Aalto University
School of Business

Is Green Paradox really a probable outcome of climate policies?

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Jenny Solkinen

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Department of Economics
Aalto University
School of Business

Aalto-yliopisto
Kauppakorkeakoulu

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Jenny Solkinen

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1. Introduction

The discussion about climate change has been somewhat neglected the past few years as the global finance crisis dominated the economies and policies set by governments. Even though reviving the economies is essential we should not forget the climate change but to focus on the means to mitigate the climate change damages.

From the 1970s literature on exhaustible resources has been driven by fear for oil exhaustion and its consequences on economic growth. As Gerlagh(2010) points out this view has notably changed and the interest is now on constraining climate change damages associated with fossil fuel use. The target of this thesis is to focus on the economics of the climate change and on how the different climate policies designed to mitigate carbon emissions actually affect the climate and the economies. The core question of this study is, whether the climate policies intended to diminish carbon emissions will indeed increase the emissions, a situation referred as a green paradox by Sinn(2008,2009).

Most of the literature of environmental economics suggests that the basic exhaustible resource model from Hotelling(1931) is the appropriate framework for modeling the extraction decision of a fossil fuel resource. Hotelling(1931) derived the fundamental equilibrium condition, by which the price of a non-renewable has to grow with the interest rate. Economists have considered various extensions of the Hotelling framework during the past decades. The main purpose of environmental economics has changed substantially from the 1970s and 1980s papers that were focusing on the scarcity problem of non-renewable resources due to concerns regarding the future availability of oil. The key question then was to find the optimal allocation of a scarce resource. Beginning of the 1990s, a new literature emerged, extending the traditional framework by the concern of climate change. After the Stern Review was published in 2007, the problem of climate change has reached the political agenda and awareness of the public. Accordingly research in environmental economics has never been more essential than today.

Climate change has induced a number of recent papers to extend traditional Hotelling frameworks. These papers study the effects of carbon taxes on the resource extraction path of carbon resource and derive crucial policy implications. Of particular relevance to this paper and to climate change literature is Sinn (2008) who introduces the green paradox as a possible outcome of climate policy today. Sinn (2008) points out that the fossil fuel resource owner will come to a conclusion that shifting extraction to the presence increases his expected total profits if in time increasing tax inflicts a threat on future extraction profits.

Sinn(2008) assumes that resource owners are confronted with in time increasing carbon taxes. If resource owners include rising taxes into their maximization problem, the result is rather a faster than a slower extraction of the fossil fuel resource. That is because an in time rising tax imposes a threat on future profits of extraction, and the resource owner will come to the logical conclusion that shifting extraction to the presence increases his expected total revenues. Thus, a fossil fuel owner would like to sell his oil as long as it is still relatively lowly taxed in order to maximize his profits.

Accordingly, the main purpose of this thesis is to uncover whether we should focus on subsidizing renewal energy resources such as solar energy and wind power, as is done in Germany, or will that only result in increased fossil fuel extraction and emissions. In other words, the goal is to reveal whether the green paradox exists or not.

2. Climate Change- The greatest externality ever

Global warming has for some years been an established scientific fact beyond reasonable doubt. Human induced carbon dioxide emissions and changing land use are the primary reason for the changing climate.

2.1. The Temperature of the Earth

The temperature of the Earth is the result of a delicate balance between the radiation received and remitted. For the Earth to sustain this temperature and these living conditions, it needs to radiate as much energy back into space as it receives (Sinn 2008). The increasing concentrations of greenhouse gases in the Earth's atmosphere result from human activity, mostly from the burning of fossil fuels. Also deforestation and agriculture cause greenhouse gases. The greenhouse gases block the sun radiation turned into warmth from being released from the Earth's atmosphere into the space, which raises Earth's temperature. This is global warming, also referred as climate change.

The greenhouse gases most induced by human activity are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The most important contribution to the climate problem is CO2 from the combustion of fossil fuels. During years 1970–2004 the greenhouse emissions have increased by 70% and carbon dioxide emissions by 80 % in comparison to the pre-industrial time and currently there is more greenhouse gases in the atmosphere than there has ever been during the last 650 000 years. (Stern 2007; www.ilmasto.org)

Stern(2007) and Sinn(2008) argue that there are tiny quantities of greenhouse gases in the air, in particular 380 parts per million (ppm) of carbon dioxide, up to 0.02% of water vapor, and, even rarer, though more effective, climate gases such as methane (1.8 ppm) and nitrous oxide (0.3 ppm). With help of these tiny amounts of greenhouse gases an equilibrium temperature of +15 °C is today's average. Stern(2007) reports that the mean temperature on Earth has increased by 0,74 °C during the past hundred years, and the temperature rise has now almost doubled. Before the Industrial Revolution the average temperature was about 14 °C. The increase to 15 °C and the resulted 20 cm increase in the sea level that we have seen in the meantime have not really been a problem. But Sinn(2008) claims that we are currently just at the beginning of a period of rapid change.

2.2. The Climate problem

The most important contribution to the climate problem is CO2 from the combustion of fossil fuels. The climate problem is thus to a large extent caused by extracting carbon resources and transferring them to the atmosphere. Logically, any discussion of the climate problem therefore ought to be linked to a discussion of the extraction of carbon resources. Hoel (2010a) Eichner and Pethig(2009) argue that ever growing scientific evidence reports that to succeed in stabilizing the world's temperature at safe levels we need to curb the world emissions of greenhouse gases. The estimates published in the Stern Review suggest that a doubling of the pre-industrial CO2 concentration, 280 ppm, could already take place up to 2035, and that by 2100 a value of about 900 ppm would be reached in a business-as-usual scenario. The estimated temperature increase in the Stern Review, resulting from the doubling concentration level, is about 2°C or more. A partial melting of glaciers as well as the thermal expansion of the sea water would increase the sea level by about another 20 cm.

The most pessimistic scenario of the Stern Review, the 5°C increase up to 2100 would increase the sea level by about one meter. As an example, this would flood more than one fifth of Bangladesh. IPCC (Intergovernmental Panel on Climate Change) suggest that sea level will rise during the 21st century on average 17 cm. There are further dangers including more powerful and devastating tropical storms, the elimination of a substantial fraction of the world's species, floods and droughts causing mass migrations toward more fertile countries and regions. Infrastructure, agriculture and manufacturing suffer and lead to a global instability. Stern is also concerned about the fact that 15 – 40 % of the different species of the world will become extinct if the temperature rise is 2 °C. (Stern 2007; www.ilmasto.org)

The effects of climate change on economies will vary widely over the world. Developing countries are particularly vulnerable to the impacts of climate change because of their exposure to an already fragile environment and economic structure, and low incomes that restrict their ability to adapt. (Stern 2007)

Economists have challenged the Stern result that an increase by 5°C could cost mankind up to 7 trillion dollars in present value terms(Nordhaus 2006). Even though economists argue about how much the climate change would actually cost to the global economy, these kinds of developments are nevertheless extremely alarming. However the researchers are remarkably insecure about how much will the temperature rise and how will this temperature rise affect the Earth. This global warming caused by carbon emissions will according to Stern(2007) lead to the "greatest and widest-ranging market failure ever seen" and according to the highest temperature rise scenario in Stern Review would cause in 2050 under 1 %, in 2100 2.9 % and in 2200 13.8 % average loss in the worlds GNP.

With regard to the use of fossil fuels, we truly face an extremely difficult choice problem between the reduction of the stock underground and accumulation of the stock above ground. The limited absorption capacity of the air may actually constrain extraction more than the scarcity of the resources itself. From an economic perspective the question is to what extent market failures distort the extraction paths relative to the optimum and which policy measures could revise them.

2.3. Climate Change Mitigation

Stern(2007) argues that it is not possible to totally prevent the climate change but it is still possible to protect our economies from its impacts to some extent. The adaptation to the climate change is crucial. There will be significant costs from stabilizing the greenhouse gases in the atmosphere though these cost are low in comparison to the risks of inaction.

2.3.1. Greenhouse gas levels

The current level of greenhouse gases is 430ppm CO_2 equivalent and it is rising at more than 2ppm each year. To avoid the most extreme impacts of climate change the greenhouse gas levels should be stabilized between 450 and 550ppm CO_2. Gerlagh(2010) suggest that atmospheric concentrations should be held well below 500ppm and cumulative emissions below 1000 GtC or otherwise there will be a high probability of global mean temperatures rising more than 2°C. This means that cumulative emissions from 2010 onwards should stay well below 500 GtC. According to Stern(2007) the stabilization will require at least a 25% cut in the current emission levels by 2050. Stern(2007) continues that central estimates of the annual costs of stabilization are around 1% of global GDP, if we start to take action immediately.

If all the fossil fuel resources are burned, how much carbon will in fact end up in the atmosphere? The total reserves of oil, coal and methane that nowadays seem worth extracting have been estimated to be in the range between 766 and 983 Gt of carbon. From the Industrial Revolution until the year 2000, we have burned about 300 Gt of carbon from fossil fuels. Currently there are about 809 Gt carbon (380 ppm carbon dioxide) in the atmosphere. About 55% of the produced carbon dioxide is absorbed by land biomasses and the oceans and if this percentage of natural absorption remains fixed, burning the reserves means that roughly another 400 Gt of carbon will enter the atmosphere. This means an increase by 49% to 566 ppm, which would increase the world temperature by more than 2 °C above the pre-industrial level. (Sinn 2008)

Gerlagh(2010) reminds that fossil fuel combustion is not the only resource of emissions and thus we should exploit a lot less than 500 Gt of carbon of global fossil fuel resources. Gerlagh(2010) argues that conventional oil reserves and resources expected to be discovered, amount between 120 and 250 GtC. Gas amounts between 70 and 140 GtC and coal reserves are estimated to amount between 500 and 1000 GtC. Additionally there is a uncertain but potentially large reserves of unconventional oil, such as tar sands and shale oil, between 150 and 1000 GtC. Also Sinn(2008) points out that we need in addition to consider these resources that include stocks underground that currently are not worth extracting, but that could become profitable with higher prices and with more efficient technologies.

Sinn(2008) argues that estimates for the overall stock of resources of carbon range from 3,967 to even 5,579 Gt. Even if 45% of the lower quantity enters the atmosphere the stock of carbon in the air would increase by 221% from today's 809 Gt to 2,594 Gt and the concentration of carbon dioxide would accordingly increase from 380 ppm to about 1,220 ppm, which is considerably more than any model projections thus far have dared to predict. Thus, Gerlagh(2010) argues that instead of the usual worry for scarce oil ,the problem is that there is actually too much oil and fossil fuels, much more than is good for the climate.

2.3.2. Options to mitigate climate change

Di Maria et al.(2008) argue that the purpose of a climate policy according to UNFCCC is to stabilize the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic distraction with the climate system. Predictions of emission paths in the future indicate that without emissions reduction policy, this goal will not be reached. Probably the most important means to reduce greenhouse gas emissions is to reduce carbon dioxide emissions from the exploitation of fossil fuels. Di Maria et al.(2008) claim that since fossil fuels are nonrenewable resources, and since the fossil fuel resource owners would like to sell all of their resource stocks over time, this can only mean that resource extraction has to be postponed compared to business as usual economy. General climate policies have targeted at reducing fossil fuel use by making it more expensive and by subsidizing the development and supply of clean substitutes.

Gerlagh(2010) claims that we should not use all fossil fuel resources, unless we discover ways to capture and storage the carbon dioxide (CCS) at a large-scale. Gerlagh(2010) argues that so far CCS has not proven to be the solution to the climate change problem. As Gerlagh(2010) argues, it seems logical to fully exploit gas and most of the conventional oil. Gas is relatively highly energy intensive per unit of emissions as conventional oil is the main fuel for transport. This implies that coal and unconventional oil are the energy resources we should not fully exploit. As Gerlagh(2010) reports, coal is highly polluting, but still the prime fuel for power plants world-wide. Gerlagh(2010) argues that basic calculations propose that gradually the use of coal has to be brought to an end during the 21st century to prevent the worst climate change problems. Gerlagh(2010) claims that the driving force of this must either be a price wedge attached to coal use, the development of a clean backstop or a combination of these two. Finally, exploiting unconventional oil resources such as tar sands is highly energy intensive, and thus the emissions per final energy supply are very high. Unconventional oil should therefore be totally left unused.

Gerlagh(2010) argues that global efforts to diminish climate change may not change the value of conventional oil and gas but will decrease the value of coal and unconventional oil resources. Gerlagh(2010) points out that countries such as Canada which have enormous tar sand resources may protest measures that reduce the value of their resources. Gerlagh(2010) claims the problem of international distribution of costs and benefits of climate change policy needs to be solved before we can expect any effective global climate measures. In Stern's(2007) opinion climate change costs will be higher if innovation in low-carbon technologies is slower than expected or if policy makers don't succeed to make the most of economic instruments that allow emissions to be reduced whenever and wherever it is cheapest to do so.

Stern(2007) highlights that action on climate change will create prominent business opportunities, as markets are created for low-carbon energy technologies and low-carbon goods and services. These markets could increase to be worth of hundreds of billions of dollars. Averting climate change could create opportunities for economic growth while ignoring climate change will eventually damage economic growth. This describes what Sinn(2008) is concerned about, because as the fossil fuel suppliers try to respond to the competition of these new energy markets they will only accelerate the climate change instead.

According to Stern(2007) global actions on climate change demand three elements on policy: pricing of carbon, implemented through tax, trading or regulation, policy to support innovation and the deployment of low-carbon technologies, and the third, action to remove barriers to energy efficiency, and to inform, educate and persuade individuals about what actions they can take to restrain climate change. Most of the economists agree with Weizman(2007) who highlights that substantial carbon taxes must be levied to restrain the climate change.

3. Green paradox

Gerlagh(2010) argues that there are two economically fundamental problems that mankind needs to solve in the 21st century. The first one concerns the secure supply of energy after cheap oil is no longer available and the second one the management of global climate change. The literature of the green paradox interacts between the two problems. Green policies that are set up for to develop energy sources to substitute for oil in the long run, may actually enhance climate change.

During the last couple of years, in the climate change debate, there has been a considerable literature discussing the so-called "green paradox". This term originates from Sinn(2008,2009), who argues that some climate policies, intended to mitigate carbon emissions, might actually increase carbon emissions, as oil markets anticipate a future reduction in demand by increasing current demand. (Hoel(2010b), Gerlagh(2010))

3.1. Definition of the Green Paradox

Hans-Werner Sinn(2008) wants to draw more attention to the supply-side of the fossil fuels in the debate of climate change. According to Sinn(2008) we should be asking how to persuade the resource owners to leave more carbon underground. Sinn(2008) sees this as the sole way to solve the major problems of climate change and is not convinced with the fact that demand-reducing public policies such as increasing ad-valorem taxes on carbon consumption or increasing subsidies for replacement technologies are going to solve the climate problem. Eichner and Pethig(2009) share this opinion.

Although climate change is a global problem, only a fraction of countries currently sets policies to reduce greenhouse gases. Van der Werf(2010) argues that, as a consequence to such unilateral climate policies, non-abating countries might increase their emissions because the world price of fossil fuels declines due to reduced demand from the abating countries. For example in Europe, countries that have signed the Kyoto protocol, have invested billions in developing cleaner energy sources, such as wind energy, water power stations, biofuels, wood pellets and solar heating, aimed at reducing demand for fossil fuels. These measures to reduce consumption put a downward pressure upon the world's fossil fuel market price and weaken the rate of increase in such prices. Hoel(2008) adds that instead of joining the Kyoto agreement the US administration has proposed subsidies for R&D directed towards lowering costs of alternative energy sources. Hoel(2008) argues, that there are many reasons why a focus on technology development instead of policies focusing directly on emissions will not result in significant emission reductions. Hoel(2008) argues, that as the supply side of fossil fuels is taken into consideration, fossil fuel prices may decline as a result of improved renewable energy technology.

Sinn(2008) continues that high taxes on fuels have also given incentives to diminish the expansion of traffic, to install better insulation of homes and to develop lighter cars with hybrid engines. The EU system of CO2 emissions trading has induced business, especially electricity producers and the chemical industry, to economize on their combustion processes. Sinn(2008) argues that governments think that if a country or a group of countries is able to mitigate their CO2 emissions, aggregate emissions will be cut by the same amount. Even if other countries won't follow and cut down their emissions, global warming will still be restrained at least slightly.

We might assume that all these actions taken to mitigate the impacts of climate change would be worthwhile. Sinn(2008,2009) argues the opposite. In his opinion these actions might even be harmful to our climate, because the supply-side effects of the energy markets are neglected. All the new low-carbon technologies are means to reduce the demand for fossil fuels. But Sinn(2008) asks how do these affect the supply side of energy? Sinn(2008) continues that the public debate has not considered the supply side of the climate problem at all.

Sinn(2008) argues that if the supply path for carbon remains the same demand reducing measures will only mean that domestic demand is replaced by foreign demand, which is accelerated through a decline in world energy prices relative to what they otherwise would be. Alternative energy sources may also reduce the price of energy and stimulate demand elsewhere, but if, as Sinn(2008) assumes, they do not affect the extraction path of carbon, the general equilibrium reaction of world energy markets must be such that the alternative energy is consumed in addition to the energy from the fossil fuels. There is a positive impact on economic growth but not towards mitigating the greenhouse gases. Ironically, measures that enhance the technical efficiency of combustion processes by avoiding the emission of unburned fossil fuel components, would according to Sinn(2008) accelerate the global warming.

3.2. Carbon leakage

Eichner and Pethig(2009) argue that any national policy to curb emissions is bound to increase domestic energy costs and thus enables countries that are not abating emissions to expand carbon consumption.

Therefore the efforts of abating countries to mitigate emissions will to some extent be offset by non-abating countries that increase emissions. This is the phenomenon known as carbon leakage. The net emissions cutback is smaller than the emission reductions of the abating countries.

Van der Werf(2010) states that carbon leakage occurs when emission reductions by some countries results in increasing emissions by other countries, due to a lower world price for fossil fuels, relatively cheaper carbon intensive goods in non-abating countries, or lower marginal damage from carbon emissions in non-abating countries. Eichner and Pethig(2009) add that in the extreme case, in the case that Sinn(2008,2009) calls the green paradox, the demand reducing policies of abating countries actually increase aggregate world emissions compared to emissions in the absence of demand reducing measures. Harstad(2012) argues that carbon leakage discourages countries from reducing emissions and it may even motivate tariffs or border taxes on trade. Additionally, capital may relocate and firms might move.

3.2.1. Levels of Carbon leakage

Van der Werf(2010) argues that in the literature, the percentage of emission reduction that gets offset by the increased emissions by countries outside the Kyoto Protocol generally ranges from 2 to 41%, and even a leakage rate of 130% is announced. This means that as a response to an emission reduction in some countries, other countries raise their emissions by an even larger amount, such that global emissions go up and climate change actually accelerates. Harstad(2012) argues that commonly the estimates of carbon leakage are between 5% and 20%, but that, it can be even higher if the coalition of countries is small, the policy ambitious, and the time horizon long.

According to Eichner and Pethig(2009) models researching carbon leakage show estimates from leakage rates of 20% to lower bound estimates of 2% to 5%. This prevailing view of modest leakage rates is challenged by researchers like Sinn(2008,2009) in the area of intertemporal theory of nonrenewable natural resources. The point of departure of Sinn(2008) is an extraction path of fossil fuel that is suboptimally steep in laissez-faire scenario e.g. because of the externality of global warming. In models that differ with respect to their assumptions on market power and strategic behavior the question is how are various kinds of taxation able to restore efficiency by flattening the extraction path. According to Eichner and Pethig(2009) under various conditions a majority's result is that carbon taxes tend to have only little impact on the time path of extraction and that the extraction path is steepened if tax rates rise in time.

3.3. The Supply Side

Eichner and Pethig(2009) share Sinn's(2008) opinion about the fact that the prevailing discourse of the effectiveness of demand reducing policies is flawed since it largely neglects the close link between the economics of climate change and the economics of non-renewable resources and therefore fails to account for the supply side of the problem. Hoel(2008) adds that as the climate problem is to a large extent caused by extracting carbon resources, it is only logical that any discussion of the climate change should be closely linked to a discussion of the extraction of carbon resources. Hoel(2008) is surprised that in spite of this obvious fact, so little of the literature thus far has made this link.

Hoel(2008) argues that most of the literature that makes this link are discussing optimal climate policies, in spite of the fact that a global and cost effective climate agreement seems to be unlikely in the near future. Hoel(2008) continues that only few researchers make the link between climate policies and exhaustible resources when policies are not optimal or international agreements are not complete. Sinn(2008,2009) is one of them showing that not optimally designed climate policies may increase emissions instead of reducing them, as the exhaustibility of carbon is taken into account. Hoel(2008) adds that, while the impacts of technology change have recently been linked in the discussion of climate policy, most of this literature ignores the fact that such technology change may have an effect on the supply of carbon.

Eichner and Pethig(2009) argue that even though the very understanding of carbon leakage requires distinguishing abating and non-abating countries, the supply-side literature aggregates all fossil fuel consuming countries into a single country assuming full cooperation of all countries. Eichner and Pethig(2009) add that there are no studies that model intertemporal wealth maximizing resource supply and at the same time take into consideration the leakage of carbon from the abating countries to non-abating countries.

Thus a piecemeal expansion of these demand-reducing public policies may aggravate the problem as it gives resource owners the incentive to avoid future price reductions by bringing forward their sales. The resource owners fear that the rate of capital gains on the resources diminishes. To get the biggest possible profits from the resources they react by bringing forward their extraction plans converting a larger portion of their wealth into cash now. They thus increase the fossil fuel supply when demand for them goes down. This is what Sinn(2008,2009) calls the green paradox.

4. The Model of Green Paradox by Sinn(2008)

Many of the studies considered in my thesis apply Sinn's(2008) model as a basis to their research, and therefore I will present it here as well. Sinn(2008) uses an extension of the standard Hotelling model showing that an over time increasing tax leads to a faster extraction of the fossil fuel resource.

4.1. Hotelling framework

Since Hotelling(1931) revealed his formulation for the optimal extraction path of exhaustible resources, numerous of variations of his model have been presented and discussed in the literature. As Ghoddusi(2009) lists, considerations of variable production costs, various uncertainties, oligopolistic competition, capacity limits, backstop technology, deposits multiplicity and the investment in exploration are meaningful examples of the extensions.

Hotelling(1931) raised the important question of what is the optimal rate of extraction for a particular exhaustible resource. The answer to that was introducing the r-percent rule implying that price net marginal cost, marginal revenue, will increase at interest rate for competitive market. Furthermore, Hotelling(1931) argues, that the extraction rate should decrease over time if the demand is isoelastic.

Ghoddusi(2009) argues that Hotelling(1931) does not consider any uncertainty in the problem. As Ghoddusi(2009) reports, to bring Hotelling’s model closer to the real world problems we need to include different uncertainties, for instance, regarding demand process, production and investment costs, time to build, geological properties and deposits and the capacity constraints. Ghoddusi(2009) also argues that, Hotelling does not explicitly incorporate the issue of limited production capacity in his model, and thus the results are valid only for an unlimited rate of extraction.

4.2. The Model of Green Paradox

In Sinn's(2008) opinion the market failure generated by CO_2 emissions has little in common with the static marginal externality model, which is also in the center of the Stern report(2007). According to Sinn(2008) an intertemporal analysis that focuses on the wealth society hands over to future generations is needed to understand the market failure. Society's inheritance includes natural capital, man-made capital and the industrial waste. There are two choice problems involved. One is the optimal mix between the natural capital, man-made capital and the stock of waste and the other is the overall wealth that society donates to future generations. Sinn(2008) considers as an essential question the extent to what market forces can be expected to find an appropriate solution to these problems and, if markets fail, which kind of policy instruments are suitable to enhance the intertemporal allocation of resources.

4.2.1. Neoclassical world

Sinn(2008) approaches the question by first considering the neo-classical world of intertemporal resource allocation with exhaustible resources, abstracting from market failures in general and specifically the problem of climate change. Sinn(2008) considers a resource owner who possesses a stock of the resource in situ, S, with different degrees of accessibility so that extraction costs can be written as $g(S)R$, $g'(S)< 0$, where $R= -\dot{S}$ is the current flow of extraction and g is the extraction cost per unit. In Sinn's(2008) model the resource owner chooses his extraction path to maximize the present value of his cash flow $(P–g(S))R$ where P is the price of carbon and i the market rate of interest. If the resource owner extracts a unit today and invests the profit in the capital market he will get a return of $i(P–g(S))$. If he postpones extraction instead, his return will be $\dot{P}$. Thus,

(1) $$i = \frac{\dot{P}}{P-g(S)}$$ (positive)

is a necessary condition for both an optimal extraction scheme of the resource owner and a market equilibrium. Sinn(2008) remarks that in the special case of $g = 0$ this equation reduces to Hotelling's condition that the percentage rate of price increase equals the rate of interest.

Sinn(2008) supposes that output is given by the production function

(2) $$Y= f(K,R,t)$$

where K is the stock of man-made capital and t is time. Output can be used for consumption of man-made goods C, investment of man-made goods $\dot{K}$, and resource extraction:

(3) $$Y= C + \dot{K} + g(S)R .$$

Then, according to Sinn(2008), it is impossible to increase consumption in one period without decreasing it in another if, and only if,

(4) $$f_K = \frac{\dot{f}R}{fR-g(S)}$$ (normative; Pareto).

Sinn's(2008) equation (4) is a generalization of the efficiency condition of Solow(1974a) and Stiglitz(1974) for the extraction of exhaustible economic resources with the case of stock-dependent extraction costs.

