that this discount rate typically rises with relative risk aversion and decreases with intergenerational inequality aversion of policy makers.
each country there is dirty private consumption, clean private consumption and clean public consumption. Dirty private consumption brings along two types of pollution: local pollution, as a consequence of local dirty consumption, and global pollution, as a consequence of total worldwide dirty consumption. The welfare of each consumer depends on all 5 elements: private dirty consumption, private clean consumption, public consumption, local pollution and global pollution. These are the main ingredients of the model.\textsuperscript{12} The world planner, or the world environmental protection agency, attaches weights to each of the countries and calculates the optimal allocation of the endowments to each consumer in each country. The world EPA can implement the optimum by imposing a tax on the consumption of the dirty good. The tax consists of two components. One is related to local pollution, and differs across the consumers in the countries, whereas the other is related to global pollution and is identical for all consumers. Hence, we can say that there is a uniform part in the carbon tax. The revenues of the tax are used for financing the public good and for the redistribution of welfare across the countries. So far, there is no role for local governments. However, the world EPA can safely leave much of the implementation to local governments. It levies and cashes the uniform part of the carbon tax and redistributes it over the countries’ governments, not to the consumers. The individual governments take care of the local component of the carbon tax and of providing the public good.\textsuperscript{13}

Let us now take one step back and assume that the international environmental protection agency still aims at implementing the optimum, but faces the constraint of the transfers to the consumers being non-negative. It could be that in the original optimum all transfers to consumers were already positive, due to large tax revenues from the global part of the carbon tax. If that is the case, nothing changes of course: the first-best optimum is reached again and the public goods are financed through the uniform Pigovian tax. One can say that the cost of public funds equals zero: The impossibility of giving negative transfers is not relevant. However, if this is not the case only a second-best optimum can be reached, because now the pollution tax has to be used as an

\textsuperscript{12} We also assume inelastic labor supply, abstract from a dynamic perspective and from the option to abate.

\textsuperscript{13} We assume perfect competition. With imperfect competition countries might manipulate the carbon tax. See Verbon and Withagen (2014).
instrument to get non-negative transfers, and this will have a distorting effect on the economy.\footnote{14 If a government could arbitrarily tax the consumers in a way that does not depend on their economic behavior for instance only tax people with red hair, it would be possible to finance public goods production without introducing distortions to the economy.}
The cost of public funds is positive. But the more or less surprising finding is that we can still decompose the carbon tax, in three parts now. One is the tax on local pollution, one is the so-called Ramsey tax, that is needed to deal with the non-negativity of transfers, and the final one is the uniform carbon tax dealing with the global externality. The important implication is that the global component of the carbon tax does not include any redistribution element, because that feature is taken care of by the Ramsey tax. We can then apply the subsidiarity principle to implement the second-best in a decentralized way. The international environmental protection agency levies the uniform part of the carbon tax and redistributes it to the local governments in such a way that they are able to finance the provision of public goods through a positive reallocation to their consumers. Then they also deal with the local pollution. This way, the second-best can be implemented in a decentralized setting.

So, the bottom line of this exercise is that if we allow for negative transfers to governments, but insist on non-negative transfers to consumers, we still will have a uniform global carbon tax, which is likely to differ, however, from the social cost of carbon.

This may sound reassuring, but there is still a major problem. It could well be that local governments want to receive at least the revenue of the uniform global carbon tax paid by their inhabitants to the international EPA. This consideration leads us to consider the third best optimum.\footnote{15 This possibility was also considered by a.o., Shiell (2003) and Sandmo (2005). See also Sandmo (1975, 2000).} Then we no longer get a uniform global carbon tax. This argument is supporting the basic finding of Chichilnisky and Heal (1994), that marginal abatement costs should not be equalized, if inter-country transfers are impossible. Instead, low income countries should face a lower carbon tax.

Concluding, in a single country setting, a uniform carbon tax is justified on the basis of a welfare analysis. However, when countries are not willing to make transfers among themselves, a uniform carbon tax cannot be justified, in many cases. It is important to approach this problem empirically, in the sense of trying to actually calculate the welfare loss of a differential carbon tax.
4. The Green Paradox and limit pricing

4.1 The Green Paradox.

The price of crude oil has decreased tremendously over the past year. This is illustrated in figure 3. Every economist is intrigued by the question how this is possible and whether this situation is going to last long. Many issues play a role, among which also geo-political ones. Hence, economics can only offer a partial insight. Clearly an important role is played by shale oil and shale gas, as well as the rapid and spectacular decrease in the cost of solar and wind, due to technical progress, stimulated among other things by subsidies.