Sinn(2008) argues that the Solow-Stiglitz condition refers to the special case where $g = 0$ and points out that the extraction scheme is chosen such that the growth rate of the marginal product of the resource is equal to the marginal product of capital. Sinn(2008) includes extraction costs to this condition such that the increase in the marginal product of the resource relative to the marginal product net of the extraction cost be equal to the marginal product of capital. Sinn(2008) continues that as competitive markets imply that $f_K = i$ and $f_R = P$, equation (4) evidently coincides with equation (1), describing the efficiency of the market equilibrium.

Equations (1) and (4) by Sinn(2008) describe an optimal portfolio mix between man-made and natural capital to be handed over to future generations but not the amount of wealth that should and will be bequeathed. Answering this question involves difficult intergenerational welfare judgments specifying the altruistic value present generations are willing to give future generations. Sinn(2008) argues that a general utilitarian specification uses an additively separable utility function:

$$\int_0^{\infty} N(t)U\big(c(t)\big)e^{-\rho t}dt$$

where N is the number of people in a country, $c(t) = C(t) / N(t)$ is per capita consumption, U instantaneous utility and ρ is the rate of utility discount within and across generations.

Sinn(2008) emphasizes that if people have the opportunity of investing their wealth at the present market interest rate, they allocate their consumption across the generations such that they equate their rate of time preference to the market rate of interest:

(5) $i = \rho + \eta \hat{c}$ *(positive, utilitarian).*

The rate of time preference is composed of the rate of utility discount ρ and the relative decline in marginal utility resulting from an increase in per capita consumption over time, $\eta \hat{c}$, where η is the absolute value of the elasticity of marginal utility.

According to Sinn(2008) the normative counterpart of equation (5) is

(6) $f_K = \rho + \eta \hat{c}$ (normative)

because a central planner who respects individual preferences would allocate consumption over time such that people's rate of time preference equals the return that a real investment is to be able to produce. Sinn(2008) argues that the market solution and the social planner's solution coincide again.

4.2.2. Ethics and discounting

Stern(2007) argues that on ethical grounds the market solution just cannot be accepted because discounting future utility discriminates later generations relative to earlier ones. Sinn(2008) claims that discounting could only be justified by the probability of extinction for exogenous reasons, but the discount rate following is considerably smaller than the discount rates normally used, being in the order of one tenth of one percent. Sinn(2008) argues that without discounting of utility, only technical improvement that increases per capita consumption would in the long run be able to explain a positive rate of time preference from an ethical perspective, but as that rate would be considerably lower, equation (6) would imply a lower marginal product of capital. Sinn(2008) highlights that this would mean more capital accumulation and, because of (4), more resource preservation as the marginal product of the resource would have to increase at a lower speed, which requires a flatter extraction profile with a lower extraction rate in the present.

According to Sinn(2008) the argument that people make a mistake when they underestimate future needs has been repeatedly argued by scientists during the past century. However, Sinn(2008) argues that from the perspective of economic policy this argument is infeasible, because the philosophers are not the ones who make collective policy decisions, the current generation of voters themselves are. Thus, if the current voters discount utility when making their private intertemporal allocation decisions, they will elect politicians who act accordingly. These politicians will find the intertemporal allocation pattern to be correct and hence will not take countervailing policy actions.

From a philosophical perspective someone could claim that it would nevertheless be wrong to follow the current generations' preferences, because these preferences are wrong. Sinn(2008) argues that this would imply that parents do not consider the needs of their children and further offspring at all and finds this argument totally unconvincing as he sees no indication that parents might be inadequately altruistic towards their children.

4.2.3. Insecure property rights

Sinn(2008) claims that resource owners often face insecure property rights which might lead them to overextract. According to Sinn(2008) various scientist have argued this, yet more general, and not focusing on the intertemporal dimension of the problem.

Sinn(2008) is considering an oil sheik who feels insecure as to how long his dynasty will govern the oil underground, because he fears the risk of riot and following expropriation by a rival.

Sinn(2008) lets

$$e^{-\pi t},\ \pi = const. > 0,$$

be the probability of survival of oil sheik's ownership until time t, where π is the instantaneous expropriation probability. This means that a resource owner who maximizes the expected present value of his cash flow from resource extraction discounts with $i + \pi$ rather than just i. Sinn(2008) argues that hence (1) changes to

(7) $$i + \pi = \frac{\dot{P}}{P - g(S)}$$ (positive, insecure property rights).

Sinn(2008) states that the probability of being expropriated denotes only a private damage, and thus the welfare optimum continues to be given by (4) and (6). As $i = f_K$, equation (7) displays that for any given P the price path becomes steeper, which refers to overextraction and is a legitimization for conservative policy actions.

Sinn(2008) argues that there is a similar implication of overextraction if the property rights are improperly defined in that a multitude of firms extract from the same reserve of fossil fuel. In Sinn's(2008) opinion the common pool problem has been largely solved by consolidating the oil fields or sharing agreements between extracting firms.

Unfortunately, as Sinn(2008) points out, the problem of insecure property rights can still be substantial, in particular in the case of oil and gas extraction. It is estimated that in Venezuela, the Arab countries, Iran and the former Soviet Union, in countries where the political situation has been extremely insecure over the last decades and is likely to remain so in the future, there are between 70% and 80% of the world's oil and about three quarters of the world's gas reserves. If the resource owners in these countries feel insecure about for how long they or their descendants will be able to extract and profit from the resources they currently own, they better rush to extract the resources now and secure the profits.

Sinn(2008) states that it is still under debate precisely how political risk affects resource extraction as it has also been argued that political risk may actually slow down extraction because it reduces the incentive to invest in development of new fields and in extraction technology. Sinn(2008) continues that researchers have even found that dictators tend to conserve the oil more than democracies do, while constitutional changes tend to accelerate extraction. Sinn(2008) argue that one interpretation of this is that, while democracies offer more safety for investors and thus attract direct investment, they also challenge the property rights of the countries' resource owners, who would not have carried out investments. Democracy for these resource owning clans is a serious ownership risk, which gives them every reason to accelerate extraction as would increasing political chaos do. This interpretation supports the argument that increased ownership risk leads to overextraction.

4.2.4. Global warming

According to Sinn(2008) global warming is an externality that does not affect the conditions that characterize market behavior. Hence equations (2) and (6) remain valid. The emissions of carbon dioxide are an externality par excellence as they are divided evenly around the planet Earth, ruining the world's most precious public good, air quality.

Sinn(2008) claims that we should focus on how the normative conditions describing intertemporal allocation of resources are affected. Sinn(2008) assumes that the temperature on Earth is a monotonically increasing function of the stock of carbon dioxide in the atmosphere, that the stock of carbon dioxide in the air is a monotonically increasing function of stock emitted, and that the stock emitted is proportional to the stock of fossil fuels extracted. As temperature deviates from the preindustrial level, it creates damages in terms of costs of air conditioning, reconstruction of buildings, agricultural damages etc. Sinn(2008) claims that as the damage can be described as a loss of output, a reduced form of the aggregate production function with the damage from global warming is

(8) $$Y = f(K, R, S, t),$$

where the resource in situ, S, represents the environmental quality in the sense of carbon being left in the ground. With $f_S > 0$, $f_{SS} < 0$, the normal properties of a production function are assumed, which then inscribe positive and increasing marginal damage from cumulative resource extraction. According to Sinn (2008) it follows from (8) and (3) that it is impossible to make one generation better off without making another one worse off, if and only if,

(9) $$fK = \frac{\dot{f}R + fS}{fR - g(S)}$$ (normative, with global warming effect).

Consequently, Sinn(2008a) argues that (9) is a condition for intertemporal Pareto efficiency in the extraction of fossil fuels with stock-dependent damages from global warming, equivalent for equation (4) above.

Sinn(2008) states that equation (9) shows that with greenhouse effect and hence $f_S > 0$, $\dot{f}_R$ must be smaller for any given time and any given values of *K, S* and *R.* Thus it calls for a flatter extraction path with less extraction in the present, but a lower decline afterwards. Sinn(2008) concludes that the wider the damage from global warming is, the wiser it is to relocate extraction to the future.

Sinn(2008) mentions that if compared with the market equation (7) two points are worth noticing. On the one hand, because of global warming, $f_S > 0$, the relative increase in the cash flow per unit extracted resulting from delaying extraction should be less than the interest rate:

$i > \frac{\dot{P}}{P-g(S)}$ (normative).

Sinn(2008) continues, that on the other hand, because of the risk of expropriation, $\pi > 0$, the relative increase in the cash flow per unit extracted resulting from delaying extraction is even greater than the rate of interest:

$i < \frac{\dot{P}}{P-g(S)}$ (positive).

Sinn(2008) concludes that the resource owners consider a risk that they should not consider, and they neglect a risk they should not neglect and thus there is overextraction. This result confirms the common thought that, because of global warming, the carbon dioxide emissions should be reduced. Sinn(2008) remarks that, however, it does not entail a value judgment that derives from considerations of inter-generation equity or sustainability, but follows from economic efficiency considerations alone.

Sinn(2008) claims that equation (9) implies an optimal composition of wealth formed of man-made capital, fossil fuels in situ and carbon waste in the air that society should leave for future generations whatever the size of the legacy is. Sinn(2008) states that unfortunately society does not obey this equation, thus leaving future generations too little fossil fuels relative to the capital.

4.3. A simplified model

A graphical presentation that uses a somewhat simplified version of the neo-classical production function may be useful to summarize Sinn's(2008) conclusions so far. Assuming that $F(K,R,S,t) = iK + \varphi(R) + \psi(S)$ with $i = const.$ and otherwise the properties assumed above, i.e. $\varphi' > 0$, $\varphi'' < 0$ and $\psi' > 0$, $\psi'' < 0$. $P(R) = \varphi'(R)$ denote the inverse demand function for carbon and assume that the price elasticity of demand, $-\varepsilon$, is a constant.

Sinn(2008) demonstrates the extraction path in *R,S* space. The slope of the plausible time paths in *R,S* space is given by

$$(10) \qquad \frac{dR}{dS} = \varepsilon \hat{P}$$

as and $\varepsilon = \hat{R} / \hat{P}$ by definition. Sinn(2008) rearranges (7) and uses (10) which gives

(11) $\frac{dR}{dS} = \varepsilon\,(i + \pi)\,\left(1 - \frac{g(S)}{P(R)}\right)$ (positive).

According to Sinn(2008) equation (11) uniquely defines a slope for each point in *R,S* space and hence the set of possible paths which coincide with the derived marginal condition. Sinn(2008) assumes that *g(S)* and $\psi'(S)$ are differentiable and bounded from above, so that they cannot go to infinity as *S* goes to zero. At the same time the price is unbounded as *R* goes to zero by the assumption of a constant ε. Sinn(2008) shows that this assures that the extraction paths will lead to the origin. Thus, as Sinn(2008) argues, (11), uniquely defines the equilibrium path itself.

Sinn's(2008) figure 1 demonstrates the equilibrium paths for three alternative specifications. The middle path depicts a path that characterizes a market equilibrium where $\pi = 0$. The economy follows this path as time proceeds and on the way, the stock and the current extraction volume, *S* and *R,* both diminish to zero. The steeper path characterizes the market equilibrium with insecure property rights, $\pi > 0$, and it starts with higher extraction at $S=S_0$, the given initial stock. Sinn(2008) remarks that, even though extraction is higher than with secure property rights for any given value of the stock in situ, it does not mean that extraction is higher for any given point in time. Sinn(2008) adds that, as the stock diminishes more rapidly, there must be a finite point in time after which extraction is permanently lower than it otherwise would have been.

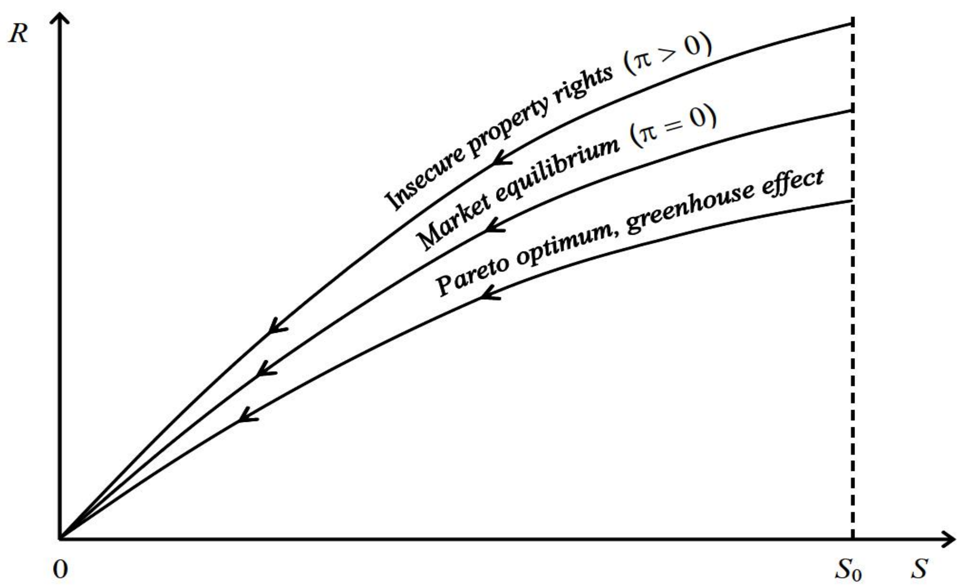

Figure 1: Efficient and actual time paths in the presence of global warming and stock dependent extraction costs (Sinn 2008)

Sinn(2008) reports that the middle path showing the market equilibrium with properly defined property rights would be Pareto efficient without the greenhouse effect. Thus, with the greenhouse effect the lowest path is Pareto efficient and its slope follows from (9) and (10) with the simplifying assumptions:

(12) $\frac{dR}{dS} = \varepsilon\left[i\left(1 - \frac{g(S)}{P(R)}\right) - \frac{\psi'(S)}{P(R)}\right]$ (normative, with greenhouse effect).

Sinn(2008) argues that equation (12) gives a lower slope for each point of the *R,S* space. Comparing the three paths reiterates the point that the insecurity of property rights implies a higher current extraction volume than in standard analysis while the extraction volume should actually be lower because of the greenhouse effect.

4.4. Greener policy paradoxes

Sinn(2008) claims that the public policies affecting only the demand side are useless if the supply path of carbon is fixed. Sinn(2008) highlights that alternative ways of generating energy, carbon taxes or attempts to reduce the energy intensity of economic activities are all inconclusive if the oil owners do not take their part in the game. Green policies in one country just help the other country buy energy at lower prices, and there is no effect on global warming.

Sinn(2008) argues that the assumption of exogenous supply has relevance for the resource problem for the simple reason that, apart from the extraction cost, fossil fuels need not be produced but are available at a given quantity on Earth. This still leaves room for supply reactions in the sense of altering the time path of extraction. Sinn(2008) claims that, however, if fossil fuel owners react to a change in demand today by extracting less, they must extract more in the future. Therefore policies that make the extraction path flatter are required, which implies less extraction in the present and more in the distant future.

Sinn(2008) claims that, while some of the demand-reducing measures may reduce the stock worth extracting as time goes to infinity, it is not evident that they will alter the time path of extraction in the right direction and the reason is that they exert two countervailing effects on the current extraction volume. Sinn(2008) argues that on the one hand, they reduce the incentive to extract because they press down today's prices. On the other hand, they increase the incentive to extract because the expected demand and price decline that these policies generate in the future reduces the opportunity cost of the resource in situ. Sinn(2008) points out that unless it is shown that the former effect dominates the latter, the policies cannot be proposed as a means to mitigate global warming. Thus, rational public policy against global warming should therefore focus on trying to flatten the time path of extraction rather than reducing the stock that will be exhausted as time goes to infinity.

Sinn(2008) makes this policy discussion more concrete by analyzing tax systems. First, Sinn(2008) considers a cash flow tax to be paid by the fossil fuel owners. A cash flow tax will be challenging to implement, but it is a good basis for understanding the problem. Sinn's(2008) tax revenue equation for a cash flow tax is

(13) $T = \tau Z,\ \ Z\,(P - g(S))R$ (cash flow tax)

where T is the tax revenue, τ the tax rate and Z is the cash flow, $\theta = 1 - \tau$ denotes the tax factor. Sinn(2008) argues that a cash flow tax does not have an impact on the extraction path, because choosing the extraction path to maximize the present value of θ times the cash flow stream is the same as choosing it so as to maximize θ times the present value of this stream. Maximizing a constant times the economic result is the same as maximizing the result itself. Sinn(2008) concludes that a cash flow tax that is implemented at a constant rate reduces the shadow price of the resource in situ exactly by the amount necessary to create behavioral neutrality.

Second, Sinn(2008) regards an ad-valorem sales tax on the extraction of carbon. It is otherwise similar to cash flow tax but the extraction costs are not tax exempt. Here, a star indicates the ad-valorem tax. Sinn(2008) states that the tax forces a wedge between the consumer price P and the producer price, $\theta^* P$. This kind of a tax might be hard to implement as well. Though, Sinn(2008) argues that a consumption tax levied by the consuming countries would be possible, and would have the same allocative effects as the sales tax.

Sinn(2008) claims that if extraction costs are zero or only negligible, the consumption tax is as neutral as a cash flow tax, because without extraction costs it becomes a cash flow tax. As the stock of the fossil fuel resource that will be extracted in the long run is given, there will not be any supply reactions at any point in time and the only impact the tax has is that it makes the producers of carbon worse off by effectively expropriating part of the stock in situ.

Sinn(2008) continues that if there exists extraction costs, the consumption tax loses its neutrality. As the resource owner tries to maximize the present value of the cash flow stream $\theta^* RP - g(S)R$ which is equivalent to maximizing the present value of the stream $RP - (g(S)R/\theta^*)$ it is obvious that equation (7) changes to

(14) $$i + \pi = \frac{\dot{P}}{P - \frac{g(S)}{\theta^*}}$$ (constant ad-valorem tax)

which implies that, with any given values of i, π and P, $\dot{P}$ is becoming smaller. Thus, as Sinn(2008) adds, the extraction path becomes flatter, meaning less extraction in the present and more in the distant future. This emphasizes the basic policy conclusion of the Stern Review, that a world-wide tax on the consumption of carbon would diminish the greenhouse effect. However, Sinn(2008) points out that there are two significant caveats. First, the tax only functions through increasing the marginal extraction costs. Sinn(2008) claims that as marginal extraction costs are only going to be a small fraction of the price of the extracted resource, the impact on the extraction path may be minuscule. Sinn(2008) adds that, for instance, in 2006 the average production costs of crude oil amounted to only about 15% of the average spot price. The second is that the tax rate is assumed to be constant. Sinn(2008) asks if resource owners will rely on governments keeping the tax rate constant over time even though the environmental concerns are becoming more and more popular?

Sinn(2008) answers this question with an intertemporal optimization model depicting the market reactions to a changing ad-valorem tax rate. To explicate the implications of a changing tax rate Sinn(2008) returns to the cash flow tax , which coincides with the ad-valorem tax if extraction costs are zero. Assuming that the tax factor changes at a constant rate $\hat{\theta}$:

(15) $$\theta(t) = \theta(0)\, e^{\hat{\theta} t}, \hat{\theta} = \text{const.}$$

Sinn(2008) concludes that as the resource owner maximizes the present value of his cash flow net of the tax, (15) together with the neutrality of a constant cash flow tax demonstrates that he behaves as if he used a discount rate $i + \pi - \hat{\theta}$ instead of only $i + \pi$ as assumed before. Thus, instead of (14), Sinn(2008) gets

(16) $$i + \pi - \hat{\theta} = \frac{\dot{P}}{P - g(S)}$$ (changing cash flow tax).

Equation (16) demonstrates that with a changing tax rate, the neutrality of a cash flow or consumption tax disappears, making room for considerable intertemporal distortions. Sinn(2008) claims that with an increasing tax rate, i.e. with $\hat{\theta}< 0$, $\dot{P}$ would have to be higher, with any given P indicating steeper price and extraction paths meaning more extraction in the presence, which indicates exacerbating rather than mitigating the problem of global warming. Sinn(2008) adds that this also applies to the ad-valorem tax on the extraction rate if the transaction costs are negligible.

Sinn(2008) argues that when extraction costs are assumed, this problem diminishes, and with sufficiently strong extraction costs, current extraction may even decrease. Sinn(2008) concludes that in general, with or without extraction costs, the borderline case where taxation is neutral for the extraction is characterized by an absolute tax wedge that grows at the discount rate, i.e. in the current model at the rate $i + \pi$, so that the discounted revenue loss per unit of the resource extracted is constant. Sinn(2008) adds that as the absolute tax wedge with an ad-valorem tax is $\tau *P$, the borderline case is characterized by

(17) $\hat{\tau}^* + \dot{P} = i + \pi$ (borderline case for ad-valorem consumption tax neutrality).

According to Sinn(2008) faster increase of the tax wedge implies the resource owners anticipate extraction and a smaller increase implies they will delay extraction. Using (7), Sinn(2008) converts condition (17) to

(18) $\hat{\tau}^* = (i + \pi)\frac{g(S)}{P(R)}$ (borderline case for ad-valorem consumption tax neutrality).

Sinn(2008) claims that this condition proves that, without extraction costs ($g(S)=0$), a constant ad-valorem tax would be neutral, $\hat{\tau}^* = 0$. With extraction costs, P increases at a lower rate and thus tax neutrality is compatible with a rising ad-valorem tax rate. Sinn(2008) adds that if the tax rate increases faster than in the borderline case, the extraction path will again become steeper, and current extraction increases. If the unit extraction costs are small relative to price, this case remains a plausible possibility. Thus, Sinn(2008) concludes that the risk that ad-valorem taxes levied on emission of carbon dioxide are fruitless or even hazardous is far too big to justify their implementation.

Sinn(2008a) demonstrates his argument in R,S space using again the cash flow tax, that with $\hat{\theta}< 0$ produces qualitatively the same result as an ad-valorem consumption tax with $\hat{\tau}^* > (i + \pi)\, g(S)/ P(R)$. Sinn(2008) reports that from (10) and (16) it follows that, instead of (11), we now have

(19) $\frac{dR}{dS} = \varepsilon\, (i + \pi - \hat{\theta}) \left(1 - \frac{g(S)}{P(R)}\right)$ (changing cash flow tax) .

The normative condition (12) remains valid.

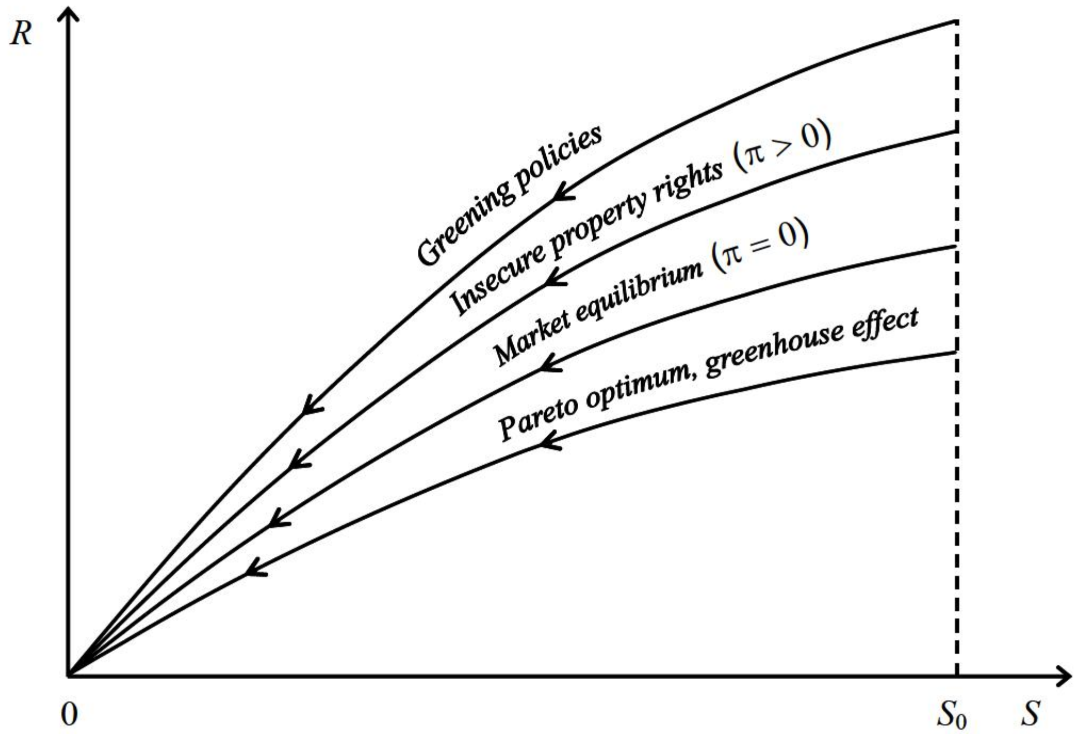

Figure 2: The green policy paradox(Sinn 2008)

These results are demonstrated in figure (2) by Sinn (2008). The three lower paths are the same as in figure 1. The highest path is the path resulting from an increasing cash flow tax rate or an ad-valorem tax on the flow of extraction whose increase satisfies the condition $\hat{\tau}^* > (i + \pi)\ g(S)/\ P(R)$. According to Sinn(2008) it demonstrates a green policy paradox as an increasing cash flow or sufficiently increasing consumption tax rate will make the flow of current extraction even higher, and accelerate global warming even more, than would be the case without government policies.

Unfortunately, as Sinn(2008) argues, this result also applies to the bulk of other green demand reducing policies. It applies to measures that directly reduce the demand for fossil fuels like better insulation of homes, lighter cars and traffic reductions as well as to green policy measures that reduce demand for fossil fuels by providing non-fossil energy alternatives like the generation of electricity from wind, water, sunlight and biomass. According to Sinn(2008) also nuclear energy, nuclear fusion in particular, belong into this category because the electricity generated from nuclear energy could be used to produce hydrogen, which would facilitate storing and transportation of the energy provided. Sinn(2008) adds that pellet heating, bio diesel, heat pumps or solar heating are also measures that reduce the demand for fossil fuels because the energy comes from other sources. Modern diesel engines and optimized power plants are examples of devices that reduce the demand for fossil fuels because they increase the technical efficiency of combustion processes.

Sinn(2008) concludes that all of these measures are currently debated in the industrialized countries, and governments grant subsidies to develop them further. As the world keeps warming up and the more people understand the mechanics of the greenhouse effect, public support for such measures will rise so that the demand reducing effect becomes more intense. Sinn(2008) claims that this kind of progress will have similar consequences for the development of the prices resource owners will be able to charge as a general ad-valorem tax on carbon consumption that increases in time. Sinn(2008) re-interprets the tax wedge τ *P assumed as a demand wedge that pushes the demand curve downward relative to the position that would have been without the government policies aiming at reducing the production of carbon dioxide. Sinn(2008) argues that $\hat{\theta}$*P in this case is the observable market price, and P is the price that would have prevailed without the demand reducing policies. Thus, this anticipation of a piecemeal greening of public policies that satisfies the condition $\hat{\tau}^* > (i + \pi)\ g(S)/\ P(R)$ will actually give resource owners the incentive to anticipate the price weakening effect by extracting more in the present and less in the future. Sinn(2008) states that the extraction path is shifted upward, which, is the wrong direction aggravating the distortion that already results from insecure property rights and the greenhouse effect. Thus, the demand reducing measures may even worsen the global warming problem, because they induce the resource extracting countries to accelerate their extraction. Sinn(2008) concludes that as these measures take place the current price of carbon falls enough to induce the unconstrained countries to buy more so that the reduction in consumption of the constrained countries is overcompensated.

5. Green Paradox in literature

The literature of economics of climate change uses the model of exhaustibility of energy resources by Hotelling(1931) as the starting point. Sinclair(1992) used the basic model of exhaustible resource markets and combined it with climate change damages to note that carbon taxes as such would not necessarily lead to decreasing emissions from fossil fuels. Sinclair(1992) argues that the key decisions of fossil fuel resource owners is not how much to produce it but when to extract it. Already Sinclair(1992) reasoned that climate policy, a tax on fossil fuels, should aim to postpone the extraction of fossil fuels, transfer supply from the present to the future. This means that under an optimal carbon tax fossil fuel owners could increase their net present value rent by postponing supply. Ulph and Ulph(1994) included to the model the notion that the marginal damages from fossil fuel related carbon emissions are not constant over time but the higher the higher are the atmospheric CO2 concentrations. Thus, Ulph and Ulph(1994) argued that as the marginal damages increase, the carbon taxes should increase in line, to be reduced in the future as the climate system slowly returns to the natural state.

Hoel and Kverndokk(1996) included rising extraction costs for fossil fuels to the analysis, as well as the existence of a substitute energy source, a backstop, available at constant marginal cost and at infinite supply. The backstop analysis is significant as it verifies the fact that economic production is possible even without the use of fossil fuels. It prevents the seller to setting the prices too high as it gives the buyer another option. Hoel and Kverndokk(1996) conclude that optimal climate policy will shift part of current oil use to the far future, when the CO2 concentrations in the air have cleared from their peak. In the literature it is commonly assumed, such as Nordhaus(2002) does, that technological change in substitutes will be generated by higher conventional energy prices resulting from resource scarcity as well as by climate policy. Nordhaus(2002) assumes that finite resource prices are constant to endogenous changes in the cost of the rising substitute technology.

Sinn(2008) identifies the possibility that hazardous supply side effects may arise in the case of carbon taxes and emphasized the term green paradox. Hoel(2008) supports Sinn's(2008) view using a model of investment in a backstop technology, and extends earlier work on the optimal fossil fuel taxation. Grafton, Kompas and Van Long(2010) show that these arguments are equally valid in the context of biofuels subsidies.

In the literature of climate policies and green paradox there exist multiple options on how to mitigate global warming. Here we consider carbon taxes, emissions caps, biofuel subsidies, deposit markets and backstop adoption in various settings that differentiate in assumptions about market parameters and on how the climate policies are announced and implemented. Various studies differ among other things in their assumptions about extraction costs, scarcities, price elasticities, and in substitutability of fossil fuels and clean technology, as well as in their assumptions on supply and demand elasticities and extraction capacities. There are also differences in market structure assumptions, as for example others consider fossil fuel producers as a monopoly and others as an oligopoly. Researches also vary on how the damages of climate change are internalized.

The fact whether the clean technology and the fossil fuels are handled as perfect or imperfect substitutes also divides researchers. Sinn(2008) correctly argues that it is unlikely to find a backstop that would be a perfect substitute for fossil fuels. For example in aviation electricity there is no substitute for fossil fuels and fuel, for example hydrogen, made from electricity is no perfect substitute either due to its low energy density. Thus in real world fossil fuels and clean resources are likely to be imperfect substitutes.

5.1. Biofuel subsidies

First we consider subsidies given to biofuel producers, and what are the effects on extraction and carbon emissions. Grafton, Kompas and Van Long(2010) approach the problem of green paradox studying if subsidies for biofuel production causes reactions of the fossil fuel supply side that overwhelm the substitution to biofuels. Grafton, Kompas and Van Long(2010) show that, under a wide range of parameter values, subsidies for biofuels will increase the extraction rate of fossil fuels in the short and medium term, and thus possibly lead to the green paradox. Grafton, Kompas and Van Long(2010) show also that the structure of energy demand, isoelastic versus linear, can deteriorate or strengthen the occurrence of the green paradox.

5.1.1. Biofuels

Biofuels have the potential to reduce greenhouse gas emissions and thus biofuel subsidies have been publicly promoted about their potential environmental benefits. Grafton, Kompas and Van Long(2010) report that the support for biofuel subsidies is quite strong regardless of the fact that the first-best policy to control carbon emissions would be to levy a carbon tax or a cap-and-trade scheme. There has been an assumption that increasing the supply of an available substitute, as biofuel, would depreciate the price of fossil fuels, thus lowering the incentive of fossil fuel owners to extract. However, Grafton, Kompas and Van Long(2010) argue that, if fossil fuel resource owners optimally extract their reserves and expect continuing or growing subsidies for biofuels then resource owners may increase their present extraction rate. Grafton, Kompas and Van Long(2010) agree with Sinn(2008) that it is even possible that this supply-side effect may more than offset the substitution effect from fossil fuels to biofuels and increase emissions leading to a green paradox. Though, as Grafton, Kompas and Van Long(2010) remind, this would depend on assumptions made, including assumption about the direct reduction in carbon emissions that arises from the substitution from fossil fuels to biofuels. There is some debate about to which extent this direct substitution reduces greenhouse gas emissions and Grafton, Kompas and Van Long(2010) use a reduction in emissions of 12% for ethanol and of 41% for biodiesel.

5.1.2. Weak Green Paradox

Grafton, Kompas and Van Long(2010) show that policies designed to reduce emissions by subsidizing biofuel production may instead increase fossil fuel extraction and cause the green paradox. Grafton, Kompas and Van Long(2010) determine this as a weak green paradox. As a strict green paradox Grafton, Kompas and Van Long(2010) define the outcome when increased fossil fuel consumption raises greenhouse gas concentration levels in the atmosphere. This greenhouse gas concentration levels depend on many factors such as future technological change that may have an effect on extraction costs, the decrease in emissions from biofuel-fossil fuel direct substitution, and the impacts of emission concentration levels on the decay rate of carbon in the atmosphere.

Grafton, Kompas and Van Long(2010) develop sufficient conditions under which the weak green paradox would hold in terms of the direct subsidization of biofuels production or quantitative regulations that ensure minimum targets of biofuel consumption. Their analysis concentrates on the supply side responses and the resulting general equilibrium changes in price and quantity paths.

5.1.2.1. The model of biofuel subsidies

Grafton, Kompas and Van Long(2010) develop a model of energy demand in a perfectly competitive world, with two consumption goods, a numeraire good, leisure, and a manufactured good. Fuels are used as an input for the manufactured good, thus, the demand for the manufactured good increases the demand for fuels. Grafton, Kompas and Van Long(2010) assume two types of fuels, fossil fuels and biofuels, that for simplicity are assumed to be perfect substitutes. Grafton, Kompas and Van Long(2010) argue that if an increase in the subsidy factor brings the exhaustion date closer to the present, then the weak green paradox is confirmed.

Grafton, Kompas and Van Long(2010) assume that biofuel producers receive a constant ad valorem subsidy rate for each unit sold. The suppliers of fossil fuels are assumed to be farsighted and perfectly competitive firms, thus, the suppliers of fossil fuels can perfectly forecast the equilibrium price path which they take as given. The marginal cost of extraction is assumed to be a constant. Grafton, Kompas and Van Long(2010) conclude that if extraction rates are strictly positive over some time interval then, by Hotelling's Rule, the net price must increase at a rate equal to the rate of interest. Grafton, Kompas and Van Long(2010) define the demand for fossil fuels as the difference between the demand for fuels and the supply of biofuels.

As considering a special case where the fuel demand function and the supply function of biofuels are both linear, Grafton, Kompas and Van Long(2010) report a result that does not support the weak green paradox. Under perfectly competitive extraction, if extraction costs are zero, a rise in the biofuel subsidy factor will have no impact on the time of exhaustion of the resource stock. If extraction costs are positive, a rise in the biofuel subsidy factor will postpone the date of exhaustion of the resource stock.

Grafton, Kompas and Van Long(2010) also consider a nonlinear demand because with linear demand, the demand for fuels becomes zero at some finite price. Grafton, Kompas and Van Long(2010) add that it is commonly argued that the demand for fuels is always positive at any finite price. Grafton, Kompas and Van Long(2010) suppose that to produce one unit of the manufactured good needs one unit of fuels and one unit of labor. They assume perfectly competitive market and constant returns to scale in the manufactured good industry. Now the price of the manufactured good is equal to its unit cost, which is sum of the price of fuels and wage rate. Under these assumptions, Grafton, Kompas and Van Long(2010) report that an increase in the subsidy factor will bring the exhaustion date forward under some plausible specifications of parameter values.

Grafton, Kompas and Van Long(2010) also show some numerical examples of their base-line scenario, assuming interest rate, r = 0.05, demand elasticity $\varepsilon = 1$, supply elasticity of biofuels $\mu = 1$. The reserve size is assumed to be large enough so that under this base-line scenario, the exhaustion time is $T = 100$ years. Now Grafton, Kompas and Van Long(2010) show that, starting at the initial subsidy factor $z = 1$ an increase in z leads to an earlier exhaustion date, that is,

$$\frac{dT}{dz} = -2.09$$

Thus, the weak green paradox holds if the reserve size is such that $T = 100$. To find out if this result is sensitive to the size of the reserve Grafton, Kompas and Van Long(2010) vary the reserve size so that T varies from 50 years to 200 years, and find that dT/dz remains negative, and not far different from -2.09. Table 1 from Grafton, Kompas and Van Long(2010) in the appendix shows the value dT/dz for different reserve sizes. Table 2 reports their considerations on different initial subsidy levels, and shows there is a weak green paradox for this set of parameter values. Keeping other parameter values set, Grafton, Kompas and Van Long(2010) also consider different values for demand elasticity, ε, of the manufactured good, and these results are reported in their Table 3. Table 4 shows the considerations differing the values for supply elasticity of biofuels, μ. Grafton, Kompas and Van Long(2010) find that the weak green paradox holds for a wide range of μ. Only with the exception of the supply elasticity of biofuels being small, an increase in the subsidy rate will accelerate the exhaustion of fossil fuels.

5.1.2.2. Cartel extraction

Grafton, Kompas and Van Long(2010) also take into consideration cartel extraction assuming that oil is supplied by a cartel that behaves like a monopolist, and that the monopolist takes the subsidy factor as a given constant. Grafton, Kompas and Van Long(2010) assume that the monopolist's extraction equals the demand for fossil fuels. The optimization problem of the monopolist comprises of choosing a time path of price and a exhaustion date to maximize the present value of its flow of discounted profit.

To find out how an increase in the subsidy factor affects the extraction path, Grafton, Kompas and Van Long(2010) consider a few special cases. First, they assume that the demand function for fuel and the supply function of biofuel are both linear. Then, under monopoly extraction, if extraction costs are zero, an increase in the biofuel subsidy factor will have no impact on the date of exhaustion of fossil fuel, and on the other hand, if extraction costs are positive, an increase in the biofuel subsidy factor will postpone the time of exhaustion of the fossil fuel resource stock. As Grafton, Kompas and Van Long(2010) assume both demand function for fuel and the supply function of biofuel as non-linear functions, it appears that the weak green paradox is a possibility when fossil fuels are supplied by a cartel.

5.1.2.3. Two countries

Grafton, Kompas and Van Long(2010) also consider the case where there are two countries, home and foreign, with different energy policies. There is no biofuel production in the foreign country and home country biofuels are not exported to the foreign country, because of high transport costs or other barriers to trade, or because the production subsidies are only given to domestic consumption. Extraction costs are zero, there is perfect competition and the market sizes of the both countries are the same.

Grafton, Kompas and Van Long(2010) conclude that with a positive constant subsidy factor, the world equilibrium consists of two phases. Under the first phase, fossil fuels are consumed in both countries. The first phase ends at an endogenously determined time, T^u. In the second phase, fossil fuels are only used in foreign country, and fuel demand in the home country is entirely fulfilled by biofuels. This phase ends at time T^w, when the world price of fossil fuels reaches the choke price and the foreign country's demand for fossil fuels becomes zero. Now Grafton, Kompas and Van Long(2010) reveal that an increase in the subsidy factor will lengthen the second phase and may shorten the first phase.

5.1.2.4. Stock-dependent extraction costs

Grafton, Kompas and Van Long(2010) investigate the possibility of a weak green paradox when the extraction costs are stock-dependent and increasing as the remaining stock falls. Fossil fuel firms are assumed to be perfectly competitive and to take the price path as given. Grafton, Kompas and Van Long(2010) consider two possible scenarios. First, the marginal cost of extracting the last bit of oil, is high, but still below the choke price for fossil fuels, and thus the whole fossil fuel stock will eventually be exhausted. In the second scenario, the marginal cost of extraction is larger than the choke price for fossil fuel, and thus as the resource level falls enough owners will abandon their resources without exhausting them.

Grafton, Kompas and Van Long(2010) include in the Hotelling Rule the fact that the marginal extraction cost is stock-dependent and the assumption that firms internalize the added future cost caused by its current extraction. This internalized Hotelling Rule follows from optimizing behavior of far-sighted firms in the absence of externalities.

Grafton, Kompas and Van Long(2010) conclude that with the stock-dependent extraction costs and finite exhaustion date, weak green paradox holds if a marginal increase in the subsidy factor leads to an earlier exhaustion date. Grafton, Kompas and Van Long(2010) show that under the linear demand function case the weak green paradox does not hold as an increase in the subsidy factor will postpone the date of exhaustion, and add that higher sensitivity of extraction cost with respect to the remaining stock leads to a later exhaustion time.

With the more general case of non-linear demand Grafton, Kompas and Van Long(2010) conclude that an analytical solution cannot be reached. Grafton, Kompas and Van Long(2010) argue that a small increase in the subsidy factor leads to an increase or a decrease in the exhaustion date depending on various parameters, particularly cost sensitivity. The numerical simulations of Grafton, Kompas and Van Long(2010) demonstrate that if extraction costs rise faster than the stock is exhausted, a small increase in the subsidy will delay the date of exhaustion. On the other hand, if extraction costs rise slower than the stock depletes, then an increase in the subsidy may bring the exhaustion date forward. Grafton, Kompas and Van Long(2010) illustrate this in their Table 5 that is displayed in the appendix. Grafton, Kompas and Van Long(2010) describe that it is possible to address a wide range of cases where fossil fuel stocks are exhausted earlier, and the weak green paradox holds.

The findings of Grafton, Kompas and Van Long(2010) do not implicate that the weak green paradox is a general result, but that actually, with linear demand and marginal extraction costs that linearly increase with accumulated extraction, and without technological change, fossil fuel deposits are discarded before exhaustion and a biofuels subsidy leads to a smaller overall consumption of fossil fuels. Thus, the weak green paradox does not hold in the long run. Grafton, Kompas and Van Long(2010) remark though that the long run is indeed very long, abandonment takes place at infinity, the weak green paradox is plausible in the short or medium term. Grafton, Kompas and Van Long(2010) conclude that depending on supply and demand elasticities, biofuel subsidies could increase fossil fuel extraction in the near future and, therefore, result in a weak green paradox.

5.2. Emissions cap

Next, let us examine emissions cap, as Eichner and Pethig(2009) study the determinants of carbon leakage and the green paradox in a two-period three-country general equilibrium model with finite endowment of fossil fuel where one country enforces an unilateral emissions cap in the first or second period. As that cap is tightened the magnitude of carbon leakage depends on the interaction of various parameters and elasticities, which specify the conditions for the green paradox. Eichner and Pethig(2009) establish these conditions under which global emissions increase in response to a tightening of the emissions cap, and argue that all determinants of carbon leakage from tightening the first-period cap work in opposite direction when tightening the second-period cap. Eichner and Pethig(2009) show that tightening the cap in second period does not necessarily cause the green paradox.

5.2.1. Emissions cap and carbon leakage

The three country economy of Eichner and Pethig(2009) consists of a fossil fuel exporting country, an abating country representing the coalition of countries that have committed to binding national emission caps and a non-abating country representing the rest of the world not taking action to curb emissions. Eichner and Pethig(2009) use the means of comparative static analysis to reveal how much carbon leaks into the non-abating country when the abating country tightens its emissions cap. Eichner and Pethig(2009) want to keep the focus on carbon leakage and thus do not consider environmental damage from emissions nor any optimal corrective policies. Leaving the environmental damage from the analysis differs strongly from Sinn's(2008) interpretation.

The emission caps can either be imposed directly or through a tax or through an emissions trading system, they are all equivalent in the model. The resource supplier in Eichner and Pethig's(2009) model follows a simplified Hotelling rule and no extraction costs are assumed. Eichner and Pethig(2009) do not discount the second period profits because the model does not include capital investment and hence the market rate of interest is zero. This assumption differs from most of the literature of green paradox.

5.2.2. Tightening the emission cap in the first period

Eichner and Pethig(2009) denote that in a competitive equilibrium if country A(abating) tightens its emissions cap in the first period the world market price of fossil fuel in terms of first-period consumption depreciates and first-period consumption becomes more expensive relative to second-period consumption. Consequently it is profitable for the firms in country N(non-abating) to enlarge their output and hence their fossil fuel consumption. According to Eichner and Pethig(2009) the price change of consumption good X in period 2, is the key determinant for the green paradox because it is crucial how large the reduction in price must be to bring about the necessary equilibrium condition. Eichner and Pethig(2009) also mention that the condition for the green paradox does not depend upon the pure rate of time preference.

Eichner and Pethig(2009) argue that with homothetic utility functions (not restricted to constant elasticity substitution functions) green paradox might occur. Eichner and Pethig(2009) argue that the lower the substitution elasticity the greater is the price effect and the more likely is the green paradox. Eichner and Pethig(2009) focus on the intertemporal substitution elasticity as a determinant of the green paradox noting, however, that the size of the threshold value also depends on the size of the price elasticity of demand for fossil fuel, which is entirely technology-determined.

Eichner and Pethig(2009) highlight the relevance of the production technology in country N and period 1 and the relevance of the interaction of supply and demand conditions for the green paradox. Eichner and Pethig(2009) claim that a highly elastic demand for fossil fuel in country N is conclusive to the green paradox. The elasticity is the higher the closer to one is the production parameter, i.e. the more the production function tends to be linear. Yet even if the production parameter is small the green paradox occurs if substitution elasticity, is sufficiently small. Eichner and Pethig(2009) sum up that the green paradox depends on the order of magnitude of the substitution elasticity, and production parameter, and that a profound discussion of the empirical estimates of these parameters is needed.

5.2.3. The size of the abating countries

Eichner and Pethig(2009) enlarge their model by considering the sizes of the countries by introducing a fixed world endowment of an internationally nontradable factor, land. The production functions are assumed as Cobb-Douglas. Eichner and Pethig(2009) note that in the absence of emissions capping the aggregate demand functions for fossil fuel are independent of the size of the countries. Eichner and Pethig(2009) interpret an increase in size of A as new countries joining the group of abating countries and consider that the new countries entering the abatement coalition commit to the same constraint as the other members.

Eichner and Pethig(2009) show that the conclusions are qualitatively same as before. Eichner and Pethig(2009) conclude that if the aggregate demand curve in second period, LM, would remain unchanged (which it will not) there would be carbon leakage but no green paradox. According to Eichner and Pethig(2009) the price of consumption good X in period 2 must decrease causing the LM curve to shift downward to a curve L'M'. To how far the curve LM shifts down depends on the determinants. Eichner and Pethig(2009) argue that a green paradox occurs when the demand conditions require a decline in the price of the consumption good which is so forceful that the second-period demand curve LM is forced to shift below the line L′M′. However, Eichner and Pethig(2009) add that this is less likely, the closer we are to a global coalition to reduce emissions in which all countries commit. Thus, as global coalition is reached no leakage occurs no matter how strong the downward shift of the curve LM.

When there exists a global coalition to cut the carbon emissions the model of Eichner and Pethig(2009) becomes a simple version of Sinn's(2008a) model, considering a single fuel demanding country representing the global coalition of all fuel demanding countries. Eichner and Pethig(2009) add that in this case carbon leakage and green paradox are trivially absent. However, as the problems of Kyoto protocol shows, the global coalition is not the most realistic scenario.

5.2.4. Tightening emissions cap in the second period

Eichner and Pethig(2009) also consider regulating emissions in country A both in the first and also in the second period. In qualitative terms, the conditions for carbon leakage and the green paradox are the same as under the policy of constraining only the emissions in period 1, when emissions in second period are unconstrained. Eichner and Pethig(2009) conclude that if the first-period cap is tightened and at the same time either the second-period cap is kept constant or not implemented at all the green paradox can be ruled out for sufficiently large values of substitution elasticity. In contrast, if the second-period cap is tightened and the first-period cap is kept constant the green paradox is excluded for sufficiently small values of substitution elasticity.

Eichner and Pethig(2009) summarize that all changes in parameter values that make the green paradox more likely when the first-period cap is tightened work in opposite direction when the second-period cap is tightened. Especially, the green paradox will probably occur when the second-period emissions cap is tightened, if it does not originate from strengthening the emissions control in the first period and vice versa.

Eichner and Pethig(2009) find the carbon leakage unavoidable and also that the green paradox may occur depending on the interaction of demand conditions, especially the elasticity of intertemporal substitution in demand, and supply conditions, particularly the price elasticities of fuel demand. Eichner and Pethig(2009) add that there are parameter constellations under which the green paradox may even occur when the emissions constraint is tightened in the first period instead of the second period. Thus Eichner and Pethig(2009) do not unambiguosly support Sinn's(2008) proposition which assumes the green paradox to originate from the gradually greening demand-reducing policies. Eichner and Pethig(2009) show that parameter constellations under which the green paradox is avoided, when the first-period cap is tightened, tend to induce a green paradox, when the cap in second period is tightened, and vice versa.

5.2.5. Limitations of the emissions cap model

Eichner and Pethig(2009) have excluded from their study many real-world complexities such as expanding the time horizon beyond two periods, or including stock-dependent extraction costs, capital accumulation and insecure property rights. Even though all of these aspects are empirically relevant, but according to Eichner and Pethig(2009), they do not seem to be at the core of the green paradox. Eichner and Pethig(2009) also are not taking a stance on the controversial debate on normative social discounting, time preference and intertemporal inequality aversion.

5.3. Asymmetric backstop adoption

Next, we consider introducing a backstop as a policy against the climate change. Van der Werf(2010) investigates backstop adoption and carbon emission paths in a two-region Hotelling model with one-sided climate policy and non-renewable resource consumption. Van der Werf(2010) assumes that fossil fuel resource is an internationally tradeable resource and that both regions have an equal share of the fossil fuel resource and a backstop technology. Van der Werf(2010) reports that in the case of a unilateral carbon concentration constraint, the non-abating region makes the final transition to the backstop before the abating region does and that one-sided climate policy does not result in international carbon leakage. Van der Werf(2010) argues that implementing a global intertemporal carbon budget instead of a stock constraint, the order of final backstop adoption is the opposite and that the emissions in the abating region are always lower.

5.3.1. Backstop

Van der Werf(2010) considers as a backstop a clean, renewable energy technology. Energy from a fossil fuel resource and a clean backstop are perfect substitutes. Van der Werf(2010) examines the social planner's solution to the problem, and as there are no market failures, both the decentralized economies give the same optimal extraction and consumption paths. The marginal cost of the backstop is constant and it is only domestically available. Van der Werf(2010) argues that the backstop can be considered as being solar energy, which is barely traded internationally.

Van der Werf(2010) investigates the order of backstop adoption by the two regions, that are identical in their endowments and preferences, and the carbon emissions path of the abating region, assuming that the resource is internationally tradable, and resource owners in the two regions take the one world price of the resource as given as well as the internationally determined interest rate. Van der Werf(2010) shows that the abating country need not be the first one to adopt the backstop, but that the order of final adoption of the backstop depends on the type of climate policy regulated.