Figure 3. Crude oil prices over the past 10 years. Source: U.S. Energy Information Administration (2016).

One can ask the question why bother about low oil prices? High oil prices as during the seventies and eighties of the last century were considered bad and they have had a large negative impact on employment and economic growth. Low oil prices are good for the economy, one could argue. This is not necessarily true as I will explain below.
Burning fossil fuels is one of the main contributors to global warming. Climate change is beginning to get a place on the policy agendas. We should get rid of coal fired power plants. We should stimulate wind and solar power. In general terms: A transition should be made to a carbon-free economy\(^{16}\). This is not an easy task. It is a road with many pitfalls. One of them is the Green Paradox, a notion introduced first by Hans-Werner Sinn (2008, 2012). Sinn mainly dealt with carbon taxes, but I think the paradox can very easily be illustrated when we consider subsidies on solar or wind energy. When it comes to climate change the interplay between fossil fuel prices and those of renewables is crucial.

Let me say beforehand that subsidies for renewables are a very poor instrument, in principle. I have already pointed at CO\(_2\) emissions causing a global externality. The appropriate instrument to tackle negative externalities is to tax the cause of the externality, that is, the emissions of carbon, and hence the use of fossil fuel, differentiated with respect to carbon content. Some governments are afraid to use the tax instrument, justifying this by referring to the competitiveness argument: Our capacity to compete will be jeopardized if we levy a carbon tax. They rather subsidize renewables such as solar and wind, although no compelling evidence for loss of competitiveness is available. Subsidization of these energy sources may be warranted, but only in as far as positive externalities are involved, for example through learning by doing. However, this is not a convincing argument anymore today. But I am not against subsidies just as a matter of principle. They can also have adverse effects, in the sense of accelerating global warming, as I will show now.

The simplest model of the oil market can be attributed to Harold Hotelling (1933), the founding father of resource economics. Suppose you own an oil well, from which you can extract oil at a constant cost per barrel. You exactly know how much oil there is in the well. The market for oil is competitive, so that you have to take the oil price over time as given. The price of oil in the current year is known with certainty and you have expectations with regard to next year’s price. After next year oil is worthless. The interest rate is also given. So, you have to decide on how much to extract this year and how much to extract next year. What counts for your decision are net profits per unit this year and net profits per unit next year, taking account of the interest rate. If unit net profits this year are larger than the unit discounted profits next year, you will extract everything today. If net profits today are smaller than net discounted profits next year, you will

\(^{16}\) See also Ploeg and Withagen (2014).
extract everything next year. Both outcomes are not considered to be an equilibrium, because there is demand for oil in both periods and in the cases described in one of the periods there is no supply. Hence in equilibrium these net profits must be equal. This implies that net profits increase at a rate equal to the interest rate. This is known as the Hotelling rule. It implies also an increasing market price over time. An extension of the reasoning beyond two periods of time is straightforward.

Hotelling’s rule is criticized for many reasons. The data on prices of non-renewables do not fit the simple version of the model.\(^{17}\) This should come as no surprise. For that reason the theory is extended in various directions, which I will just mention without going into detail. We deal with new discoveries, with stock-dependent extraction costs, and changes over time in demand, for example by China. We study alternatives to the objective of profit maximization and market structure. We also consider alternatives which become available in the future. We can also think of carbon taxes that will be imposed in the future. Nevertheless, the Hotelling model provides a convenient vehicle to illustrate the essence of Green Paradoxes, as I will do now. Consider figure 4.

![Figure 4](image.png)

**Figure 4. Illustration of the Green Paradox.**

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\(^{17}\) However, investments in drilling do follow a Hotelling rule even though depletion of an individual well does not.
Let us assume for the moment that solar and fossil energy are perfect substitutes and suppose solar energy can be produced at a constant cost per unit. Then fossil cannot have a price above the price of solar. If the extraction cost of fossil is below the price of solar, all fossil fuel will be extracted eventually. Hence, according to the Hotelling rule, the price path of fossil will look as the solid curve in figure 4. The price of oil will reach the cost level of renewables exactly at the moment of full exhaustion of oil. What happens if we are going to subsidize solar, so that the maximal oil price goes down? Clearly, the new price path, the dashed curve in figure 4, must lie below the old one. So, initially more oil is extracted. This is called a weak Green Paradox. Since all oil is extracted eventually, this means that the subsidy accelerates global warming, a strong Green Paradox. Hence, the subsidy, which has to be paid by the consumers, is a bad instrument from the perspective of damages from climate change. This is a strong Green Paradox. Finally, the well-intended but ill-designed policy has an adverse effect on welfare in the broad sense (a super strong Green Paradox).