5.3.2. Backstop Model

Van der Werf(2010) models carbon emissions and adoption of a clean backstop technology in a two-region model where emissions are caused by the use of a physically exhaustible fossil fuel resource. The study about carbon leakage is also incorporated. Van der Werf(2010) studies two types of unilateral climate policies with assuming that consumption only stems from energy use. First, policy is a stock constraint, or CO2 concentration target in the atmosphere, which is designed to achieve the stabilization of greenhouse gas concentrations in the atmosphere at a safe level. However, there is scientific uncertainty on how concentration levels affect the temperature levels, and thus, Van der Werf(2010) uses also another policy, which is to restrict global cumulative emissions over time. Such a policy implicitly inflicts a global cumulative carbon budget, which means that some stocks of the world's fossil fuels will have to be left in the soil.

Van der Werf(2010) argues that climate policy needs to be studied in the context of exhaustibility of energy resources with the model of Hotelling(1931). Van der Werf(2010) combines the studies of the adoption of a clean backstop technology and the open economy in the context of a exhaustible resource. If assuming, for instance as Hoel(2010b) does, the non-renewable resource not physically exhaustible, but that its use declines in time as the unit extraction costs increase with cumulative extraction, fossil fuel resource use will be positive for all finite time. However, as Van der Werf(2010) adds, as treated as a physically exhaustible resource, and assuming the marginal cost of the backstop sufficiently high, the resource stock will be deployed in finite time, and the economy finally only uses the backstop.

Stock of carbon increases due to emissions from both countries with one unit of resource consumption causing one unit of emissions. Van der Werf(2010) assumes the stock to decline due to natural decay, and uses exponential decay, that is a generally used approximation. The natural decay of carbon in the atmosphere occurs by natural sinks like forests and the oceans. Van der Werf(2010) assumes no storage of the resource, hence, at each point in time, each region has to decide how much resource it should supply to the world market, and how much energy it should consume, both of the resource and of the backstop. If domestic extraction differs from domestic consumption, the region increases or lowers claims on the resource of the other region. The Hotelling rule that the scarcity rent of the resource has to grow at the rate of time preference applies. Van der Werf(2010) argues that as long as the cap on the stock of CO2 is not yet binding, the carbon price needs to grow. Utility only comes from the consumption of energy.

5.3.3. Unilateral stock constraint

Van der Werf(2010)studies the emission path in the abating country and backstop adoption in the two countries with a unilateral stock constraint. Van der Werf(2010) assumes a stock constraint target for the abating region of 450 ppm CO_2 concentration level, and that this constraint is feasible. The stock of CO_2 in the atmosphere is assumed to reach the unilateral ceiling at some date and to stay there for a non-zero period of time. Van der Werf(2010) presumes that initial emissions in the abating country are lower than under laissez-faire, which implies that the decline in the initial scarcity rent in abating country is larger than the initial shadow price for carbon emissions. The ceiling on the stock of CO_2 is assumed to cease to be binding at the instant as the non-abating country switches to the backstop.

Van der Werf(2010) examines the effects of high, intermediate and low marginal costs of backstop technology on the backstop adoption and emission paths. In the case of high marginal cost of the backstop, Van der Werf(2010) argues that the emission path of the abating country has an inverse N-shape. This implies that emissions first decline until the stock of CO_2 reaches the cap, then they increase until the constraint ceases to be binding, after which emissions decline again following a standard consumption path until the switch to backstop has been made. Emissions then become zero.

The result of Van der Werf(2010) that emissions increase in the abating country during the period for which the constraint is actually binding is rather surprising. Van der Werf(2010) argues that as the abating country wants global emissions not to be larger than aimed level once the stock of CO_2 reaches the cap, it cannot release more emissions than the difference between natural decay and emissions in the non-abating country. Since emissions in the non-abating country reduce over time, can the abating country increase its emissions in the period in which it wants global emissions to be constant and equal to natural decay. Van der Werf(2010) argues that since during some time phase, the abating country can consume less of the fossil fuel, more is available during time phases in which it is not confronted with positive carbon price. Van der Werf(2010) adds that as a result, the scarcity rent of the abating country is lower than under laissez-faire, and hence lower than in the non-abating region. Therefore, the non-abating region adopts the backstop before the abating region does.

If the marginal cost of the backstop is intermediate or sufficiently low, Van der Werf(2010) argue that the abating region will adopt the backstop during the phase for which the cap on the stock of CO_2 in the air is binding, and energy consumption in the abating country is continuous at each point in time. Van der Werf(2010) argues that now the emission path of the abating region has an inverse N-shape with a downward jump at the instant as the stock of CO_2 reaches the ceiling. Thus, emissions decline until the stock of CO_2 reaches the cap at which instant they jump down. Then they increase until the constraint ceases to be binding, after which emissions decrease again and become zero once the switch to the backstop has been made.

Van der Werf(2010) states that the abating region has two distinct periods when the backstop is used. Originally only fossil fuel is used. At the instant at which the ceiling of CO_2 is reached the fossil fuel is partly substituted by the backstop and as long as the ceiling is binding the abating country gradually uses more of the fossil fuel until only it is used. Van der Werf(2010) states that as the price on emissions decreases over time, and as emissions by the non-abating country reduce, the abating region can rise its emissions and after some time period the backstop is no longer used. The second period of backstop use is the end-phase in which only the backstop is used. Van der Werf(2010) argues that as the scarcity rent in the abating country increases over time, the abating country switches to the backstop again. Now its fossil fuels are exhausted. Van der Werf(2010) argues that also in this case the non-abating region adopts the backstop before the abating region does, but only after the cap ceases to be binding.

The last case of Van der Werf(2010) is the case of low marginal cost of the backstop. Now Van der Werf(2010) argues that energy consumption and hence utility of the non-abating country is no longer continuous. Van der Werf(2010) still claims that the emission path of the abating country has an inverse N-shape with first a downward jump and then an upward jump. Emissions reduce until the stock of CO2 in the air reaches the ceiling at which instant they jump down. After that emissions increase until the non-abating country switches to the backstop, at which instant emissions jump up and then decline again. After the switch to the backstop emissions are zero. Van der Werf(2010) argues that also in this case he abating country has two distinct periods of backstop use.

Van der Werf(2010) states that after the non-abating region switches to the backstop and until the final switch to the backstop by abating country, emissions in abating country are larger than those in non-abating region, although initially the abating country still has effective climate policy. Van der Werf(2010) claims that the abating region must have larger emissions than the non-abating region for some time period, for otherwise it would not deploy its fossil fuel resource, which cannot be optimal.

Chakravorty, Magne, and Moreaux(2006) also examine a stock constraint, rather than optimal climate policy, with a physically exhaustible resource by assuming an imposed ceiling on the stock of carbon in the air. Chakravorty et al.(2006) report that at one point in time, emissions from the resource use become smaller than natural decay of the stock of pollution, the stock begins to decline and thus the ceiling no longer binds. With a fixed demand curve, the backstop will be used during the period when the ceiling is binding, only if its marginal cost is sufficiently low. However, Chakravorty et al.(2006) claim that, the backstop will be used simultaneously with the fossil fuel, until the resource stock gets exhausted. If initial demand is sufficiently high but decreases fast over time as the demand curve is inward-shifting, the backstop will be used in two disjoint phases, if its marginal cost is sufficiently low. Chakravorty et al.(2006) argue that in this case the backstop will first be used jointly with the fossil fuel, as the ceiling becomes binding, with increasing resource use until the backstop becomes too costly. The second period is the end period when all fossil fuel stocks are exhausted.

Van der Werf(2010) examines how the non-abating country responds to an emission reduction in the abating country, and to what extent this possibly leads to carbon leakage, and argues that over time each country consumes the fossil fuel resource equal to its own endowment. Van der Werf(2010) shows that the non-abating country will not change its emission path in response to a reduction in emissions in the abating country, which denotes that a unilateral climate policy will not lead to any carbon leakage. This extension from the standard closed-economy non-renewable resource model to a two-country model, leads in a totally opposite result than the suggestion by Sinn(2008,2009) that a unilateral climate policy might be completely ineffective. Van der Werf(2010) states that unilateral climate policy is completely effective, and that this result is independent of whether a backstop technology is available.

Van der Werf(2010) reports that the result stems from the fact that both of the countries will consume equal to their own resource stock in order to meet their transversality conditions. The non-abating country follows a laissez-faire consumption and emission path which are not affected by the unilateral climate policy, and thus the non-abating country does not adjust its consumption and emission path.

5.3.4. Global carbon budget

Van der Werf(2010) also studies emission paths and backstop adoption with a unilaterally imposed intertemporal global carbon budget. As it is uncertain how concentration levels impact to temperature increases, and thus as the eventual equilibrial global mean temperature remains uncertain, it is important to consider to restrict global emissions. Van der Werf(2010)proposes a restriction in the 1750-2500 period to

1trillion tonnes carbon, meaning 3.67 trillion tonnes CO_2 . Van der Werf(2010) notes that such a global carbon budget implies that some of the stocks of fossil fuels, will have to be left in the ground. Van der Werf(2010) claims that policies based on limiting cumulative emissions of carbon dioxide are likely to be more solid to scientific uncertainty compared to emission rate or concentration targets.

Van der Werf(2010) considers a carbon budget without taking natural uptake into account, and as a result the abating region has to consume less than its total endowment. Van der Werf(2010) argues that the social planner in abating region can simply accomplish this by maximizing intertemporal utility subject to the resource constraint. As a consequence, there is no price on carbon emissions. Van der Werf(2010) adds that the smaller resource endowment simply results in a higher resource scarcity rent in the abating country. Van der Werf(2010) argues that as a result of introducing the carbon budget, emissions in the abating country are always lower than in the non-abating region, and the abating country adopts the backstop earlier than the non-abating one.

Van der Werf(2010) claims that due to the higher scarcity rent in abating country emissions are lower and, hence, lower than those in the non-abating country at every point in time. The unilateral global carbon budget causes asymmetric adoption of the backstop. Van der Werf(2010) adds that since the growth rate of the scarcity rent is the same for both countries, a higher rent in abating country implies that it equals the marginal cost of the backstop sooner, and thus, the abating region adopts the backstop before the non-abating region does. Thus, Van der Werf(2010) gets the opposite result than before, and hence, which one of the countries make the final switch to the backstop first depends on the type of unilateral climate policy imposed.

As a conclusion Van der Werf(2010) argues that in the case where the abating country imposes a unilateral stock constraint, because of the natural uptake of carbon dioxide, the abating country can still exhaust its entire fossil fuel stock over time, provided that it postpones its emissions. Furthermore Van der Werf(2010) shows that unilateral climate policy does not have a impact on emission path of the non-abating country. Consequently, emission reductions in abating country are 100% effective. Van der Werf(2010) claims that this result is due to the intertemporal budget restriction of each region. Van der Werf(2010) explains that as consumption differs from extraction, and, thus, some fossil fuel is exported or imported, a stock of claims on the other county's resource stock grows or decreases. Since, both the resource price and the value of the stock of claims grow at the rate of interest at any point in time, and since both countries have to meet their intertemporal budget constraint, both countries consume and extract equal to their initial resource endowments. Thus, regardless of the policy used, Van der Werf(2010) argues that unilateral emission reductions are 100% effective, as the non-abating region does not modify its emissions in response to a abating country's climate policy.

5.3.5. Additional changes to the model of backstop

Van der Werf(2010) investigates how the results of his simple model are affected by different types of climate policy, the use of a second input in final good production, a non-stationary demand curve, and extraction costs.

The abating country could introduce a constraint on the flow of its emissions instead of a unilateral stock constraint or impose an optimal policy, with a trade-off between energy consumption and damages from the stock of carbon. Van der Werf(2010) claims that either way, the order of final backstop adoption will be the same as under a stock constraint, as in all cases the abating country has a lower scarcity rent than the non-abating country, due to the increased abundance after the implementation of climate policy. Van der Werf(2010) adds that neither the inverse N-shape in the emission path, nor disjoint backstop use, is found, as emissions in the abating country will be constant when constrained, and afterwards declining. As the optimal climate policy is considered, Van der Werf(2010) argues that for a closed world economy, when the stock of pollution is allowed to first increase and then decrease, global emissions decrease monotonically. Van der Werf(2010) continues that a declining emission path for the non-abating country in a two-country model then implies that the emission path of the abating country can take any shape, depending on the slopes of the path of marginal damages and the path of emissions for the non-abating country. Consequently, an inverse N-shaped emission path, or disjoint backstop use, cannot be excluded.

As another change to his model Van der Werf(2010) considers the introduction of a second input in the production of a final good. An imperfect substitute for the energy good could be a fixed factor such as inelastically supplied labor, or a stock of capital. Van der Werf(2010) describes that in both cases, there would be a second source of income for both countries. Thus, as Van der Werf(2010) claims, unilateral climate policy brings forth income effects, such that the abating country has a lower return on the second input and, therefore, a smaller intertemporal budget than the non-abating country. Van der Werf(2010) claims that as a consequence, the abating country consumes less than its own endowment, leading to a higher marginal utility of income and higher scarcity rent. This may result in a final switch to the backstop before the non-abating country, and international carbon leakage might occur for some time period. However, Van der Werf(2010) argues that the inverse N-shaped emissions path, is likely to be unaffected. The introduction of an imperfectly substitutable input, and the possibility of carbon leakage then, should be considered more closely, as a model with multiple inputs describes the real world situation better.

Van der Werf(2010) raises the question of what happens when the demand curve in the non-abating country is non-stationary. Currently there is increasing demand for fossil fuels in most developed and developing countries, partly due to increasing living standards within developing countries, and due to an increasing world population. Although the world population is expected to decline in the middle or second half of this century, the pace at which living standards increase, especially in China, cannot be infinitely sustained. Van der Werf(2010) claims that a study with backstop adoption in the case of a closed economy with a ceiling on the stock of carbon in the atmosphere, reveals that disjoint use of the backstop might occur in the case of an inward-shifting demand curve with small enough marginal cost of the backstop. Van der Werf(2010) argues that the inverse N-shaped consumption and emission path of the abating country remains as long as the demand curve in the non-abating region does not shift outwards at too high speed. Van der Werf(2010) adds, that if it does, emissions in non-abating country rise over time, and thus, emissions in abating region cannot rise when the ceiling is binding. However, a demand curve in non-abating country shifting inwards steepens the rising emission path in the abating country. Van der Werf(2010) concludes that shifting demand curves do not affect the result of zero carbon leakage, each still consumes equal to its own fossil fuel endowment.

Van der Werf(2010) argues that even when including stock-dependent extraction costs, these results are not affected, as each country starts with the same endowment. Van der Werf(2010) adds that stock-dependent extraction costs only matter if initial fossil fuel stocks differ, and a second asymmetry between the countries is introduced. Van der Werf(2010) argues that, in this case, the resource of the country with lowest extraction costs is consumed, until extraction costs are equal for both countries. Further asymmetries could, for example, be development or technology, or differing region sizes.

The limitation of the study of Van der Werf(2010) is that the fact that other countries are fossil fuel producers and other countries are only fossil fuel consumers is not considered. Van der Werf(2010) assumes that all countries have the same fossil fuel endowments, which is not the case in real world.

5.4. When to switch to a backstop

In this chapter, backstop is divided in clean and expensive, and a dirty and cheap backstop. Van der Ploeg and Withagen(2010) study the green paradox by solving a model of exhaustion of non-renewable fossil fuels followed by an exchange to a renewable backstop. Van der Ploeg and Withagen(2010) pay attention especially to timing of the change and the amount of fossil fuels remaining unextracted. Van der Ploeg and Withagen(2010) show that for relatively expensive but clean backstops such as solar or wind, the green paradox occurs. If the backstop is sufficiently cheap relative to marginal global warming damages, e.g., nuclear energy, the green paradox does not occur since then it is tempting to leave fossil fuels underground and thus limit emissions. Van der Ploeg and Withagen(2010) demonstrate that, in the absence of a tax on CO2 emissions, subsidizing the backstop might actually advance welfare.

In the design of optimal climate policy the optimal intertemporal use of fossil fuels needs to be determined in conjunction with any harmful effects this may have on climate change. Van der Ploeg and Withagen(2010) add that the optimal policy of extracting fossil fuels and mitigating climate change takes into account the order in which the fuels should be extracted. This way, differences in extraction costs as well as differences in the contributions the fossil fuels make to climate change accounts. Furthermore, the timing, order and rate of extraction together with the deployment of the backstop are essential for future welfare.

5.4.1. The Model of Backstops

Van der Ploeg and Withagen(2010) analyze the socially optimal switch from oil to a clean renewable backstop in a dynamic welfare analysis, where climate change comprises a crucial negative externality. Analysis includes stockdependent extraction costs and exhaustibility of some fossil fuels. Van der Ploeg and Withagen(2010) study the green paradox and analyze its consequences in a model that is almost analogous to the Sinn's(2008a), but Van der Ploeg and Withagen(2010) consider an approach where damage adversely affects social welfare. Van der Ploeg and Withagen(2010) define backstops as renewable energy resources that are perfect substitutes for fossil fuels and cannot be exhausted.

Van der Ploeg and Withagen(2010) study the outcome in a decentralized market economy and show that the social optimum can be sustained with a rising carbon tax. Van der Ploeg and Withagen(2010) also show that in the second best case where a rising carbon tax is infeasible, subsidizing the clean backstop need not lead to a green paradox if this encourages resource owners to leave more oil in the ground and to shift sooner to the clean backstop.

First, Van der Ploeg and Withagen(2010) review the situation where marginal extraction costs of the fossil fuels depend on the existing stock, and suggest that reducing the cost of supplying the renewable backstop may result in a positive remaining stock of the fossil fuels if the backstop price is lower than the marginal extraction costs at low resource stocks. Secondly, Van der Ploeg and Withagen(2010) distinguish between backstops according to their production costs and to the degree they increase the atmospheric concentration of CO2. Van der Ploeg and Withagen(2010) consider a backstop expensive if its production cost is larger than the maximal extraction cost of fossil fuels. Otherwise it is cheap. Van der Ploeg and Withagen(2010) normalize the emission ratio of the fossil fuel to unity. Thus, if the emission ratio for the backstop is smaller than unity, the backstop is cleaner in terms of CO2 emissions than oil or gas. If the emission ratio is zero, backstop is clean. A backstop is dirty if its contribution to CO2 emissions is larger than that of fossil fuels.

Van der Ploeg and Withagen(2010) consider different categories in energy production. Clean and expensive backstops such as solar and wind energy make no contribution to the accumulation of greenhouse gases, even though a lot of energy is needed to produce these technologies. Van der Ploeg and Withagen(2010) assume that these backstops are expensive, especially when increasing the capacity. There are also costs from intermittence. However, Van der Ploeg and Withagen(2010) claim that, the costs of renewable energy sources have fallen considerably, as solar and wind energy are currently 50% more expensive than conventional electricity, and this mark-up may not be that impressive when the renewable energy sources account for a much wider market share. Van der Ploeg and Withagen(2010) show that the green paradox exists even though the backstop is becoming cheaper provided that the backstop still remains expensive.

As another source of energy that does not increase CO2 emissions Van der Ploeg and Withagen(2010) consider nuclear energy, which is considered rather competitive already, if the cost of obsolete plants is neglected. Van der Ploeg and Withagen(2010) argue that when considering nuclear cheap the green paradox no longer holds. Thirdly, Van der Ploeg and Withagen(2010) consider carbon sequestration of electricity-generating industries, which is more expensive than conventional oil or gas but has lower carbon emissions. The fourth category consists of heavily polluting and expensive backstops as tar sands as such, because their reserves are wide. A great deal of energy is consumed in producing oil from tar sands and therefore CO2 emissions are at least 50% higher. There are also adverse effects on the livelihood of communities through large-scale leakage of toxic waste in groundwater and destruction of ancient forests. Van der Ploeg and Withagen(2010) show that in this case fossil fuel reserves will be fully depleted and that it is optimal to combine a CO2 tax ramp with a high although declining CO2 tax once the tar sands are in operation.

5.4.2. Switching from dirty fossil fuels to a clean backstop

Van der Ploeg and Withagen(2010) study optimal extraction of an exhaustible, nonrenewable energy resource with a backstop being introduced when oil prices become high enough. The backstop is assumed to be a perfect substitute for the nonrenewable resource and its supply is infinitely elastic. Van der Ploeg and Withagen(2010) add climate change externalities to social welfare, and thus add a convex function in past CO2 emissions to the utility function. Moreover, Van der Ploeg and Withagen(2010) assume no natural decay which means that they can abstract from the possibility of simultaneous use of backstop and fossil fuels. Van der Ploeg and Withagen(2010) assume quasi-linear preferences and that the per unit extraction costs of the non-renewable resource are a decreasing function of the in-situ stock. Therefore, as reserves decrease, unit cost of extraction increases.

Van der Ploeg and Withagen(2010) define that the social value of the nonrenewable resources, consists of the value of the stock of resources, and of the environmental value of keeping the stock in the ground. The modified Hotelling rule of Van der Ploeg and Withagen(2010) says that the rate of increase in the scarcity rent of the nonrenewable resource must equal the rate of time preference plus the sensitivity of the marginal cost of extraction to the stock of remaining reserves minus marginal climate change damages. According to Van der Ploeg and Withagen(2010) climate change damages indicate that it is socially optimal to exhaust the stock of fossil fuel reserves more slowly. A quickly increasing unit cost of extraction also slows down the exhaustion of fossil fuels.

Van der Ploeg and Withagen(2010) argue that the decentralized market economy does not internalize the damages from CO2 emissions and therefore leads to too fast extraction of fossil fuels. Van der Ploeg and Withagen(2010) claim that the present values of the social value of the remaining stock of fossil fuels and of the social cost of the emission stock vanish as time goes to infinity. Van der Ploeg and Withagen(2010) add that there is no resource extraction if the marginal utility of the resource is below marginal extraction costs plus the social cost of the resource. On the other hand, the backstop is used unless the marginal utility of energy is below the supply price. Thus, Van der Ploeg and Withagen(2010) assume that, for the initial stock of fossil fuel reserves, the marginal extraction cost is smaller than the maximum price of fuel and furthermore, that the maximum price of fuel is such that use of the backstop energy source is profitable.

Van der Ploeg and Withagen(2010) claim that as long as resource extraction takes place, the pollution stock increases and the per unit extraction costs increase as well. Moreover, since Van der Ploeg and Withagen(2010) abstract from natural decay of the CO2 concentration in the air, after resource extraction comes to an end there will never be resource extraction again.

5.4.3. When to switch to a clean backstop

The critical question of Van der Ploeg and Withagen(2010) is how much oil and gas should be left in the ground and when should the switch to the backstop take place. According to Van der Ploeg and Withagen(2010) there are two possibilities. Either no fossil fuels are left in situ it or not all fossil fuels are exhausted, which means that its value in situ must be zero. Thus it is required that the present value of marginal future global warming damages of one unit more of remaining oil reserves equals the marginal benefit of extracting an extra unit of oil at the switch to the backstop. Van der Ploeg and Withagen(2010) argue that this is strictly positive meaning that retaining more fossil fuels in ground denotes less carbon emissions and thus less climate change damages. If the aversion to global warming is small the resource will be fully exhausted at the switch to the backstop.

Van der Ploeg and Withagen(2010) use fossil fuels given the cost of extracting and the discounted value of marginal global warming damages, and argue that if these marginal damages are not considered very important and/or the discount rate is high, and costs of supplying fossil fuels are low relative to the cost of supplying the backstop, it is optimal to totally extract conventional fossil fuels before switching to the backstop. On the other hand, if marginal global warming damages are considered important as Stern(2007) does by adopting a very low discount rate, it is optimal to leave fossil fuels in the ground. Van der Ploeg and Withagen(2010) argue that if the backstop is really cheap, the climate problem is acute, and not much fossil fuel is left in situ, it is optimal to start using the backstop immediately.

Van der Ploeg and Withagen(2010) show that a lower cost of supplying the backstop results in a higher remaining stock of oil and gas at the time of the switch to the backstop. If the challenge of global warming is already acute and the initial stock of fossil fuels is high, it is also optimal to leave more fossil fuels in situ. For example Stern(2007) supports more patience and thus uses low value of the social discount rate which results in more concern with climate change damages in the distant future, and hence a larger stock of fossil fuels is left in situ. Van der Ploeg and Withagen(2010) argue that global warming externalities lead to slower depletion of the stock of the non-renewable resource in the socially optimal outcome.

Van der Ploeg and Withagen(2010) find three regimes for the social optimum. Firstly there will be full exhaustion of fossil fuels if the backstop is expensive compared to initial marginal extraction costs of oil and gas, the global warming problem is not too acute, and the social discount rate is high. Secondly, partial exhaustion will occur if the backstop becomes cheap enough as extraction of conventional fossil fuels becomes more expensive, the global warming challenge is more acute, and the discount rate is low enough. Finally, if the backstop is invariably cheaper than marginal extraction costs of non-renewable resources, CO2 concentration is remarkably high, and the social discount rate is very low, the backstop is immediately deployed and fossil fuel reserves remain unexploited. Van der Ploeg and Withagen(2010) add that as the cost of the backstop is reduced through technical progress or when a lower discount rate is used, one moves from the regime of full exhaustion to partial exhaustion and eventually zero exhaustion of fossil fuels.

The case that fossil fuel reserves are fully exhausted may be relevant for solar or wind energy. If marginal environmental damages and the maximum cost of supplying fossil fuels are high relative to the cost of the backstop, as is the case with nuclear energy, it is optimal only partially to exhaust non-renewable reserves to avoid global warming damages.

5.4.4. Green welfare and the cost of supplying the backstop

Van der Ploeg and Withagen(2010) estimate the effect of a marginal change in the cost of the backstop on green welfare and claim that if it is optimal to completely exhaust fossil fuel reserves, a lower cost of the backstop leads in faster switch to the backstop. Van der Ploeg and Withagen(2010) admit that due to discounting and convexity of climate change damages, it is commonly argued that more rapid depletion of oil reserves must result in worsening of green welfare. Though, Van der Ploeg and Withagen(2010) claim that this argument does not hold if the backstop is relatively cheap compared with marginal extraction costs of conventional oil and gas and the present value of marginal climate change damages. Nevertheless, a cheaper backstop always results in higher total welfare.

Van der Ploeg and Withagen(2010) claim that if the backstop is relatively expensive and the present value of climate change damages is not that high, it is optimal to completely exhaust conventional fossil fuel reserves. Lowering the cost of the backstop then forwards the time of exhaustion and switch to the backstop and moreover, constrains green welfare. However, Van der Ploeg and Withagen(2010) agree with Sinn(2008) in that, if the backstop is cheap and the global warming problem acute, it is not optimal to fully deplete conventional fossil fuel reserves. Van der Ploeg and Withagen(2010) remind that a cheaper backstop brings forward the change to the backstop even more and that it is optimal to leave more oil and gas in situ at the date of the switch. A lower cost of the backstop decreases extraction of fossil fuels as a greater proportion of reserves are kept in ground, which means lower climate costs.

5.4.5. Clean backstop and competitive market outcome

Van der Ploeg and Withagen(2010) study the social optimum in a competitive market economy, by considering behaviour of households and competitive resource owners. Households maximize their utility subject to the budget constraint. Van der Ploeg and Withagen(2010) assume that the fossil fuel company has access to the backstop which is equivalent to having a separate companies supplying the fossil fuel and backstop in competition with each other. Fossil fuel owners take the fuel price, the carbon tax and the backstop subsidy as given, as they maximize profits, subject to the depletion equation.

The Hotelling rule of Van der Ploeg and Withagen(2010) states that the rate of increase in the scarcity rent of fossil fuels must equal the rate of time preference plus the sensitivity of the marginal cost of extraction to the stock of remaining reserves normalized by the shadow price of fossil fuels. Van der Ploeg and Withagen(2010) continue that the shadow price increases more quickly than in the social optimum so that exhaustion takes place too fast in a market economy unless the CO2 tax corrects for this externality. Van der

Ploeg and Withagen(2010) add that there is no fossil fuel extraction if the fuel price is below marginal extraction costs plus the carbon tax. In addition, the backstop is used unless the fuel price falls below the supply price.

Van der Ploeg and Withagen(2010) assume that the market outcome has an initial period of time, where only fossil fuels are used at a decreasing rate and afterward only the backstop is used. Van der Ploeg and Withagen(2010) state that the backstop is deployed when the fuel price has gone up to the cost of the backstop, net of the subsidy. Van der Ploeg and Withagen(2010) argue that since after the transition to the backstop, consumption of the backstop decreases in its cost, discounted future welfare at the time of the switch is obtained as the present value of the utility of consuming the backstop. Van der Ploeg and Withagen(2010) add that if any fossil fuels are left in the ground, their value is zero and the stock remaining increases in the tax rate on fossil fuels and the backstop subsidy.

As Van der Ploeg and Withagen(2010) argue, if the marginal extraction costs of fossil fuels are less than the net cost of the backstop, non-renewables must be fully depleted before the backstop is introduced. In that case, a backstop subsidy leads to an earlier exhaustion of fossil fuels, which means that green paradox occurs. As it is more than likely that all of the fossil fuel resources known today will be exhausted, the green paradox will most certainly occur when the cost of the backstop is relatively high. If the marginal extraction costs of non-renewables are more than the net cost of the backstop, the resource will not be fully exhausted and a backstop subsidy indicates that more fossil fuels are left in situ.

Van der Ploeg and Withagen(2010) consider a specific exponential tax schedule in a decentralized market economy that allows to derive the optimal date to switch to the backstop. Van der Ploeg and Withagen(2010) use linear demand function and assume that the cost of the backstop is less than the maximum price. Again Van der Ploeg and Withagen(2010) distinguish three regimes. First, there will be full exhaustion of oil and gas if the backstop is relatively expensive compared to initial marginal extraction costs of fossil fuels. A backstop subsidy reduces the date of the switch to backstop which implies that the stock of fossil fuels is depleted sooner. On the other hand a higher unit cost of fossil fuel extraction increases prices, reduces demand and thus decelerates extraction. Van der Ploeg and Withagen(2010) consider it interesting that, if oil and gas are entirely exhausted, an exponential carbon tax ramp does not have an effect on the date of the switch to the backstop and does not affect the fossil fuel extraction trajectories.

Second, a partial depletion of non-renewables will occur if the backstop becomes cheap enough as fossil fuel extraction becomes more costly. Van der Ploeg and Withagen(2010) argue that now subsidizing the backstop or increasing extraction costs of fossil fuels leads to a larger final in-situ stock of fossil fuels and a more rapid switch to the backstop. Van der Ploeg and Withagen(2010) add that this also results in a higher extraction rate at the date of transition to the backstop. Therefore, subsidizing the backstop results in less fossil fuel extraction and, assuming that the final extraction rate is higher at the date of the transition to the backstop, the initial resource extraction rate must be lower.

The third regime is an immediate introduction of the backstop and no fossil fuel utilization, if the backstop is always cheaper than fossil fuels.

5.4.6. The socially optimal tax rate

Van der Ploeg and Withagen(2010) claim that the exponentially rising carbon tax is not the socially optimal tax. Van der Ploeg and Withagen(2010) propose that the social optimum is achieved in a market economy as the rate of change in the optimal carbon tax consists of a Hotelling term equal to the rate of time preference minus a term that depends on marginal global warming damages. Thus, Van der Ploeg and Withagen(2010) claim that the carbon tax rate should increase at a slower rate than the discount rate to be socially optimal. If the socially optimal CO_2 tax is in place, technical development always promotes social welfare whereas a backstop subsidy sponsored by lump-sum taxes always lowers social welfare.

5.4.7. The second best outcome with backstops

Van der Ploeg and Withagen(2010) state that to entirely accomplish the first best social welfare, the government must implement a C02 tax ramp, not a subsidy on using a backstop. However, Van der Ploeg and Withagen(2010) agree with Sinn(2008a) that a rapidly rising carbon tax may be difficult to sell to the public, and it might be easier for governments to implement the second best policy of subsidizing the backstop and financing this with lump-sum taxes. Van der Ploeg and Withagen(2010) report the effects of introducing a backstop subsidy of varying orders of magnitude on welfare for different values of the damage parameter.

Van der Ploeg and Withagen(2010) argue that as backstop is relatively expensive, subsidizing the backstop leads to the green paradox. Green welfare will decrease as fossil fuel reserves are depleted more rapidly, but overall welfare may increase. However, as Van der Ploeg and Withagen(2010) add, if the backstop is relatively cheap compared to current extraction costs of fossil fuels, it is optimal to keep some oil/gas reserves under ground. Subsidizing the clean backstop then implies that the transition away from fossil fuels occurs faster and that a larger fraction of fossil fuel reserves are kept unexploited. Thus CO_2 emissions diminish, and the green paradox is avoided. Van der Ploeg and Withagen(2010) argue that an option is to compensate the fossil fuel resource owners for keeping some of its resources in situ.

Van der Ploeg and Withagen(2010) claim that with zero concern about global warming, deploying a backstop subsidy has negative effects on social welfare, since the competitive outcome is the socially efficient one. However, the results of Van der Ploeg and Withagen(2010) reveal that the net effect of deploying a backstop subsidy is fairly small and that even for relatively little concern about global warming, there is a significant welfare gain from introducing the subsidy. Thus, Van der Ploeg and Withagen(2010) suggest that when cost of the backstop is larger than the cost of fossil fuels it is better from a welfare perspective to subsidize the backstop, rather than taxing the backstop. Van der Ploeg and Withagen(2010) argue that if the backstop is always more expensive than fossil fuels, and the stock of CO_2 is really damaging, deploying a tax on the backstop enhances welfare. If the backstop is cheaper than fossil fuels and the stock of CO_2 is extremely damaging, subsidizing the backstop boosts social welfare.

5.4.8. Monopolistic resource owners

In real world it is most probable that the owner of the non-renewable resource is a monopolist, e.g., OPEC. Generally it is known that in markets with natural resource monopolies, limit pricing may occur. Van der Ploeg and Withagen(2010) claim that this means that in the presence of a backstop technology with price larger than constant marginal extraction costs of the non-renewables, there is an initial phase where the monopolist keeps the market price of fossil fuel below the cost of supplying the backstop. Subsequently there is a final phase where the backstop price is undercut by an infinitely tiny margin. Van der Ploeg and Withagen(2010) consider a monopolist facing a linear inverse demand function, and add that even though the model gets more complicated with stock-dependent extraction costs, limit pricing still occurs.

With a monopolist fossil fuel owner who has no control over the renewable backstop fuel, Van der Ploeg and Withagen(2010) argue that the green paradox holds if the backstop price is relatively high compared to the marginal cost of extracting a fossil fuel. In that case, extraction of the fossil fuel is slower than under perfect competition. If the backstop price is relatively small, extraction is faster while a larger stock non-renewables is left in situ. Van der Ploeg and Withagen(2010) claim that in that case, the green paradox does not necessarily occur. Van der Ploeg and Withagen(2010) assume that the effect on green welfare is ambiguous and depends crucially on the rate of pure time preference.

Van der Ploeg and Withagen(2010) emphasize that their results differ notably from the arguments of Sinn(2008a,b). Van der Ploeg and Withagen(2010) highlight that either the backstop is always more expensive to supply than fossil fuels and the green paradox prevails, but then rational speculating monopolistic fossil fuel owners extract slower than under perfect competition. Van der Ploeg and Withagen(2010) continue that if the backstop is finally cheaper than fossil fuels in which case rational monopolistic resource owners extract more quickly than under perfect competition, but then subsidizing the backstop leads to larger stock of non-renewables left in the ground and the green paradox need not hold. Interestingly, even though this the case in which Sinn(2008a,b) strongly argues that the green paradox occurs.

Van der Ploeg and Withagen(2010) conclude that a lower initial stock of non-renewable reserves, a positive shock to demand for non-renewables, and a lower cost of extracting non-renewables, imply that fossil fuels are more rapidly depleted in a first-best economy with a clean backstop. Van der Ploeg and Withagen (2010) also report that, if the atmosphere has already been badly polluted, it is socially optimal to postpone exhaustion of fossil fuels to mitigate global warming. Van der Ploeg and Withagen(2010) argue that allowing for global warming externalities, green paradox arises when the backstop is solar or wind energy. These are currently economically less attractive than fossil fuels, but attractive from an environmental point of view. As Van der Ploeg and Withagen(2010) follow Sinn(2008a), in supposing that a Hotelling ramp for carbon taxes is politically infeasible, the government may want to subsidize solar or wind energy. In this case Van der Ploeg and Withagen(2010) agree with Sinn(2008a,b) in that fossil fuel exhaustion takes place more rapidly and global warming damages increase. Thus, the green paradox occurs. Van der Ploeg and Withagen(2010) even add that total welfare might decrease. If society's concern for the environment is significant, Van der Ploeg and Withagen(2010) claim that it would be better to tax the clean backstop in order to delay depletion. However, Van der Ploeg and Withagen(2010) proceed, that if a remarkable subsidy results in a backstop cheaper than fossil fuel, total welfare will improve if the concern for the environment is great enough.

Van der Ploeg and Withagen(2010) argue that if the backstop is relatively cheap and clean compared to fossil fuels, subsidizing the backstop, say, nuclear energy will result in a larger final in situ stock of fossil fuels and to a higher rate of extraction of fossil fuels at the time the economy changes to nuclear energy. In this case subsidizing the backstop leads to less extraction, so that some fossil fuel reserves will be left in situ. Thus, no green paradox occurs.

In the long run new technologies are crucial and that is why one could support subsidizing the development of alternative energy technologies. Van der Ploeg and Withagen(2010) suggest that even though a decrease in the cost of supplying the backstop may be beneficial from a global social welfare perspective, it is not beneficial for green welfare. Unless the reduction is executed in a costless way, the policy will not be first best. If the government chooses to subsidize renewable energy, as Sinn(2008,2009) argues is done on a large scale in Germany, exhaustion of fossil fuels may occur more rapidly and climate change accelerates.

5.5. Prices versus Quantities

Edenhofer and Kalkuhl(2010) compare price and quantity instruments for mitigating climate change in their study *Prices vs. Quantities and the Intertemporal Dynamics of the Climate Rent*. Edenhofer and Kalkuhl(2010) consider the impact of policies on the incentives of resource owners who maximize their profits intertemporally. The focus is on the requirements of information and commitment of the regulator. Edenhofer and Kalkuhl(2010) find only two instruments that unleash the regulator from commitment problems: in the cost benefit world a stock dependent tax rule; in the cost effective world, only an emissions trading scheme with free banking and borrowing can shift intertemporal timing decisions to the market.

Edenhofer and Kalkuhl(2010) argue that a main insight of a successful climate policy to overcome climate change is pricing global emissions. This pricing can be achieved by taxes or quantity instruments like emission trading schemes. While these instruments are analogous in a world of perfect information, Edenhofer and Kalkuhl(2010) claim that as a social planner is confronted with uncertainties in marginal costs and marginal benefits this symmetry no longer holds. For stock pollution problems like global warming Edenhofer and Kalkuhl(2010) conclude that in the short-run tax policies are more efficient compared to quantity instruments, but in the long-run quantity instruments are superior as climate damages become more severe.

Edenhofer and Kalkuhl(2010) state that difficult question is the management of intertemporal carbon pricing when owners of the fossil fuels can act strategically. Sinn(2008) argues that even if carbon taxes are implemented globally and cover all countries, are they likely to fail to obtain socially optimal emission paths. Sinn(2008) argues that green paradox exists because future greener policies and increasing resource taxes make resource owners fear a devaluation of their resource rent. According to Sinn(2008) quantity instruments are more efficient than price instruments due to strategic behavior of the fossil fuel owners.

Edenhofer and Kalkuhl(2010) agree with Sinn(2008) in that it is important to focus on the intertemporal supply side in the context of climate change instead of focusing on the demand side, and thus, Edenhofer and Kalkuhl(2010) consider the incentive, information and rent structure rather than focusing on the social planners' perspective. Edenhofer and Kalkuhl(2010) extend the analysis of Sinn(2008) with a systematic comparison of optimal price and quantity instruments also using Hotelling-like model as a basis for their study. Edenhofer and Kalkuhl(2010) study the strategic response of the supply side that foresees the policy of the government and its implication on the intertemporal resource rent, and argue that a crucial aspect for effective climate policy are the economic rents arising from increasing climate damages and scarcities of resources.

The main policy decision concerns the choice between executing a price or quantity instrument. As the extraction problem is intertemporal, Edenhofer and Kalkuhl(2010) point out that the government has to commit ex ante to a policy for the entire time horizon. Edenhofer and Kalkuhl(2010) consider whether there exists policy instruments that need less commitment and information about optimal extraction paths for the whole time horizon.

5.5.1. The Cost-Benefit Approach

Edenhofer and Kalkuhl(2010) base their analysis of on the Sinn's(2008) modified Hotelling model when defining their cost benefit solution. As easily exploited resource stocks are extracted first, Edenhofer and Kalkuhl(2010) assume that extraction costs increase with depletion and are convex. Edenhofer and Kalkuhl(2010) want to focus on the supply side, and thus ignore decay rates of carbon dioxide in the atmosphere as well the carbon storage technologies. Edenhofer and Kalkuhl(2010) assume that by consuming fossil fuels a proportional amount of carbon is emitted into the atmosphere and, thus, damages should be described as function of cumulative extraction. Damages increase with the amount of carbon in the air which is proportional to cumulative extraction.

Edenhofer and Kalkuhl(2010) stricly assume that fossil fuel reserves are abundant so that they are not fully exploited within the planning horizon. Edenhofer and Kalkuhl(2010) argue that as the social and private Hotelling rules depart when the tax and marginal damages exist, a government should tax the resource sector such that the social and private Hotelling rules coincide.

5.5.1.1. Optimal resource tax

By equating private and social Hotelling rule, the optimal resource tax is found. Edenhofer and Kalkuhl(2010) state that if the government knows the socially optimal extraction path and can commit to the tax path at the beginning of the time horizon over the whole planning horizon, then the resource tax obtains the optimal extraction path. Edenhofer and Kalkuhl(2010) note that the sum of resource rent and resource tax describes the rent dynamics which is exactly the resource shadow price in the social planner model. The optimal resource tax can be decomposed into a pure resource extraction rent and a stock externality rent, which Edenhofer and Kalkuhl(2010) call climate rent.

Edenhofer and Kalkuhl(2010) argue that within the infinite time horizon, this kind of resource tax targets at reallocating resource extraction, postponing it towards the future, as within the finite time horizon, it is additionally essential to restrain cumulative extraction. This kind of tax requires large amounts of information as well as from the regulator a great ability to commit. Edenhofer and Kalkuhl(2010) continue that calculating the optimal tax requires a full evaluation of social costs and benefits of fossil fuel extraction from this moment until forever, as marginal damages along the entire socially optimal resource stock path need to be calculated. Moreover, the government would have to commit to this tax for now until forever. These requirements are quite unrealistic which makes divergence from the social optimum probable. Edenhofer and Kalkuhl(2010) claim that as the tax is always positive and increasing in the beginning, an inaccurate tax may accelerate extraction if the tax growth rate is high and the initial tax level too low. Hence, Edenhofer and Kalkuhl(2010) argue that only a falsely calculated tax could induce the green paradox.

5.5.1.2.Optimal stock-dependent resource tax

As Edenhofer and Kalkuhl(2010) argue, commonly governments cannot commit ex ante to a time dependent tax path for extensive time horizons. Regulation is rather a more recurring process where the tax on resources is dependent on the estimation of marginal damages from the cumulative fossil fuel extraction. Edenhofer and Kalkuhl(2010) add that as concentrations rise, the government raises the tax in order to price higher social damages. Thus, Edenhofer and Kalkuhl(2010) study if the regulator can obtain the optimal extraction path by realizing a resource tax adapted to the current concentration of carbon in the atmosphere. Edenhofer and Kalkuhl(2010) claim that the government reports explicitly how the tax is modified and the resource owners respond to this tax adjustment rule.

Edenhofer and Kalkuhl(2010) report that if the regulator implements the stock dependent resource tax, and if there are more than one resource owners, the tax rule results in a steeper (flatter) price path of resource compared to the optimal extraction if damages are convex (concave). Edenhofer and Kalkuhl(2010) continue that if there is only one resource owner the socially optimal Hotelling rule is achieved.

Edenhofer and Kalkuhl(2010) continue that stock dependent resource tax experiences an additional externality in the supply sector. If damages are convex, Edenhofer and Kalkuhl(2010) argue that a high aggregated stock leads to a low tax which benefits all resource owners. Therefore, if one resource owner delays extraction, all resource owners will benefit from lower taxes. But now, this resource owner has to extract his resources later and thus has to pay higher taxes caused by all resource owners together. Hence, as

Edenhofer and Kalkuhl(2010) state, he has an incentive to extract his resources as rapid as possible as long as taxes are still low. This describes how resource taxes result in inefficient extraction paths and how the green paradox occurs as an externality problem in the supply sector.

Edenhofer and Kalkuhl(2010) argue, that it is also possible to design a stock dependent tax on resource extraction that is bind to the individual stock of each resource owner, but this requires that all the resource owners are identical. In reality this is not the case, and there is no simple tax rule that properly internalizes the stock externality.

5.5.1.3. Optimal emissions trading scheme

Edenhofer and Kalkuhl(2010) also examine a global emissions trading scheme which Sinn(2008a) promotes, as it does not suffer from the green paradox. Edenhofer and Kalkuhl(2010) first consider emissions trading without banking and borrowing and assume that the regulator issues permits for resource extraction in each period. In order to sell a unit of resource, a fossil fuel owner has to use one permit. Thus, Edenhofer and Kalkuhl(2010) argue that the regulator can effectively restrict the resource use to the amount of permits. Edenhofer and Kalkuhl(2010) assume that optimal extraction under climate policy is always lower than the laissez faire extraction, which ensures that all permits are used at each time and there exists no undersupply of resources.

Edenhofer and Kalkuhl(2010) claim that if the regulator issues permits along the socially optimal extraction path, the optimal extraction is achieved, and that the shadow price for permits equals the optimal resource tax and therefore reflects the climate rent.

Next Edenhofer and Kalkuhl(2010) consider emissions trading with banking and borrowing. Still, a regulator might not be able to successfully commit to the optimal time path. Edenhofer and Kalkuhl(2010) argue that banking and borrowing on markets might let the regulator leave the intertemporal timing to the markets. However, Edenhofer and Kalkuhl(2010) report that a free permit trade between periods would result in a Hotelling path, which is not socially optimal because the intertemporal allocation of marginal damages is not considered properly. Edenhofer and Kalkuhl(2010) continue that this problem could be solved by introducing intertemporal trading rates, which alter the effective size of the pollution permit held from one period to the next and result in an optimal intertemporal reallocation of allowances.

Edenhofer and Kalkuhl(2010) analyze only the case where the regulator issues permits only at the beginning period for the entire time horizon, and claim that if the regulator knows the optimal extraction path it can be achieved by issuing permits in the beginning and allowing for banking of permits with the intertemporal trading rate. Edenhofer and Kalkuhl(2010) add that optimal intertemporal permit trading requires that the optimal number of permits is issued in the first period which can then be traded over the entire time horizon. Hence, the regulator needs to calculate ex ante the damages and the extraction along the social optimum. Edenhofer and Kalkuhl(2010) conclude that this result confirms that there is little evidence that banking and borrowing can increase efficiency or free the regulator from challenging intertemporal optimization decisions.

5.5.1.4. Comparing price and quantity instruments within a CBA framework

The regulator needs also consider other externalities than just the climate externality. Edenhofer and Kalkuhl(2010) argue that as the problem is intertemporal, discount rates play an essential role. Especially, with insecure property rights and with incomplete capital or future markets, player's effective discount rate could be higher than in the household economy. Thus, Edenhofer and Kalkuhl(2010) point out that policy instruments may turn out to be suboptimal if not adjusted to cover these distortions. Edenhofer and

Kalkuhl(2010) claim that if the resource sector discounts profits with discount rate differing from the social planner' s discount rate, the optimal resource tax has to be modified.

Edenhofer and Kalkuhl(2010) state that the most robust policy against suboptimal discount rates is the emission trading scheme without banking and borrowing, as its efficiency is not affected by the suboptimal discount rates. However, the distribution of the climate rent may slightly alter. On the other hand Edenhofer and Kalkuhl(2010) argue that, suboptimal discount rates with the emissions trading scheme with banking and borrowing, are hard to manage as they impact both resource path and intertemporal arbitrage conditions for permit.

Edenhofer and Kalkuhl(2010) report that even if we have perfect information and zero transaction costs, price and quantity policies still differ in their institutional and informational requirements. As the stock dependent resource tax is applied, Edenhofer and Kalkuhl(2010) argue that the regulator needs only to find out the damage function but not the optimal path, and that she does not need to commit to the whole time path of the tax but to a rule to adjust it. For every other climate policy, the government needs to calculate the optimal extraction path for the whole time horizon and to commit to the time path of this instrument. Also if the regulator knows the socially optimal extraction path, extraction could be controlled by an emission trading scheme without banking and borrowing. Edenhofer and Kalkuhl(2010) state that emissions trading without banking and borrowing might be rather effective when additional market failures like insecure property rights, incomplete future markets or liquidity constraints are taken into account.

5.5.2. The Carbon-Budget-Approach

Edenhofer and Kalkuhl(2010) also consider the carbon budget-approach in addition to the cost-benefit-approach. Edenhofer and Kalkuhl(2010) argue that the cost-benefit-approach requires balancing between the damages from the use of fossil fuels and the opportunity costs of postponed extraction. Determining the climate change damages is a complex and controversial task, and confronted with substantial uncertainties in the climate system, regional market and in normative parameters as discount rates, risk aversion or assumed substitution potential between physical capital and ecosystem services. As certain limits in the temperature increase are crossed can consequences be irreversible and catastrophic. Thus, cost-benefit-analysis in a context of global warming is certainly controversial in science and in politics.

Edenhofer and Kalkuhl(2010) point out that there is a growing consensus to restrict global warming to a temperature limit, depending mainly on the cumulative emissions until 2050. Therefore, Edenhofer and Kalkuhl(2010) claim that a more practical way of negotiating climate targets could be based on caps for cumulated carbon emissions, called a carbon budget. To approach the carbon budget Edenhofer and Kalkuhl(2010) modify the intertemporal social optimization problem from the cost-benefit analysis by removing the damage term and adding the budget constraint.

5.5.2.1 Optimal resource tax with the carbon budget

Edenhofer and Kalkuhl(2010) argue that if the regulator knows the initial tax level and can commit at the beginning to the tax path over the entire planning horizon, then the resource tax achieves the optimal extraction path. Edenhofer and Kalkuhl(2010) report that the social planner has to solve his model in order to calculate the initial tax level. An incorrect initial tax level or tax growth rate will result in exceeding the budget.

Edenhofer and Kalkuhl(2010) state that the optimal resource tax is a pure budget scarcity price that mirrors the Hotelling rule scarcity of the carbon budget. Edenhofer and Kalkuhl(2010) argue that there is only a rent for reserves with low extraction costs, and that this rent would diminish with constant extraction costs. The budget scarcity rent is called as climate rent, and Edenhofer and Kalkuhl(2010) claim that this rent is incorporated by the resource tax.