Over the past five years the European Research Council (ERC) has made funds available to Rick van der Ploeg and me to investigate Green Paradoxes further. Time and space is lacking to give a full account of what we have done. So, let me give you some highlights. Among the results of our research is the finding that in some circumstances the strong Green Paradox is mitigated. Global warming in the long run depends on how much fossil fuel the subsidy is able to lock up. In particular, if extraction costs depend on the remaining fossil fuel reserves the subsidy might lead to more fossil fuel left in the ground. Hence, in the short run there is more supply of fossil fuel (a weak Green Paradox), but eventually more is left in situ (possibly no strong nor super strong Green paradox). We have also considered the search for fossil fuel discoveries and imperfect substitutability of non-renewables and renewables. Real world phenomena mitigate the Green Paradox in case of subsidies. Nevertheless, I think that the Green Paradox literature highlights the importance of carbon taxation. In the sequel I will pay attention to another topic that has been investigated, namely imperfect competition and limit pricing.

4.2 Limit pricing

Recently, together with two other members of the ERC research group, Karolina Ryszka and Gerard van der Meijden, I have investigated the case of imperfect competition in a multicountry

setting.\textsuperscript{19} OPEC may have lost much of its monopoly power, due to the shale oil and shale gas revolution and technological progress, still the oil market is hard to characterize as perfectly competitive. So, to highlight the impact of imperfect competition we consider monopolistic supply of fossil fuel. On the demand side, however, we assume price taking behavior, in spite of the fact that nowadays collaboration among oil importing countries is attracting more and more attention. Moreover, we take into account that the world consists of multiple countries, which may differ in environmental policies. We consider are two blocks of countries. One block subsidizes renewable energy, the other does not. We wanted to find out whether this set up could learn us more about the occurrence of Green Paradoxes. In particular we wanted to analyze limit pricing. Limit pricing is a phenomenon that is known from the economics of industrial organization. It means that the supplier of a commodity just undercuts the price of a competitor, to keep the competitor out of the market.

We start by considering a single country that has developed a clean technology (also called a backstop technology, since it does not need non-renewable energy) with which electricity can be produced at a constant cost. As a source of energy this technology competes with fossil fuel, which is supplied by a monopolist, like OPEC, that has constant unit extraction cost.\textsuperscript{20} For the monopolist a modified Hotelling rule applies. Marginal profit increases at a rate equal to the interest rate, but now the marginal profit is no longer equal to the net price, as in the perfect competitive case (where individual small oil suppliers take the price as given), but lower because the monopolist knows that the price will fall if he increases his supply of oil to the market.

Because of the availability of the new technology the oil price cannot exceed the price of solar, as before. But there is an essential difference. In equilibrium with perfect competition the price cannot be constant before exhaustion, due to the Hotelling rule. In the case of a monopoly, however, matters are different. For a monopolist, it can be optimal to set a high and constant price. Consider, for example, a monopolist whose oil stock is almost depleted. He will set a price one cent below the cost of the clean technology, let us call this the backstop price, to collect as much revenue per barrel of oil as possible while at the same time just keeping renewables from the market. It is always better for the monopolist to save the last drop of oil and sell it tomorrow at the backstop price instead of increasing supply today thereby lowering the oil price. So, in the

\textsuperscript{19} See Meijden et al. (2016).

\textsuperscript{20} We abstract from other small suppliers of fossil fuel (see Groot et al. (2003)), as well as from the fact that OPEC invests in renewables itself.
final phase, when the oil stock is almost depleted, the monopolist will set a constant price just below the renewables production cost. For a large oil stock this no longer holds and the price will increase over time. The reason is quite simple. With a large oil stock, the value of oil in the ground is low, so it is better to sell oil, if necessary at a low price. Or: with a large oil stock and a high price it takes very long to sell all the oil, which is not optimal due to impatience or the time value of money. In general the equilibrium for a large oil stock consists of three phases. Initially, oil is supplied in large amounts at a price far below the backstop price. Then follows a phase with limit pricing. Eventually, once all oil is depleted, the backstop technology takes over.

After fully characterizing the equilibrium, the question arises what happens if the backstop is subsidized, leading to a lower market price for renewable energy. In the case of perfect competition this leads to a weak and strong Green Paradox, as we have illustrated before. For the case at hand the outcome is different. Of course, supply of oil during the limit pricing phase goes up, because of the lower price, which increases demand. But in the first phase oil supply goes down. The reason is that the constraint, that in the first phase extraction should not be smaller than in the limit pricing phase, is relaxed. Hence the weak Green Paradox is reversed. With a slight abuse of the English language, we can call this a “green orthodox”. What happens to the length of the limit pricing phase depends on the demand function. For demand functions commonly used in economics the interval gets longer. The total period of extraction, however, decreases.