5.5.2.2. Optimal emissions trading scheme with the carbon budget

Edenhofer and Kalkuhl(2010) claim that under the emission trading scheme without banking the optimal intertemporal use of the carbon budget is achieved if permits are issued according to the socially optimal extraction path. This requires that the regulator can calculate the socially optimal extraction path for the complete time horizon. Edenhofer and Kalkuhl(2010) state that permits must be issued in each time period according to this path.

Edenhofer and Kalkuhl(2010) argue that when banking and borrowing is allowed, the regulator could issue the permits from the carbon budget in the first period to the resource owners and enable for intertemporal flexibility to use the permits. Edenhofer and Kalkuhl(2010) add that when banking is allowed and the regulator issues permits in the initial period the optimal extraction is achieved. Edenhofer and Kalkuhl(2010) report that the initial price of permit has to be set to equal cumulative permit demand with the carbon budget. Edenhofer and Kalkuhl(2010) argue, that the problem is similar to the emission tax problem, but that here, to achieve an intertemporal market equilibrium requires a complete set of future markets.

5.5.2.3. Comparison between price and quantity instruments within a carbon-budget analysis

As well as with the cost-benefit-analysis, Edenhofer and Kalkuhl(2010) study how suboptimal discount rates in resource sector affect the efficiency of the policy instruments when carbon-budget-analysis is used. Edenhofer and Kalkuhl(2010) argue that if the supply sector discounts profits with rate differing from the social planner's discount rate and if the regulator knows the socially optimal extraction and price paths, then the resource tax has to be modified. Similarly to the cost-benefit-analysis, the efficiency of the emission trading scheme without banking is not affected, but the shadow price for permits changes. Edenhofer and Kalkuhl(2010) claim that if the supply side discount rate exceeds the social discount rate the resource tax has to increase at a lower rate compared to the case where discount rates are equal, to provide an incentive for postponing extraction. Also here, the emission trading scheme without banking is the most reasonable policy instrument when the correct discount rate is used.

Edenhofer and Kalkuhl(2010) state that an emission trading scheme with banking is suboptimal because the optimal permit price does not increase exponentially at a constant rate and is thus not consistent with intertemporal maximization of the permit rent. High discount rates of resource owners lead to a steeper permit price path and, therefore, to increasing extraction. Edenhofer and Kalkuhl(2010) argue that the regulator now has to tax resource extraction as well, which requires all the information about optimal timing and fuel demand for the complete time horizon.

The carbon budget analysis of Edenhofer and Kalkuhl(2010) changes the intertemporal resource scarcity rent into a climate rent by imposing a cumulative carbon budget on extraction. Edenhofer and Kalkuhl(2010) claim that compared to climate policies under the cost-benefit-analysis, the climate rent under the carbon budget does not need to be revised by complex stock externality dynamics as it simply obeys the Hotelling rule. Edenhofer and Kalkuhl(2010) state that the carbon budget approach does not need an explicit evaluation of damages, but extraction costs and fossil fuel demand need to be known for the entire planning horizon.

Edenhofer and Kalkuhl(2010) argue that by issuing tradable permits with free banking and borrowing, the government could transfer this evaluation problem to the market. As permits create an additional market, there could exist market failures due to competition problems, market power or information asymmetries, which will affect efficiency. Edenhofer and Kalkuhl(2010) highlight that an incorrectly set tax path could provoke a green paradox. On the other hand, the carbon budget approach of Edenhofer and Kalkuhl(2010) tells nothing about how costly the deviation from the budget is for example in terms of higher climate damages.

Thus, Edenhofer and Kalkuhl(2010) argue that in a deterministic world price and quantity instruments differ in the distribution of information requirements between market and regulator and in how robust they are against market failures. Edenhofer and Kalkuhl(2010) state that the cost-benefit-analysis needs to handle more complex intertemporal rent dynamics than the carbon-budget-analysis due to its aim to efficiently allocate climate damages in time. In a cost-benefit framework, only the stock dependent tax which depends on each fossil fuel owner's reserve size could free the regulator from finding the optimal extraction path. But the requirement of homogenous resource owners is highly unrealistic in real life. Edenhofer and Kalkuhl(2010) state that with the carbon-budget approach, only an intertemporally free permit trade could dispense the regulator from reaching intertemporally efficient extraction path.

Edenhofer and Kalkuhl(2010) conclude that when considering the robustness of climate policies secondary market failures play an essential role. Suboptimal discount rates can arise due to insecure property rights, liquidity constraints in capital markets or incomplete capital and future markets. Edenhofer and Kalkuhl(2010) claim that resource taxes can in theory clear this additional market failure but this depends on the exact extraction dynamics. Edenhofer and Kalkuhl(2010) continue that with an emissions trading scheme with intertemporal flexibility suboptimal discount rates may exist, and emissions become badly controllable. On the other hand, emissions trading schemes without intertemporal flexibility are the most robust policy against additional market failures in fossil fuel and permit markets. Edenhofer and Kalkuhl(2010) add that here suboptimal discount rates do only alter the willingness to pay for permits but do not affect final resource prices nor extraction paths.

As Edenhofer and Kalkuhl(2010) and Sinn(2008,2009) claim, incorrect taxes could accelerate global warming. Thus, quantity instruments function better in achieving a certain emission path. Even though Edenhofer and Kalkuhl(2010) suggest that emissions trading without banking and borrowing is the best policy when discount rates are suboptimal, they highlight that this should be taken rather as a hypothesis to defeat green paradox than as a firm policy recommendation, as the model does not reflect real world.

5.6. Improved Renewable Energy Technology

Next we consider the existence of green paradox when the technology of renewables is improved. Hoel(2008) argues that the extraction path of non-renewable carbon resources depends both on present and future demand, and adds that when this is taken into account, the whole price path of fossil fuel will shift downwards as a response to the decreased cost of the renewable substitute. As a result the greenhouse gas emissions in the near future may increase as a supply side response to the reduced cost of the renewable substitute. Thus, overall social welfare might be reduced, as the increased climate costs may outweigh the gains from reduced costs of a substitute.

Hoel(2008) assumes that even though technology improvement will lower the costs of alternative energy, costs of carbon resources will still be lower than the costs of a substitute. Hoel(2008) analyzes the impacts of such a technology improvement in a context where different countries have differing climate policies, but not an efficient global climate agreement. Hoel(2008) highlights that an important notion from his analysis is that climate costs may increase as a result of the improved technology of renewable energy. Although a given amount of carbon is eventually extracted, it is important from the climate point of view, when the carbon is extracted. Postponing the extraction is likely to lower climate costs, even though total emissions over time are given by the carbon resources.

5.6.1. Climate costs and carbon resource extraction

Hoel(2008) assumes that the total amount of fossil fuel resources are given, and that all resources will eventually be extracted and thus total emissions over all future years are given. However, the extraction path of carbon is important from a climate point of view. Hoel(2008) argues, that about 25% of carbon remains in the atmosphere at least for thousands of years. Therefore, if a fixed amount of carbon, denoted *C0,* is extracted over a time period, it will result in a long-run increase of about *C0* / 4 in the atmosphere. With a slow enough extraction rate, carbon in the atmosphere will increase gradually and monotonically until its long-run level is reached. Hoel(2008) claims that, such a growth of carbon in the atmosphere is linked with a piecemeal changing climate. If the extraction rate were higher, the carbon in the atmosphere will increase faster, and will overshoot its long-run value. Hoel(2008) states that this will lead to a remarkably faster climate change, and probably to temperatures above the slow extraction path for several centuries.

Hoel(2008) strongly argues that the climate costs associated with the faster extraction profile are much higher than the climate costs associated with the slow extraction profile, even if discounting is ignored. Hoel(2008) considers this particularly probable if some impacts of climate change are irreversible. Hoel(2008) models the impacts of delaying emissions under the common assumption that climate costs at any time depend only on the stock of carbon in the atmosphere through its effect on the condition of the climate. Thus the climate cost is given as a function of the stock of carbon in the atmosphere. Hoel(2008) assumes that delaying emissions reduces climate costs.

5.6.2. Market for Fossil Fuels

Hoel(2008) assumes fossil fuels to be a homogeneous nonrenewable carbon resource with a given fixed supply and no extraction costs. The resource supply is competitive, and the equilibrium producer price therefore rises at the interest rate as long as there are reserves remaining. In Hoel's(2008) model the demand for carbon is the sum of demand from numerous countries. There is a perfect substitute for the fossil fuel resource that is also supplied competitively at its unit cost. Hoel(2008) uses identical gross utility functions depending on the sum of the use of carbon and the substitute for all countries. Hoel(2008) argues that introducing different utility functions across countries would only complicate notation without changing any results.

If no environmental considerations were included, each country would choose its use of fossil fuels and substitute to maximize their utility function. However, Hoel(2008) assumes that countries have a willingness to pay for reducing the use of carbon, and this willingness to pay may be equal to the marginal climate cost of the country, but it may also exceed the direct damage of its own emissions if it contains some elements of altruism. Hoel(2008) adds that it would be difficult to explain the relatively high willingness to pay of some European countries without such an altruistic element.

Hoel(2008) assumes that the value of willingness to pay per unit of emissions , *w*, varies across countries. Hoel(2008) adds that each country sets a carbon tax equal to its willingness to pay, or alternatively, each country has a domestic quota system, where quota price equals its willingness to pay. Hoel(2008) argues that countries for which the fossil fuel price plus the carbon tax exceeds the cost of producing the substitute will select the substitute. Hoel(2008) adds, that in countries where the willingness to pay is lower the fuel price plus the carbon tax will be lower than the cost of the substitute, and thus these countries will not adopt the substitute.

Hoel(2008) argues that the aggregate demand function for fossil fuels is downward sloping as a function of the price. Hoel(2008) reminds that the price path of the fossil fuel depends both on present and future demand. As this Hotelling feature is considered, the whole price path of the carbon resource will shift downwards as a response to the decreased cost of the substitute. The resulting equilibrium conditions tell us that the sum of demand over all periods cannot exceed the available carbon resources. Hoel(2008) adds that the equilibrium depends obviously on the value of the unit cost of the substitute.

5.6.3. Effects of lower cost of the substitute

Hoel(2008) demonstrates the effects of improved technology for lowering the costs of producing the substitute. Demand for fossil fuels will differ from the demand along the original price path for two reasons. Firstly, it will be higher since the new price path is lower. Secondly, it will be lower since the cost of producing the substitute, b, is lower, as b has a direct effect on fossil fuel demand. Hoel(2008) argues that, if these two effects are equal, the price path and the date of exhaustion will be the same as before. However, these two effects on demand will generally differ. Hoel(2008) states that, if the price effect dominates, demand for fossil fuels will be higher, so the carbon resource will be exhausted earlier. Vice versa, if the direct effect of reduced cost of the substitute dominates, demand will be lower, and thus carbon resources will remain longer.

Hoel(2008) uses two special cases to illustrate the two possibilities. First Hoel(2008) considers a case in which a share of the countries have $w = 0$, while the remaining countries have $w > b$. Hoel(2008) argues that in this case there is no direct effect of b on demand, and hence the price effect dominates. Hoel(2008) argues that it is clear that a reduction in b must give a reduction in price path and in the exhaustion date. Thus the whole price path is shifted down, and the path for fossil fuel extraction is shifted up. Thus, in this case the carbon resource will be exhausted earlier as the cost of the substitute, b is reduced. Hoel(2008) points out that this does not depend on the assumed heterogeneity across countries. Instead if all countries had identical and small values of w, the result would be the same.

Hoel(2008) also considers a special case in which the demand for fossil fuels plus the substitute is independent of price. Now there is no impact from the reduced price path on carbon demand. However, Hoel(2008) adds that demand goes down as a result of reduced cost of the substitute. The altered extraction path implies that the extraction of carbon has been postponed.

Hoel(2008) argues that with a sufficiently high price sensitivity, the exhaustion date will lower as b is decreased. Hoel(2008) also states that the effect of reduction in b on the exhaustion date depends not only on the distribution function and the demand function, but also on the amount of unextracted carbon. Hoel(2008) claims that it is the natural interpretation that for a very large unextracted resource stock, the resource rent will be close to zero. Hoel(2008) adds that the direct impact of reduced b dominates the aggregate demand response, suggesting that resource extraction is slowed down and thus resources last longer.

Hoel(2008) concludes that the time of resource exhaustion may either decline or increase as a consequence of a reduction in b. Hoel(2008) shows that the higher is the elasticity of demand for the fossil fuels and the substitute and the scarcer is the carbon resource, the more likely it is that the greenhouse gas emissions increase in the near future.

5.6.4. Welfare effects of lower cost of the substitute

Hoel(2008) argues that as the cost of the substitute is reduced, there are three different effects on social welfare. The first effect is the direct effect of the reduction of b that is an increase in social welfare for all countries, since all countries will at some point use the substitute. According to Hoel(2008) the second effect is that this has an impact on the price path of the fossil fuels. The overall welfare effect of the price reduction caused by the reduction in b is always positive, meaning that the lower is b the lower is the price path. Third, there is the climate effect of the reduced b. As Hoel(2008) demonstrates, a reduction in the cost of producing a substitute may either bring forward or postpone carbon extraction, and therefore have either negative or positive effect on the overall change in social welfare.

Hoel(2008) concludes that ignoring climate costs changes, reduced costs of a substitute has an unambiguously positive impact on overall social welfare, even though the owners of the fossil fuels suffer a welfare loss. Hoel(2008) argues that if resource extraction is delayed, so that climate costs are reduced, there is an additional rise in aggregate social welfare. However, if resource extraction is hastened as a result of the reduction in b, climate costs accrue. Thus, in this case there are two positive and one negative effect on aggregate social welfare. Hoel(2008) states that the negative effect may even be so large that it overwhelms the two positive effects. This will occur if there is a group of countries with sufficiently high willingness to pay to diminish emissions. The willingness to pay needs to be so high that these countries are not using the carbon resource whatever the value of *b*. Hoel(2008) argues that since sufficiently large growth in climate costs for some countries, these cost increases may be greater than the direct benefits for all countries of the reduced *b*. Thus, in the absence of an efficient climate agreement, climate costs may rise so much that overall social welfare declines as a result of decreased costs of a substitute.

5.7. The amount of oil

Gerlagh(2010) also studies green paradox, when the technology of the clean substitute develops. Most of the studies argue that all fossil fuel stocks will be depleted, and the green paradox depends on when the fossil fuel resources are extracted. Gerlagh(2010) argues that in fact, there are too much resources to extract in a first place in order to fight the climate change. Secondly, Gerlagh(2010) claims that, there are no optimal clean energy sources at unlimited supply and constant marginal cost that can substitute for fossil fuels. Gerlagh(2010) highlights, that actually, most of the clean energy sources are imperfect substitutes and have decreasing returns to scale. Thus, Gerlagh(2010) argues that considerable market interventions are needed to prevent excessive use of oil and gas. Gerlagh(2010) adds though, that these same features make the green paradox less likely to occur.

5.7.1. Assumptions of clean substitute

Gerlagh(2010) reports that the typical analysis of climate damages considers one global resource market with countries cooperating for climate policy. As Gerlagh(2010) argues, this assumption is far from reality. In practice countries have different responsibilities for climate policy and climate policy is feared to have negative impact on countries' competitiveness. Gerlagh(2010) adds that governments worry that carbon pricing might push energy-intensive companies to move to countries without high carbon prices. Regulating domestic CO_2 emissions might then lead to carbon leakage and thus increased foreign emissions.

Gerlagh(2010) abstracts from carbon pricing policies and focuses on the development of a clean energy substitute and its impacts on energy markets and climate change. Gerlagh(2010) highlights that there are double benefits with clean substitute as it reduces dependency on oil and also decreases climate damages.

Gerlagh(2010)also distinguishes between a weak and a strong green paradox. Gerlagh(2010) considers a weak green paradox to arise when an advancement in the backstop technology increases current emissions. Although current emissions may increase, if future emissions decrease sufficiently, the climate change may be less severe in the long term. Thus, a weak green paradox means an immediate effect. According to Gerlagh(2010) a strong green paradox arises when the cheaper clean energy technology increases the net present value of cumulative damages from emissions. A strong green paradox thus refers to an aggregate welfare effect.

5.7.2. Model of clean substitute

Gerlagh(2010) analyzes the typical resource model of green paradox extending this simplest model. The analysis is analogous to Hoel(2008) except that Hoel(2008) studies a two-period model, whereas Gerlagh(2010) examines an infinite horizon. This is why Hoel(2008) finds a full analytical solution and a complete image of how assumptions of parameters affect the green paradox. Using the infinite horizon forces Gerlagh(2010) to use more restrictions on various parameters but, the infinite horizon model fits the very long time horizon of the climate problem more naturally.

Gerlagh(2010) compares three models of fossil fuel extraction and climate change damages. The first one includes a fixed resource, constant extraction costs and a backstop technology. Most of the green paradox literature uses models similar to this. The second model has increasing extraction costs, and the end of the period of fossil fuels is determined by economic depletion rather than physical exhaustion. The last model of Gerlagh(2010) replaces the assumption of a perfect substitute backstop at constant marginal costs, with an imperfect substitute with decreasing returns to scale. Gerlagh(2010) argues that moving from the first to the last model, the green paradox gradually diminishes.

5.7.2.1 Model with fixed resource and perfect backstop

The basic model of Gerlagh(2010) has fixed resource and a perfect backstop available at infinite supply at constant marginal costs. As the backstop gets cheaper than the resource, the demand of the resource will drop to zero. Also Gerlagh(2010) makes the important assumption that early emissions cause more damages than delayed emissions, thus the marginal damage per emissions increases with less than the interest rate.

Gerlagh(2010) shows that in the competitive resource model with constant extraction costs and a backstop both the weak and the strong green paradox occur. Gerlagh(2010) argues that a more competitive backstop technology results in a lower resource rents and thus an earlier exhaustion date. Lower rents indicate lower prices and thus higher demand so the weak green paradox instantly arises. Gerlagh(2010) claims that since future emissions are valued less than current emissions the climate damages increase.

Hoel(2008) assumed zero extraction costs, but claims that adding a constant unit cost of extraction does not change the results. When the unit cost of extraction is increasing with accumulated extraction, Hoel(2008) argues, that if there is an absolute and binding limit on total carbon extraction, there will not be any remarkable changes in the analysis. Hoel(2008) considers it an interesting case when the resource price is rising and the total extraction is determined by $c(A) = b$, so that a reduction in b will reduce total extraction. In this case the climate effect of reduced b is thus more favorable than before. However, Hoel(2008) adds that also in this case it is feasible that a reduction in b will result in increased extraction and emissions, that may more than outweigh the positive effect of decreased total extraction.

5.7.2.2 Model with increasing extraction costs and perfect backstop

Gerlagh(2010) claims that either the transition to the clean backstop must be supported through a tax on fossil fuels or the costs of the backstop so that it competes with the fossil fuels. Additionally extraction costs increase as unconventional oil develops. Gerlagh(2010) now shows the occurrence of the green paradox with increasing extraction costs with cumulative resource extraction, linear demand and a perfect backstop. Gerlagh(2010) alleges that as the resource rent decreases with a cheaper backstop, initial supply rises. Thus the weak green paradox arises. Gerlagh(2010) adds that while the rise in emissions increases the net present value of climate damages, cumulative supply goes down with a cheaper backstop. As these two determine whether the strong green paradox arises Gerlagh(2010) proves that now the strong green paradox does not exist.

Gerlagh(2010) argues that there is an important difference with the basic model. As extraction costs increase with cumulative supply, a cheaper backstop will reduce the duration of fossil fuels enough to decrease the net present value of climate damages. Gerlagh(2010) continues that as backstop becomes remarkably cheap, marginal cost goes to zero and cumulative oil and gas use becomes very small. As cumulative oil and gas use sets an upper limit on climate damages, these must become small too. Gerlagh(2010) claims that this is powerful enough to neutralize the strong green paradox, even when the backstop is expensive.

Gerlagh(2010) also graphically discusses whether the strong green paradox occurs in the intermediate case between basic model with constant extraction costs and the model with linearly increasing extraction costs. Gerlagh(2010) argues that when extraction costs are convex in cumulative supply, there is an intermediate case, which can be considered realistic when assumed that there is no good alternative to fossil fuels and extraction costs will quickly increase during the transition phase towards other energy sources. Gerlagh(2010) continues that if this is the case climate damages are increasing with a cheaper backstop when the backstop is competitive and decreasing when the backstop becomes inexpensive. The extraction costs can be concave when assumed that the transition phase is defined as a switch from coal, which has relatively flat extraction costs, to a backstop. Gerlagh(2010) argues that then climate change damages are strictly decreasing with a cheaper backstop.

5.7.2.3 Model with fixed resource and imperfect backstop

As fossil fuels are used for multiple purposes, it is probably easier to find good substitutes for some uses than for others. When considering electricity, Hoel(2008) argues that it makes no difference if the electricity is based on fossil fuels or on alternatives such as wind or solar, and thus the choice of electricity is solely based on relative costs. However, achieving desirable alternatives especially for oil in transportation and for direct use of natural gas in households is likely to be much more challenging. Even though the use of fossil fuels might in the future be eliminated as an energy source, there is likely to remain demand for fossil fuels for transportation and for some stationary uses even at fairly high prices. In addition, Gerlagh(2010) claims that renewables need a conversion to be used in transport.

Thus, as there is no energy source that can easily replace oil and gas, it is not realistic to assume a perfect backstop, an energy source with constant marginal costs at infinite supply. Gerlagh(2010) argues that a more realistic model would consider increasing marginal costs of the substitute energy source in every additional unit of energy. Thus, renewable energy sources are not perfect substitutes for oil and gas.

As Hoel(2008) assumes that each country in addition to its demand has some demand that will not be compensated with the substitute, no matter how low the cost of the substitute is, the aggregate demand changes, and thus the equilibrium condition in the market for carbon changes. Hoel(2008) claims that with an imperfect substitute it seems more likely that exhaustion date will decline as a result of the reduced cost of the substitute than in the case of a perfect substitute.

Gerlagh(2010) models the imperfect substitution through differentiating between primary and effective final energy supply, so that every additional unit of primary clean energy adds a lower amount to the final energy supply. As a consequence, marginal costs increase. Gerlagh(2010) proposes that now the cheaper substitute reduces fossil fuel demand throughout the equilibrium and extends the period over which fossil fuels are used. Thus, a substitute with minimal marginal costs below the constant fossil fuel extraction costs, and increasing marginal costs, neither the weak nor the strong green paradox occurs.

5.8. Learning by Doing

Next we will consider occurrence of green paradox through the impacts of technological development considered as learning by doing. Chakravorty et al.(2010) also argue that the potential for endogenous technological change in renewable energy sources may change the behaviour of fossil fuel owners. Chakravorty et al.(2010) report that as technological improvement in renewable energy can arise through learning by doing, resource owners experience incentives to extract rents from the fossil fuel resource and to prevent spreading of the new renewable technology. Chakravorty et al.(2010) demonstrate that, that scarcity-driven higher conventional energy prices may not over time stimulate alternative energy supply as resources are depleted. Instead, Chakravorty et al.(2010) report that as the learning potential in the substitute technology is increased, lower equilibrium energy prices prevail and there may be expanded resource extraction and carbon emissions. Grafton, Kompas and Van Long(2010) also claim that as the production of biofuels increases, technological progress will depreciate the costs of production as a result of learning by doing.

Chakravorty et al.(2010) state that strategic action of the oil companies to maintain low fuel prices influences the introduction of clean energy. Too high fossil fuel prices could lead to increased deployment of alternative energy and lead to a permanent residual demand shift. Even though oil prices have declined since 2008, Chakravorty et al.(2010) argue that there still remains the possibility that alternative energy sources may threaten the rents of fossil fuel owners. Chakravorty et al.(2010) state that, besides energy policies, behavioural changes will have some effect on demand patterns.

Chakravorty et al.(2010)examine a case where resource oligopolists consider the future supply of an alternative energy sector when determining the optimal production from their finite fossil fuel resource. Commonly, it is assumed that scarcity driven increasing resource prices will induce higher deployment rate of substitute energy which will generate cost reductions in those clean sources. Chakravorty et al.(2010) suggest that the high potential of learning by doing of substitute energy sources may provoke increased resource extraction and thus lower energy prices and less alternative energy production regardless of resource scarcity. Further, Chakravorty et al.(2010) demonstrate that growing potential for learning by doing in clean energy affects both the effectiveness and price effect of climate policies.

5.8.1. The Model of learning by doing

Chakravorty et al.(2010) model an economy using energy with decreasing returns to scale. There are two sources of energy, fossil fuels and alternative energy, which is considered as an experience good, and thus its total and marginal production costs go down with cumulative production. Chakravorty et al.(2010) assume the energy sector as an oligopoly with symmetric price setting, fossil fuel extracting firms each owning an equal share of the existing resources. There is also a competitive, price taking alternative clean energy sector. Naturally, each firm is maximizing the net present value of revenues with perfect information of the future. Chakravorty et al.(2010) assume energy demand to be constant, and also make a strong assumption that the fossil fuel and the alternative energy source are perfect substitutes.

Energy is used as an input to production. Chakravorty et al.(2010) use a model where the marginal product of energy is the first derivative of a Cobb-Douglas production function. Chakravorty et al.(2010) consider extraction costs constant in the rate of extraction in each period and also in cumulative extraction.

Chakravorty et al.(2010) simplify things by assuming that experience is a public good and perfectly transferable across firms in the substitute energy sector. Thus, firms get private gains from learning by doing even if these gains are smaller than the total value of learning by doing to the whole sector. Chakravorty et al.(2010) assume that the aggregate marginal cost for each firm will be weakly increasing in production in any period, and weakly decreasing in the accumulated experience. Chakravorty et al.(2010) allow no experience depreciation, so that all experience accumulated remains for all future time periods. Chakravorty et al.(2010) add that depreciation would imply a lower future value of current substitute energy supply.

Chakravorty et al.(2010) use a model which is simplified relative to most Integrated Assessment Models because no climate change damages arising from emissions are included. Chakravorty et al.(2010) claim that this simplification is not crucial since the purpose is not to predict the magnitude of climate change or to construct optimal climate change policy, but to provide meaningful comparative dynamics regarding energy supply.

5.8.2. The Equilibrium of learning by doing

Chakravorty et al.(2010) study resource extraction effects in a case where fossil fuel resource owners encounter competition from a substitute energy source. The substitute energy may initially have remarkably higher costs, but potential learning by doing suggests that the costs are affected by the actions of the resource owner. Chakravorty et al.(2010) consider that each of the symmetric fossil fuel resource firm takes the extraction decisions of the other resource firms as given. Chakravorty et al.(2010) assume that the marginal future value of fossil fuel resources will be decreasing in remaining stock and increasing in the cost of the substitute energy. Chakravorty et al.(2010) argue that even though the extracting firms do not act as leaders, as they do not internalize the impact of extraction on substitute energy supply, the response of the clean energy sector impacts extraction strategies. Chakravorty et al.(2010) claim that higher learning rates imply higher alternative energy supply, and that increase in supply decreases the costs of future alternative energy and lowers the future value of fossil fuel resources. A low extraction decision would similarly imply higher substitute energy supply, higher gain in experience and thus lower future fossil fuel resource value.

Chakravorty et al.(2010) argue that in the economic literature there is evidence implying that market power matters in fossil fuel pricing and that OPEC plays an important role in the global pricing of fossil fuels. Chakravorty et al.(2010) assume that a part of the difference between extraction costs and market prices arise from the collection of oligopoly rents, with the remainder fixed within extraction costs. Chakravorty et al.(2010) argue that oligopoly rents are endogenous, and thus will be altered by the resource owners as a counteraction to competition or future market share loss.

Chakravorty et al.(2010) assume that there is alternative technology to supply small quantities of energy at prices competitive with energy from fossil fuels and that the marginal cost of alternative energy would rise if attempted to supply a larger quantity today. Thus, as Chakravorty et al.(2010) claim as learning by doing occurs, costs will decrease and the market share of clean energy will increase. Chakravorty et al.(2010) add that only part of the gains will be actualized by the firms currently in alternative energy production.

Chakravorty et al.(2010) assume an upward sloping marginal cost curve for clean energy. The supply curve shifts downward in response to learning by doing. Chakravorty et al.(2010) consider a progress rate of 15%, and test also rates of 0% and 30% of learning for comparison, using both simulations across time and projections of stationary Markov strategies and marginal values onto the state space. For the results of Chakravorty et al.(2010) the lower bound for clean energy supply is important since its magnitude relative to the extraction cost of fossil fuels will define whether economic exhaustion occurs before physical exhaustion. Chakravorty et al.(2010) claim that once learning potential has been depleted, the marginal cost of supplying the amount of energy used today would roughly be the cost of the cheapest clean energy offered today. Chakravorty et al.(2010) argue that with their assumptions fossil fuel supply would not be completely replaced by clean energy and thus resource scarcity will always bind in the long run, although the depletion may occur a lot later. Chakravorty et al.(2010) argue that this implies that clean energy substitution will not change cumulative emissions but may widen the time path over which they occur.

The results of Chakravorty et al.(2010) are most sensitive to four assumptions. First, Chakravorty et al.(2010) argue that the combination of the intercept and slope of the substitute energy supply are such that there cannot occur an equilibrium in which fossil fuels are left in situ. Thus, any impact of policies on emissions are questions of timing. Second, Chakravorty et al.(2010) claim that assuming that the slope of the marginal cost of substitute energy production does not decrease in time may underestimate the effects of learning. Third, Chakravorty et al.(2010) use the simplified fossil fuel sector in their model in that either technological progress or increasing extraction costs are included. However, as more challenging fossil fuel wells are being extracted later, and by assuming constant extraction costs Chakravorty et al.(2010) have implicitly built in some technological change. Finally, Chakravorty et al.(2010) admit that their results are probably not consistent under increasing or decreasing energy demand.

5.8.3. Effects of learning by doing on energy supply

Chakravorty et al.(2010) argue that the potential for learning by doing affects both clean energy supply and decisions on resource extraction. Chakravorty et al.(2010) argue that if learning is not possible, the time path of fossil fuel extraction and clean energy introduction is analogous to a perfectly elastic backstop. Chakravorty et al.(2010) continue that as learning is possible, future costs decrease and the clean energy firm will produce at a price below marginal production cost in order to obtain experience to reduce future costs. Clean energy firms internalize the future benefit of cost reductions. This results in prolonged fossil fuel extraction with faster adoption of the clean energy. Chakravorty et al.(2010) continue that it is difficult to make significant generalizations based on a time path since the results will probably not generalize to all initial conditions.

Chakravorty et al.(2010)claim that the impact of learning potential on extraction is more obvious when alternative energy is more expensive, as extraction is more firmly decreasing in the learning potential. Chakravorty et al.(2010) add that learning has an ambiguous effect on fossil fuel extraction depending on remaining resources. When there is plenty of resources, extraction is decreasing in learning potential. Chakravorty et al.(2010) claim that this is mostly due to the willingness of the clean energy firm to produce more than it normally would in order to benefit from learning to lower future costs. When learning occurs and as resources become scarce, the resource owner does not have the same incentive to store because the market will not tolerate higher prices when there is a substitute available. Chakravorty et al.(2010) add that extraction is increasing in learning as resources are scarce, and thus green paradox occurs. The increased threat from higher potential for learning will lead to increasing extraction rates. However, Chakravorty et al.(2010) show that this result is sensitive to market structure assumptions and that, under certain assumptions greater potential for learning may even lead to decreased clean energy supply as resources become scarce. This may occur since there is a greater incentive to conserve fossil fuels and to gather rents when the clean energy is more expensive provided that resources are scarce. Chakravorty et al.(2010) argue that the key factors behind these results are future values of resources, and the future value of cost reductions from current substitute energy supply.

Chakravorty et al.(2010) show that the future value of fossil fuels is monotonically decreasing in the learning rate and increasing in the present cost of the substitute technology, and thus green paradox occurs. The results of Chakravorty et al.(2010) suggest that the greater is the potential for learning, the lower are resource prices, rather than that higher resource prices will drive learning in the clean energy sector. Also, the faster is learning, the lower is the energy price. Chakravorty et al.(2010) add that as energy prices decline or flat, increasing clean energy supply and relatively small resource rents are combined. Chakravorty et al.(2010) suggest that, in cases where there is learning potential, lower and possibly declining energy prices might occur. This is in contrast with the view in much of the climate change economics literature that increasing fossil energy prices, taken as given, will steer clean energy production and endogenous technological change.

Chakravorty et al.(2010) argue that in the case without learning, where resource rents rise at the rate of discount until fossil fuels are exhausted, the opportunity cost of resources after exhaustion is constant. Chakravorty et al.(2010) add, that in cases with learning, resource opportunity costs peak at the exhaustion point and after that decline over time. Chakravorty et al.(2010) claim that with learning, their dynamic problem of the fossil fuel owner is analogous to a resource extraction model with a backstop and decreasing demand for resources.

Chakravorty et al.(2010) show that with both the 30% and 15% learning rates, the willingness of clean energy firm to produce at a price below marginal cost is decreasing over time because of decreasing returns to learning in terms of future cost reductions. Chakravorty et al.(2010) continue that the 30% learning rate is so fast that after the first 50 years rents from experience are negligible. Chakravorty et al.(2010) argue that the gains from producing at a price below marginal cost are higher as more potential for cost reductions through learning remains, or the higher is the rate of learning.

Chakravorty et al.(2010) highlight that induced technological change is not a shortcut to climate change mitigation, but that strategic responses should be considered when adapting models to include potential technological development. Chakravorty et al.(2010) highlight the importance of assessing resource pricing and clean energy supply jointly, as a function of the potential for endogenous technological change. If this is not done,Chakravorty et al.(2010) argue that it is easy to overestimate resource prices, and thus underestimate emissions and climate change damages, as well as the optimal carbon tax. Chakravorty et al.(2010) prove that equilibrium resource pricing functions are most probably negatively related to the potential for future cost reduction as well as to the effectiveness of climate change policy.

5.8.4. Effects of learning by doing on carbon taxes

It is generally known that resource taxation affects rent extraction. Chakravorty et al.(2010) study how these effects may vary with the potential for learning by doing in a clean energy source. As carbon taxes are set, energy prices are generally expected to increase, fossil fuel supply to decrease, and clean energy supply to rise. Chakravorty et al.(2010) show that these effects do occur, but that the magnitudes vary along the assumed rate of technological change. As energy prices will rise in response to a carbon tax, the effect is negatively influenced by learning rates. Chakravorty et al.(2010) argue, that the greater is the potential for learning, the smaller is the influence of the tax on energy prices. Chakravorty et al.(2010) continue that this effect is most visible at the points where there would normally exist the greatest effect of a carbon tax. These are points where the clean technology is most expensive, and/or where resource scarcity is not at once going to speed the change to substitute energy sources.

Chakravorty et al.(2010) claim that there exists both direct and indirect effects of carbon taxes. The direct effect is an increase in the effective marginal cost of extraction, which is is always captured in models of climate policy. The indirect effects are not necessarily included. Chakravorty et al.(2010) argue that the carbon tax diminishes the future value of resource stocks and thus reducing the incentive of resource owners to conserve. Chakravorty et al.(2010) claim that the effect of the carbon tax on the alternative energy shadow values is ambiguous. The carbon tax raises fossil fuel prices and thus leaves less incentive for the clean energy firm to oversupply to gather experience. On the contrary the carbon tax makes the substitute energy more cost competitive, and thus ensures an increase in the willingness to oversupply. Chakravorty et al.(2010) show that the sum of both direct and indirect effects equals the reduction in resource extraction. Chakravorty et al.(2010) conclude carbon taxes will be more efficient at reducing emissions when learning is possible. The effectiveness of a carbon tax is also increasing in the stock of remaining resources, and/or the cost of clean technology.

5.8.5. Sensitivity to assumptions of learning by doing

Chakravorty et al.(2010) also test how sensitive their results are to changes in market structure. Chakravorty et al.(2010) argue that if assumed oligopoly structure exists in the fossil fuel sector, it implies less incentive to conserve resources and lower energy prices than would be predicted by a monopoly structure. On the contrary, compared to a perfectly competitive market, oligopoly implies more incentive to conserve and higher energy prices. Chakravorty et al.(2010) continue that the assumption that the finite number of firms in the clean energy sector internalize the private benefits of learning on their own future production costs denotes greater dynamic behaviour than if learning was taken as given and less dynamic behaviour if learning was fully internalized.

Chakravorty et al.(2010) now consider a model where the oligopoly structure for fossil fuels is maintained, but clean energy production is allowed to maximize sector net present value. This means effectively a first-best subsidy which corrects the market failure in learning by doing. Chakravorty et al.(2010) also consider a case where each firm is infinitesimal, and thus learning is a public good. Finally, Chakravorty et al.(2010) look at a case of monopoly, and so the net present value of fossil fuel stocks to the owner is maximized conditional on the presence of the competitive fringe.

Chakravorty et al.(2010) reveal remarkable sensitivity to the degree of market power and the degree to which learning gains are internalized. The first-order effect of a monopoly is that eliminating competition results in a steep decrease in extraction. Chakravorty et al.(2010) argue that the second-order effect is that rents are maximized through rising extraction as learning potential is increased. Chakravorty et al.(2010) claim that increased extraction leads to lower production of substitute energy and to less future rent loss. Chakravorty et al.(2010) add that even though monopoly is better for the environment than oligopoly, it may be worse for clean energy technology since the larger market power enables for greater response to the threat to market share.

Chakravorty et al.(2010) claim that when learning by doing occurs as an externality, also an incentive to over-extract occurs where learning potential is highest. Chakravorty et al.(2010) show that extraction by the oligopolists is highest when learning takes place at the fastest rate, and lowest when learning is not possible at all. Chakravorty et al.(2010) continue that this result is reversed where gains to learning are fully internalized by complete patent protection or by first best subsidies to clean production. The previous outcome is driven by lower resource rents, while the latter is driven by much larger shadow values of current clean energy production and smaller resource rents induced by the alternative technology with higher learning potential. Chakravorty et al.(2010) argue that as the potential gains from a clean innovation are internalized by the energy buyer, collected rents decline.

Hence, the effect of learning potential on resource extraction is ambiguous. At the same time the negative effect of learning potential on scarcity rents is very strong. Chakravorty et al.(2010) say that, where the most market power exists, highest rents are charged, and the lowest rents are charged where the greatest threat to fossil fuel producers exists. Chakravorty et al.(2010) emphasize that irrespective of market structure, resource pricing functions are sensitive to the potential for technological change. Chakravorty et al.(2010) add that the important implication of these results is that keeping resource pricing functions fixed when modeling technological progress in climate policy models may lead to biased results, which will hold under a variety of assumptions.

Chakravorty et al.(2010) argue that clean energy supply is no longer monotonically increasing in learning potential when the gains to learning are effectively a public good. Chakravorty et al.(2010) claim that now the reduced resource rents push down energy prices such that equilibrium supply in the highest learning scenario is the lowest among the considered cases. Thus, the oligopolists are certainly slowing the progress of clean energy. On the contrary, when a monopoly owns resources, rents are maximized, and high energy prices will enhance more production and learning by doing in the substitute. Prices under monopoly are lower when learning is possible, but still much higher than under oligopoly. Under monopoly, Chakravorty et al.(2010) argue that production from both energy sources are increasing in learning even though clean energy production does not grow by as much as it would if rents were invariant to learning.

5.9. Carbon tax expectations

Hoel(2010a) investigates the climate change problem incorporating carbon tax expectations of investors and resource owners. Hoel(2010a) states that if investors fear that future carbon taxes will be lower than currently announced, long-run investments in greenhouse gas mitigation may be lower than advisable. On the other hand Hoel(2010a) investigates whether it might be true that if owners of oil and gas resources believe the carbon tax path will increase at a lower rate than optimal, they will postpone extraction compared with the extraction path they would have realized if the government had been able to engage to the optimal tax path. This suggests that even though lack of commitment obviously reduces welfare, it is not clear whether near term emissions will increase or decline as a result of this lack of commitment.

5.9.1. The Model of Carbon Tax Expectations

Hoel(2010a) uses a simple two-period model of an aggregate economy to study how the expected future CO_2 tax affects both emissions and investments in substitutes for the fossil fuels. Hoel(2010b) also uses a two-period model to investigate what happens if governments cannot commit to future carbon tax rates, but the investments to substitute are excluded from that model. Hoel(2010a,b) ignores carbon capture and storage assuming that emissions are identical to carbon extraction. Period 1 in the model of Hoel(2010a,b) describes the near future, estimated 10 -15 years, where one has reasonable confidence about the rate of the carbon tax. Period 2 represents the remaining future.

In the model the government sets the CO2 tax in period 1 and declares its intended CO2 tax for period 2. Hoel(2010a) argues that once the tax is set, fossil fuel resource owners and investors in mitigation capital simultaneously decide their extraction and investment for period 1. Now, given the period 1 outcome, the government sets the carbon tax for period 2, after which the fossil fuel owners make their choices of period 2 extraction. Hoel(2010a) mentions that there will be no further investment in mitigation capital in period 2.

Hoel(2010a) constructs the market for the general purpose good and for the fossil fuel resource. The output, the general purpose good, is increasing in the carbon input and also in a capital good that is a substitute for carbon energy. Hoel(2010a) normalizes the price of the general purpose good to 1 and reports that producers of the general purpose good take the resource price in period 1 and 2 as given. Hoel's (2010a) interpretation is that there is a substitute that has high capital costs and low operating costs (e.g. wind and solar energy). Thus once the investment in capacity is made, the full capacity is used. Other interpretation is that that the substitute would be knowledge capital, as an improved technology that is valid at a low cost once it has been developed.

Even though the investment in the carbon substitute takes place only in period 1, Hoel(2010a) assumes it to affect output in both periods. A parameter tells what share of the total revenues to investment are obtained already during period 1. The output functions are assumed to be concave , and Hoel(2010a) also assumes that the cross derivatives are negative, so that the marginal productivity of using the fossil fuel resource is lower the higher is the investment in in the substitute. Hoel(2010a) restricts the analysis to the case in which the fossil fuel and the substitute are perfect substitutes.

Hoel(2010b) considers it possible to make a political commitment about the carbon tax rate for up to 10-15 years, but resource owners needed to know the tax for a longer period in order to make optimal decisions about their resource extraction. Without a political commitment resource owners base their decisions on their expectations about future carbon tax rates. Hoel(2010b) argues that this may in turn depend on the current carbon tax rate.

Emissions in both periods have an effect on the climate. As there is a time lag of the climate system, the effect of emissions in period 1 on the climate in period 1 are negligible. Especially as the period 1 in Hoel's(2010a) model is only 10-20 years, this can be considered certainly true. Therefore, as Hoel(2010a,b) assumes, climate costs depend on the temperature increase in period 2 which is increasing in emissions in both periods. Climate costs are given by a damage function, which Hoel(2010a,b) assumes to be increasing and strictly convex. Hoel(2010b) argues that it is not obvious that the net affect of period 1 extraction on the temperature rise for a given resource stock is positive. Though, as for the green paradox it matters how rapidly the climate changes, this seems reasonable. Here as well the environmental concern includes both the maximal stock of carbon in the atmosphere, and the fact how rapidly this maximal stock is reached. Thus, Hoel(2010a,b) agree with Sinn(2008a,b) that a postponement of emissions is desirable for the environment. With these assumptions Hoel(2010a) argues that the carbon tax thus rises at a rate lower to the rate of interest.

5.9.2. The Market Equilibrium of Carbon Tax Expectations

Hoel(2010a) describes the market equilibrium for exogenous CO2 taxes in the two periods and the first-best social optimum, and shows what the taxes must be so that market equilibrium coincides with the social optimum. Hoel(2010a) also derives the results if the expected future carbon tax deviates from the optimal one. Hoel(2010a) argues that these results depend on how sensitive extraction costs are to total fossil fuel extraction, and reports that if costs increase quickly with total extraction, near-term emissions are higher the higher is the expected future tax for carbon.

However, Hoel(2010a) claims that if extraction costs rise slowly with total extraction, the opposite result is possible. On the other hand, Hoel(2010a) reports the effect of the expected future CO2 tax on investments in a clean substitute depend on the time profile of the revenues to the investment. If most of the revenues come in the near future, investments are increasing in the expected future CO2 tax, while the opposite is true if most of the revenues come in the distant future.

Hoel(2010a,b) also assumes, as Sinn(2008) does, that climate costs are higher the higher are total emissions, and higher the higher are near-term emissions for a given value of total emissions. Hoel(2010a) shows that if extraction costs rise rapidly as total extraction increases, climate costs are higher the higher is the expected future CO2 tax. Near-term emissions increase as a result of a downward bias in the expected future CO2 taxes. Hoel(2010a) adds that whether investments in emission mitigation increase or decrease due to the expectation error depends on the time profile of the returns to the investment. If extraction costs only rise slowly with total extraction, the opposite result is possible.

Hoel(2010a) emphasizes that the optimal CO2 tax should at all times be equal to the discounted value of all future marginal climate costs caused by the current emissions. Hoel(2010a) argues that at an early stage, as the optimal path of carbon in the air is increasing, rising marginal environmental costs will denote a rise over time in the optimal carbon tax.

Notable subsidies are offered to investments in renewable energy and energy saving capital in several countries. Hoel(2010a) argues that one reason often given for such subsidies is the assumed lack of confidence among private agents in a high future CO2 tax . Hoel(2010a) analyzes whether a subsidy to the clean substitute brings the first-best optimum closer. Hoel(2010a) claims that a small subsidy to clean substitute energy will transfer near-term emissions and investments in clean energy towards their socially optimal values if a large enough fraction of the revenues to the investments realize in the distant future. Hoel(2010a) adds that, if a sufficiently large fraction of the revenues realize in the near future, either near-term emissions or investments will be moved in the same direction by a subsidy as by a low expected future carbon tax.

5.9.3. Effects of a change in the expected future carbon tax

Hoel(2010a) investigates also the effects of a change in the expected future carbon tax on carbon extracted and used in period 1, and the investment in the substitute. Hoel(2010a) argues that while tax rate for period 1 is known when decisions are made for the first period, tax rate for period 2 has the status of an expected price. Similarly, carbon extracted and used in period 2 has the status of a planned variable for the resource owners, and status of an expected variable for the other agents.

Hoel(2010a) first considers the limiting case in which the capital good is not a perfect substitute for the resource. In this case the cross derivatives between the capital good and the resource are zero. Thus, the investment in the substitute is independent of the expected tax rate, and moreover, the carbon extracted and used in period 1 is increasing in the expected future tax rate. Thus, in this case near-term emissions are higher the higher is the expected tax.

Hoel(2010a) argues that a more interesting case is when the cross derivatives are negative and capital and resource are perfect substitutes. Hoel(2010a) argues that as the expected tax rate rises, extraction in period 2 becomes less profitable. Thus period 1 extraction increases and period 2 extraction decreases. Hoel(2010a) adds that the increase in period 1 extraction reduces the payoff to the investment in period 1, while the reduction in period 2 extraction increases the period 2 payoff. Hoel(2010a) states that the former effect will dominate if the share of the total returns to investment that are obtained already during period 1 is large, while the latter effect will dominate if the share is small.

5.9.4. Governments not able to commit to future carbon tax rates

Hoel(2010b) perceives the expectations so that they are rational in the sense that market participants believe that the government in period 2 will set the carbon tax optimally based on the preferences of the government. Hoel(2010b) verifies that an increase in the expected carbon tax, holding period 1 carbon tax constant, will give an increase in the period 1 extraction. Hoel(2010b) considers it more relevant to question how a change in period 1 carbon tax will affect the consumer price and hence the period 1 extraction, when the expectation about period 2 tax might depend on period 1 tax. Now, what are the conditions for a green paradox to occur, in the sense that an increase in the period 1 carbon tax gives a rise in period 1 emissions?

If the total resource extraction is exogenous, Hoel(2010b) argues that a green paradox occurs if and only if the tax rate is assumed to grow at a rate higher than the interest rate. Hoel(2010b) adds that if this is the case, an increased period 1 tax will give an expectation of an increase in period 2 tax that in present value is at least as large as the tax rise in period 1.

Hoel(2010b) reports that an increase in the carbon tax in period 1 increases the consumer price in period 1 and reduces it in period 2. Therefore, the extraction of the fossil fuel declines in period 1 which implies that there is no green paradox with such reasonable assumptions about how expectations of future taxes are formed. Thus, as Hoel(2010b) states, as the current carbon tax increases, the expected future carbon tax decreases, and obviously, no green paradox can occur.

5.9.5. The effects of subsidizing investments in the renewable energy

Hoel(2010a) argues that one reason that is often given for subsidies offered to investments in renewable energy, particular in the EU, is the alleged lack of confidence in a high future CO_2 tax among private agents. Hoel(2010a) investigates whether a subsidy to the substitute brings us closer to the first-best optimum such that it moves the first period extraction and investment in the substitute in the opposite direction of what the error in the carbon tax expectation does.

Hoel(2010a) claims that if the share of the total returns to investment obtained during period 1 is high either first period emissions or investments, or both, will be moved in the same direction by a subsidy as by a low expected future carbon tax. Hoel(2010a) adds that if most of the returns occur in the distant future, can a subsidy partly offset the effect of carbon tax expectations on first period extraction and investment being too low. Hoel(2010a) thus argues for subsidizing such investments, assumed that market participants typically underestimate the size of future carbon taxes.

Hoel(2010a) states that there will be problems with implementing an optimal climate policy since policy makers cannot commit to a high future carbon tax. It is often argued in the climate policy debate that long-run investments in emission mitigation may be lower than desirable since investors are afraid of future carbon prices being lower than currently announced by governments. If this is the case, carbon emissions may be higher than they would optimally be, if government could commit to the optimal carbon tax path. However, Hoel(2010a) highlights that it is not evident how expectations about future CO_2 taxes influence investments in renewable energy and near-term emissions. Hoel(2010a) claims that the impacts of carbon tax expectations on these variables depend to a large extent on the properties of the extraction costs of carbon resources. Hoel(2010a) states that most of the researchers that treat the resource aspect explicitly, assume that there is a strict physical limit of the resource available, and that the entire resource will eventually be exhausted. However, Hoel(2010a) considers it a much more realistic to assume that no such absolute limit exists, but that extraction costs are increasing in total extraction.

Therefore, Hoel(2010a) argues that the effects of the future carbon tax expectations on near-term emissions and investments in clean substitutes depend substantially on how fast extraction costs increase with increasing total extraction. Moreover, Hoel(2010a) states that how the returns to the investment in the substitute distribute in time is consequential for the effects of the future carbon tax expectations.