We can accurately describe the effect of a carbon tax increase. Suppose the carbon tax is constant (ill-designed so that it does not correspond with the optimum). A higher carbon tax leads to lower initial supply of oil. The interval of time where limit pricing prevails gets longer. Hence, like a subsidy on renewables, the higher tax does not lead to more oil supply initially (no weak Green paradox), but climate damages might still be higher because of acceleration of extraction in the limit pricing phase (strong Green Paradox) and faster exhaustion.

We also investigated the effect of a subsidy on welfare, defined in a dynamic way, taking account of the accumulation of greenhouse gases over time. The outcome is ambiguous, which makes sense. On the one hand energy gets cheaper, but, on the other hand, the subsidy has to be financed. And, since we want to avoid the question what happens after oil has been exhausted, and just before, we assume that the government is committed to subsidize forever. This of course constitutes a distortive cost. So, we typically find a deterioration of welfare. On the contrary,
imposing a (marginal) carbon tax is always good for welfare in the broad sense, since then the problem is tackled where it has its roots. Hence, no super strong Green Paradox.

A next and obvious step is to extend the model so as to include two countries, or blocks of countries, where one country conducts no environmental policy at all (the brown country), and the other one has a policy in place (the green country). Having no climate policy can be justified by the stage of development, as in Ploeg and Withagen (2014). We assume that the production cost of renewables is equal across the two countries. For the supplier of fossil fuel, demand comes from two countries, where the demand functions may differ. But the supplier cannot discriminate between the two countries, so that the producer price is the same across the two countries.

If speculators are able to buy large amounts of oil and store them temporarily at low costs, the supplier of oil needs to price oil in a continuous way, meaning that upward jumps in the price setting are ruled out, because otherwise speculators will step in and make large profits through arbitrage. In the absence of speculators, price discontinuities are possible. I will limit myself here mainly to continuous price paths. In principle, the equilibrium has 5 phases. If the initial fossil fuel stock is large, the price of fossil fuel will be strictly below the price of the subsidized renewables in the green country. There is demand from both countries. Then comes a phase with limit pricing in the green country, where the price just below the net price of renewables, leading still to a large demand from the brown country that benefits from the policy in the other country. This is a form of carbon leakage. Then follows a phase where demand from the green country is zero. Renewables in that country are cheaper than oil, not so in the other country. Subsequently we have a phase with limit pricing in the brown country. Finally, also in that country, renewables take over.21

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21 The equilibrium looks different in case of no speculators. In that case, the monopolist is no longer forced to choose a continuous price path. As soon as the limit pricing phase in the active country comes to an end, it is indeed optimal for the monopolist to choose an upward jump in the oil price, to compensate for the loss of demand from the green country.
What is the effect of policy changes? Like in the case with just one country, there is no weak Green Paradox. An increase of the subsidy leads to smaller initial supply. But exhaustion of fossil fuel takes place earlier, so that a priori it is unclear what the effect on green welfare is. Simulations indicate that subsidies on wind and solar reduce welfare from consumption, because the subsidy has a distortive effect, even after exhaustion of fossil fuel. Initially, emissions of carbon decrease, but increase later on. We typically find that subsidies decrease total welfare. A welfare increase can be realized by replacing subsidies by a carbon tax. Then renewables become competitive eventually, without the subsidy. The revenues of the tax can be used to reduce, for example, the price of labor. This is an old story: the double dividend story, but still a story to be taken seriously.

5. Conclusions
The important lessons, I think, from this lecture are the following. Abolish subsidies, first of all on fossil fuels, and then also on renewables such as solar and wind. Install a carbon tax. But there is a priori no reason to have a uniform carbon tax, especially not for developing countries.
My crusade against subsidies stops about here. When it comes to negotiations on climate change, subsidies given to climate coalitions can have a substantial and positive impact on reaching an improvement on global warming. Another result is that the Green Paradox is a phenomenon that needs to be taken seriously, but we have to be aware that its effects may be mitigated depending on the prevailing characteristics of the economy: market structure, extraction costs, and other features.

In case more time is left for further research, here is a list of other topics that are worth investigating.

- Environmental policy and competitiveness.
- Migration and climate change.
- Environmental policy and inequality.
- Green growth.
- Prices (carbon tax) versus quantities (CO$_2$ reduction).

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