5.9.6. Optimal Carbon Taxes

Hoel(2010b) argues that the reason for the possibility of green paradox is the fact that fossil fuels are nonrenewable scarce resources. Hoel(2010b) points out that the key decision of the fossil fuel owners is not so much how much to produce it but when to extract it. As Sinn(2008) argues, if a carbon tax rises sufficiently fast, profit maximizing resource owners will forward the extraction of their resources. Thus, near-term carbon emissions increase as carbon capture and storage (CCS) is not included. Hoel(2010b) admits that with such a carbon tax path total costs related to climate change may reduce, since with such a tax the total carbon extraction may reduce. Hoel(2010b) claims that regardless of the expectations about future carbon taxes, near-term emissions will reduce for a sufficiently high carbon tax. However, Hoel(2010b) adds that if the near-term tax rate is set below its optimal level, increased concern for the climate may change taxes in a way that rises near-term emissions.

Hoel(2010b) states that one of the insights from the literature of the optimal carbon tax path in the presence of fossil fuel resource scarcity is that the principles for setting an optimal carbon tax are the same as when the physical limit of carbon resources is ignored. Thus, the optimal price of CO2 emissions should be equal to the present value of all future climate costs caused by present emissions. Though, Hoel(2010b) adds that when actual policies differ from optimal, results might be different from what would be if carbon resource scarcity were ignored. Hoel(2010b) focuses on the effects of carbon taxes that are not optimally designed and considers also the case of a CO2 tax that is currently set optimally but without the regulator committing to the future tax evolution.

5.9.6.1. Carbon extraction as given

Hoel(2010b) considers the simplest model of resource extraction, where available amount of the carbon resource is given, and unit extraction costs are constant. Producers are price takers and there is an exogenous interest rate. Hoel(2010b) regards a sufficiently large carbon tax, defined as a time path per unit of extraction. Hoel(2010b) finds out that for a this kind of carbon tax the resource constraint is not binding, as the competitive supply of the resource is like the supply of any good, and therefore the resource rent is zero. Hoel(2010b) highlights that for this case no green paradox occurs, as the carbon resource extraction at any date is simply equal to demand, and thus independent of the rate of future carbon tax.

Hoel(2010b) admits that it is unrealistic to consider a carbon tax path so high that it drives all carbon resource rents to zero. However, as Hoel(2010b) argues, with resources with differing extraction costs, a carbon tax designed to reach fairly ambitious climate targets may drive the resource rent to zero for the resources with the highest costs.

Hoel(2010b) assumes next that the carbon tax rises at a constant rate that equals the exogenous interest rate, i.e., the present value of the tax rate is constant. In this case the extraction profile that maximizes profits for producers without the carbon tax also maximizes the profits as the present value of the CO2 tax is included. Hoel(2010b) argues that this result can be generalized to all cost functions, as long as the total amount extracted is not affected by the tax.

If the carbon tax rises at a rate higher than the interest rate, Hoel(2010b) argues that to maximize profits, resource owners will extract more earlier and less later compared to the case without taxation. Thus, the green paradox occurs, as there will be more extraction and hence more emissions in the near future. Moreover, Hoel(2010b) claims that this effect is stronger the higher is the current tax rate, so that present and near-term emissions increase as the present carbon tax rises.

Now if carbon tax rises at a rate lower than the rate of interest, which is what models that derive optimal climate policy typically suggest, Hoel(2010b) claims that the result is exactly the opposite of the previous. Extraction and hence emissions are lower in the near future than without a carbon tax. Similarly here, Hoel(2010b) adds, that this effect is stronger the higher is the current tax rate, so that present and near-term emissions decrease as the current carbon tax rises.

5.9.6.2. Total carbon extraction is endogenous

It is not realistic to assume that the carbon resources are homogeneous and have the same extraction costs. It is more realistic to assume that the unit cost of extraction is increasing in accumulated extraction. Hoel(2010b) argues that if there is an absolute limit on total fossil fuel extraction, and this limit is binding both with and without the carbon tax, there will be no remarkable differences compared to the case of constant extraction costs. The more interesting case is when the total extraction is determined endogenously, and there will be no absolute binding limit on total carbon extraction. Hoel(2010b) makes a simplification by assuming a choke price so that demand for a carbon resource is zero if the price is sufficiently high. All carbon resources that have an extraction cost below the choke price are extracted with a positive resource rent.

Hoel(2010b) argues that without any carbon tax, the equilibrium stays as before. Hoel(2010b) claims that the implementation of a carbon tax will reduce total extraction as there will be resources that would have been extracted without the carbon tax but which will be left unextracted with a carbon tax. Thus, as Hoel(2010b) adds, total emissions reduce as a consequence to a carbon tax, regardless of the time profile of the carbon tax.

When considering the green paradox, the obvious question is what happens to the present and near-term emissions. As the total extraction reduces, emissions must also reduce in some time periods. Hoel(2010b) argues that if the carbon tax rises at a rate equal to interest rate, the present and near-term emissions go down, as the initial consumer price goes up as a response to the carbon tax. Hoel(2010b) adds that the same applies when the carbon tax rises at a rate below the interest rate. Hoel(2010b) claims that the near-term emissions may decline even if the tax rate rises by a rate somewhat higher than the interest rate. Only for a sufficiently rapidly increasing carbon tax the green paradox may occur as near-term emissions increase. However, Hoel(2010b) argues that even then the carbon tax may be desirable as it reduces total emissions. Hoel(2010b) concludes that total extraction is lower the higher is the level of the carbon tax path, and that the costs of the climate change may be lower when a tax is implemented, even if near-term extraction would be higher.

5.9.6.3. No green paradox with a high carbon tax

As Hoel(2010a,b) has shown it can generally be said, that a sufficiently high initial carbon tax will reduce carbon emissions, regardless of what the cost function is and no matter what expectations about future carbon taxes are. Hoel(2010b) argues that this is true under the mild assumption that fossil fuel owners will never sell their resource at a price lower than their extraction costs. If the policy makers introduce a CO2 tax that is higher than the resource rent prior to the introduction of the tax, the consumer price must increase for resource owners to cover their extraction costs. Thus, the demand for the resource, and therefore the carbon emissions, must reduce.

Hoel(2010b) investigates exactly how high must a carbon tax be for carbon emissions to decline. Hoel(2010b) states that the answer will differ between the two most important sources of carbon, oil and coal. Hoel(2010b) uses as an example data from 2010 prices arguing that 49 dollars corresponds tonne of CO2 from coal. This is the coal price that is split between extraction costs and resource rent. Hoel(2010b) argues that the resource rent is most likely much lower than 49 dollars per tonne. In addition, Hoel(2010b) highlights that in any case, a carbon tax above 49 dollars per tonne of CO2 will certainly rise the consumer price of coal, and thus reduce CO2 emissions from the use of coal. Similarly, Hoel(2010b) argues that 179 dollars corresponds tonne of CO2 from oil, and that a carbon tax above 179 dollars per tonne of CO2 will certainly rise the consumer price of oil, and thus reduce CO2 emissions from the use of oil.

Hoel(2010b) states that since there are extraction costs for oil, the threshold for the carbon tax is actually lower than this 179 dollars. Hoel(2010b) assumes extraction cost of oil of 30 dollars per barrel, which means that the threshold is actually 109 dollars per tonne of CO2. Hoel(2010b) emphasizes that even this is much higher than tax rates or emission quota prices in most countries. For instance, Hoel(2010b) reports that EU's quota price is only about 19 dollars per tonne of CO2 . Yet in some countries there are carbon taxes well above 109 dollars per tonne of CO2, for instance in Sweden. Hoel(2010b) argues that most integrated assessment models state that an optimal present price of emissions is explicitly below 100 dollars per tonne of CO2.

Hoel(2010b) argues that for carbon taxes below the optimal 100 dollars per tonne of CO2 the possibility of increasing emissions from oil use cannot be ruled out. Yet, emissions from the use of coal will certainly decrease with a carbon tax above 49 dollars per tonne of CO2. As an extraction cost of coal of 50 dollars per tonne is considered, the threshold is reduced from 49 to 24 dollars per tonne of CO2. Hoel(2010b) reports that for the ambitious climate goals the optimal near-term carbon prices derived from integrated assessment models are in many cases above 24 dollars per tonne of CO2. Thus, a worldwide carbon tax above 24 dollars per tonne of CO2 is likely to reduce emissions from coal. However, as Hoel(2010b) claims, there is still a possibility of increasing oil extraction as a consequence to a global carbon tax between 20-100 dollars, and thus near-term emissions might increase as a response to a carbon tax in this range.

5.9.6.4. Green paradox with endogenous carbon taxes

Hoel(2010b) also analyzes a green paradox with endogenously determined carbon taxes, since in real life, tax rates will be determined endogenously, depending on the government's preferences related to climate change. Hoel(2010b) analyzes the effects of an increased concern for the climate, and shows that a green paradox may occur if there is some obstacle that prevents the period 1 tax being as high as its optimal level. Thus, if the tax rate is equal to its optimal value, increased concern for the environment postpones extraction and emissions.

5.10. Early Announcement of a Climate Policy

Next we consider how an early announcement of a climate policy affects the carbon emissions. Di Maria et al.(2008) study the effectiveness of a climate policy in a model with fossil fuel resources that differ in their carbon content, by examining the response of coal and oil owners to an early announcement of an anticipated climate policy. Di Maria et al.(2008) find that the inelastic supply of the fossil fuel resources might induce lower prices before to the policy implementation, encouraging emissions. Di Maria et al.(2008) show that, when there is some time between the policy announcement and implementation of a cap on carbon dioxide, emissions from fossil fuels increase at the time of announcement. Di Maria et al.(2008) argue, that this id due to two things. First, as a binding constraint restricts emissions and thus energy use during some time period, more must be extracted during other periods. Second, Di Maria et al.(2008) claim that since lower carbon energy sources are relatively more valuable after the policy is implemented, it is optimal to conserve them now, which might cause a switch to dirtier resources before the policy is executed.

Smulders et al(2010) and (2012) argue that imposing a carbon tax by surprise involves discontinuities in consumption and saving processes, which is unlikely to satisfy general public. Di Maria et al.(2008) and Smulders et al(2010) argue that policies are announced early to give firms a chance to reorganize their production process and consumers the possibility to rethink the purchase of durable goods before policies are actually implemented. This would reduce compliance costs. However, as Di Maria et al.(2008) claim, this may not be the case in the context of energy and climate change policy. By increasing the price of fossil fuels, climate policy should induce both firms and consumers to substitute away from carbon intensive energy. However, as Di Maria et al.(2008) argue, when fossil fuel owners face a lower demand for their products, they have an incentive to reduce their price. In particular, when energy is produced from non-renewable resources, the owners of resources with high carbon content have an incentive to lower their prices in anticipation of future CO2 reductions, in order to ensure their resources to be exploited.

Smulders et al(2010) and (2012) agree with Di Maria et al.(2008) in that a green paradox may originate from early announcement of an intended climate policy. Smulders et al(2010a) also study the consequences of announcing climate polices well ahead of their implementation and show how the announcement of a carbon tax implies an increase in emissions in the interim period. However, Smulders et al(2010) deviate from the interpretation of Di Maria et al.(2008) arguing that scarcity of the polluting input is not required to generate the paradoxical announcement effect. Smulders et al(2010) argue that this is relevant to abundant resources like coal for which the scarcity rent is small. Smulders et al(2010) claim that the results hold both when households take the announced implementation date as a credible threat and when households believe that the government is not able to implement the policy announced.

Smulders and van der Werf(2005) investigate how an anticipated emission constraint affects the extraction of two non-renewables that differ in their carbon content, and are imperfect substitutes. Smulders and van der Werf(2005) argue that it depends on the relative scarcity and productivity of the resources whether emissions increase once the announcement is made. Smulders and van der Werf(2005) claim that production per unit of carbon emissions is relatively high at the time the constraint is binding, and low when constraint ceases to bind. Thus, when the constraint is binding, the resource with the lowest amount of emissions per unit of output is used more, and this resource is necessarily not the resource with lowest amount of emissions per unit of energy.

Smulders et al(2010) pay attention to saving decisions made by households and to the effect of capital stock on energy demand. Smulders et al(2010) argue that as households anticipate the future increase in the price of fossil energy, they reduce consumption and increase saving in order to smooth consumption at the time the carbon tax is implemented. Smulders et al(2010) argue that higher saving implies larger capital stocks, and as capital and energy are complements as factors of production, the accumulation of capital also enhances the demand for energy.

5.10.1. The Model of Early Announcement

Di Maria et al.(2008) modify the model of Hotelling(1931) in which utility is derived from consuming a final good, which is produced using two non-renewable resources differing in their carbon content, coal and natural gas. Di Maria et al.(2008) do not consider physical capital and focus on the optimal extraction path and the associated optimal emission path, that follows the announcement.

Di Maria et al.(2008) examine the optimal response of consumers, producers, and resource owners to an announced ceiling on flow of the carbon emissions. In their model Di Maria et al.(2008) assume a high-carbon nonrenewable resource, and a low-carbon one, to be perfect substitutes in the production of electricity. Di Maria et al.(2008) also assume that the economy faces a constraint on the CO2 emissions at some exogenously set and known time in the future. Di Maria et al.(2008) include no market failures in their model as they study cost-effective rather than optimal climate policy. Thus, Di Maria et al.(2008) present the decentralized economy by the social planner's solution in which utility is maximized subject to the technology, resource and constraints on emissions.

The climate policy of Di Maria et al.(2008) states that emissions arise from resource use, but from time T on they are constrained not to exceed a certain limit. The key point of the model of Di Maria et al.(2008) is the fact that the policy is announced at the beginning of the planning horizon but only becomes effective with a delay. Thus, the planning horizon is divided in two phases. First period is the interim phase when the constraint is not yet reinforced, and second, the enforcement phase when the constraint is enforced and becomes binding. If the constraint never binds, environmental policy has no influence on the agent's selection.

Di Maria et al.(2008) argue that since the two non-renewables are perfect substitutes as sources of utility, the two are identical as long as their carbon content is irrelevant. Di Maria et al.(2008) report that it is not optimal to leave any fossil fuels in the ground, and hence the whole stock will be exhausted over the infinite time horizon. Di Maria et al.(2008) claim that in the laissez-faire economy, optimal extraction paths are solely determined by the initial scarcity of the resource. Since the resources are identical as long as their carbon content is irrelevant, the exact composition of extraction is not determined, and thus, so is carbon intensity of energy.

5.10.1.1. Model with saving and capacity

In the model of Smulders et al(2010) the economy consists of a final good sector, an energy sector and household sector that owns capital and labor. In the final good production, inputs are capital, energy and labor all with constant returns to scale technology. Smulders et al(2010) divide the energy sector in fossil energy firms and solar energy firms, and assume that the two sources of energy are perfect substitutes and allow for a competition between these two energy sources. Smulders et al(2010) argue that timing and technological opportunities of these technologies are decisive in determining the announcement effects. Smulders et al(2010) consider both, investment in productive capacity, and equipment and knowledge capital for alternative energy supply.

As fossil energy is produced by burning fossil fuels at a constant marginal cost, Smulders et al(2010) argue that solar energy is produced by capital input, and that once the solar technology has been set up, there is no additional variable cost associated with solar energy production. Thus, the cost of solar energy is purely the capital cost. Smulders et al(2010) continue that solar energy firms decide their investments based on current and future prices of energy and capital in order to maximize the present value of their profits. Smulders et al(2010) report that, at each point in time, the equilibrium interest rate, thus the price of the capital, equates the capital demand and supply. The capital supply is determined by saving of households. Smulders et al.(2010)and (2012) use the simplest specification of a Cobb-Douglas technology and a mild tax rate. Smulders et al.(2010)and (2012) claim that, these assumptions are not essential and the green paradox can be obtained in a more general setting.

Smulders et al(2010) argue that if the energy price is low relative to the discount rate, the high time cost of capital averts the accumulation of capital to make solar energy competitive relative to the fossil fuel. Smulders et al(2010) continue, that the low discount rate then creates abundance of capital and, in turn, low opportunity cost of solar energy investment. When also the fossil price is high, these together generate high returns to solar energy. Smulders et al(2010) report that as the initial capital stock is small, energy is derived exclusively from fossil fuels and investment in solar capital is postponed. Smulders et al(2010) argue that investment in solar capital starts once capital reaches the threshold level, which is the lowest level at which investment in solar capital is profitable. Smulders et al(2010) argue that now simultaneous investment in capital and solar cannot happen since the return to further investment in capital reduces below the return to solar investment, which is defined by the fossil energy price as long as fossil fuels are needed to fill energy demand. Only after solar energy has fully replaced fossil fuels, investment simultaneously in both capitals becomes attractive.

5.10.2. The Abundance Effect

Di Maria et al.(2008) claim that as the policy is announced before enforcement, the amount of resource that cannot be used during the constrained period, can be extracted not only after the constraint ceases to be binding, but also in the interim phase before the constraint becomes enforced. Consequently, it is optimal to increase the amount of energy consumed in the interim phase, thus resource use jumps up at the instant of announcement. This is, how Di Maria et al.(2008) denote the essence of the abundance effect. Di Maria et al.(2008) continue that in order for both fossil fuels to be exhausted over time, extraction during interim phase needs to be larger than under laissez-faire. Di Maria et al.(2008) claim that this abundance effect occurs irrespective of the number of resources in the economy.

Di Maria et al.(2008) argue that keeping emissions per unit of energy constant, the announcement of climate policy results in an instant increase in emissions. Di Maria et al.(2008) add that as energy use increases, so does the level of emissions, unless the carbon intensity of energy decreases proportionally more than the increase in energy use. Smulders et al(2010) agree in that the early announcement increases the use of fossil fuel energy during the intermediate period between the announcement and the actual implementation. Thus, the green paradox may occur. Smulders et al(2010) report that this announcement effect holds both when the economy remains fossil based even after the tax and when it switches to solar energy after the tax. Smulders et al(2010) argue that there is also a favorable effect when parties start abating pollution, partly as it is less costly to decrease emissions over time rather than do it all at once. The unfavorable effect occurs when parties increase pollution, as they want to use the stocks of polluting inputs quickly before they are forbid.

Smulders et al(2010) find also another effect in addition to the announcement effect, the leakage effect. The leakage effect arises with incomplete participation and coverage of the policy, as the response of unregulated parties and countries could invalidate some or all of the emission reductions in the regulated sectors and countries. When the emission reduction of regulated countries is more than offset by increased emissions in unregulated countries, green paradox exists.

5.10.3. Relative Scarcity

As Di Maria et al.(2008) argue, the clean fuel allows more energy to be consumed during the constrained period, and thus producers prefer to conserve it for the implementation period. When there is only small amount of clean fuel available, it is desirable to use only the dirty fuel in the interim period, so that all of the clean fuel is left to use during the enforcement period. If there is enough clean fuel available, it can be used already in the interim period, and still have enough of it available for use at the implementation phase. Di Maria et al.(2008) claim that the introduction of a binding constraint has different effects on the relative scarcity of the two resources, depending on the initial endowment of each resource.

Di Maria et al.(2008) claim that the scarcity rent of the dirtier resource never exceeds the rent of the cleaner resource. However, the optimal extraction path during the unconstrained periods will be very different depending on whether the scarcity rents are equal, or whether the scarcity rent of the dirtier resource is strictly smaller. Di Maria et al.(2008) add that in the latter case, only the cheaper, dirtier fuel will be used during these periods. Di Maria et al.(2008) report that scarcity rents are equal when welfare cannot be enhanced by changing initial endowments, replacing one unit of resource by one unit of the other. Di Maria et al.(2008) add that this indifference situation arises, if the initial stock of low carbon resource is large enough, while the stock of high carbon is not too large.

5.10.4. The Ordering Effect

In a economy with multiple resources, emissions intensity is determined by the order, or composition, of extraction. Di Maria et al.(2008) investigate a case of two resources that differ in their carbon content and show that in addition to the abundance effect, there exists an ordering effect of the announcement on the carbon intensity. Di Maria et al.(2008) argue that an ordering effect occurs when the cleaner resource is relatively scarce and the announcement of the constraint shifts extraction from cleaner resource to the high-carbon one in the interim phase. Di Maria et al.(2008) argue that depending on initial endowments, the intensity of ordering effect differs. Large total energy reserves, mainly consisting of the high carbon fuel, provide the incentive to consume a large amount during the interim period. The relative scarcity of the low carbon resource makes it optimal to leave this more valuable energy resource in the constrained period as it as cleaner energy allows more energy consumption. Di Maria et al.(2008) explain that the announcement makes the scarcity rent of clean resource exceed that of dirty one, and thus it becomes optimal to extract only the dirty resource in the interim period. Di Maria et al.(2008) call this the extreme ordering effect.

Di Maria et al.(2008) argue, that on the other hand, the policy announcement does not make the low carbon fuel relatively scarce, as rents are equal for the resources. Now there is enough of the clean fuel available to use in the interim phase and yet have enough for the constrained phase. Di Maria et al.(2008) claim that no ordering effect occurs, and the expected emissions intensity is the same as under laissez faire. Next, Di Maria et al.(2008) claim that even though the scarcity rents are equal, clean resource is still scarce enough to dictate an exact requirement for extraction. Di Maria et al.(2008) add that this restriction inflicts a lower bound on the amount of dirty resource that needs to be extracted in the interim period, and practically introduces a weaker ordering effect. Thus, Di Maria et al.(2008) conclude, that the weak ordering effect increases the expected carbon intensity of extraction during the interim period. Di Maria et al.(2008) also point out that, the impact of the weak ordering effect is weaker, the lower the carbon content of initial stocks are. Di Maria et al.(2008) point out that an ordering effect also exists when the two resources are imperfect substitutes.

5.10.5. The Effects of Early Announcement

Di Maria et al.(2008) argue that regardless of the number and carbon content of resources, energy use jumps up at the instant when the future constraint on emissions is announced, which leads to an increase in emissions. When ordering effect is added, Di Maria et al.(2008) report that the resulting carbon content of extraction can be determined. When the abundance effect operates, but there is no ordering effect, Di Maria et al.(2008) argue, that even though anything specific about actual extraction paths can be revealed, there is no reason to expect that the announcement would affect the ordering of extraction. Thus, Di Maria et al.(2008) expect emissions to jump up at the instant of announcement.

Next, when the abundance effect is combined with the weak ordering effect, given that the energy use increases as a consequence of the policy announcement, and that the expected carbon intensity increases as well, Di Maria et al.(2008) expect emissions to increase in the interim period as well in this case. Finally, in a case where abundance effect is compounded with the extreme ordering effect, Di Maria et al.(2008) argue, that emissions increase in the interim period. The extraction increases due to the abundance effect, and additionally all of this extraction is from the most polluting resource due to the extreme ordering effect. Thus, green paradox occurs.

Di Maria et al.(2008) conclude that the energy use, and thus emissions, increase as a consequence to the policy announcement. Then it depends on the scarcity of the the clean resource, of how much the emissions increase still. Di Maria et al.(2008) argue that there is a trade-off with respect to climate policy: reducing costs of compliance through announcing the policy in advance, versus the environmental risk that this will increase carbon dioxide emissions, and thus accelerate global warming. The existence of this trade-off should be recognized, and the risk of causing an increase in emissions should be taken into account.

Smulders et al.(2010) argue that even if it sounds desirable to announce the intention to levy a carbon tax in future in order to allow households and firms a period to prepare for the forthcoming tax, this turns out to be harmful as it raises emissions during the interim period. Smulders et al(2010) continue that this paradox occurs disregarding the scarcity of fossil fuels. Smulders et al.(2010) claim that the paradox exists due to households' decisions about saving and consumption tradeoffs. These tradeoffs arise from the households' desire to smooth consumption at the transition to the tax regime. Smulders et al.(2010) argue that anticipating the higher future price of fossil fuels, due to the carbon tax, households reduce consumption and increase saving, giving rise to a faster accumulation of capital in order to diminish the decline in energy use at the time the carbon tax is implemented. Before the tax is implemented, the larger capital stock implies a higher rate of fossil energy use. Smulders et al.(2012) add that uncertainty in the timing of introducing and executing the carbon tax is another mechanism to cause green paradox without resorting to the scarcity of the fossil resource.

Smulders and van der Werf(2005) state that the announcement of the constraint causes a decrease in the extraction of the relatively more productive resource in terms of GDP per unit of emissions, so that this resource is conserved more for the constrained period. Thus, the less productive resource is used more before the constraint becomes binding, and the more productive resource as the constraint becomes binding. Smulders and van der Werf(2005) add that on the one hand, scarcity results in a high relative price, low extraction, and high productivity. On the other hand, as emissions cost, producers substitute towards the resource with highest productivity per unit of carbon emissions. Smulders and van der Werf(2005) argue that this is the scarce factor. Smulders and van der Werf(2005) conclude that scarce resource is not necessarily the high-carbon resource, as emission and productivity coefficients, and substitutions elasticity determine whether the low-carbon or the high-carbon resource is considered as relatively scarce. As the emission constraint is announced, agents anticipate that the now scarce resource will be even scarcer in the future, and thus they start using less of this scarce resource now.

Smulders and van der Werf(2005) suggest that these things considered, the fast transition to a low-carbon energy is not necessarily the best way to mitigate the climate change. Even though emissions per unit of energy are larger for coal than oil, and although coal is more abundant, it is an imperfect substitute to oil or gas in for example transportation. Thus, Smulders and van der Werf(2005) claim that it is ambiguous whether a shift away from coal will lead to lower emissions per unit of GDP.

5.10.6. Uncertain implementation date

Smulders et al.(2010) and (2012) also consider a case where the precise carbon tax implementation date is uncertain, and show that the paradox exists also when parties do not believe in the government's capability or willingness to execute the policy as announced. Smulders et al.(2010) and (2012) consider the occurrence of the implementation date exogenous as it may depend on global issues, as the ratification and implementation of some international agreement or on political conditions.

Smulders et al(2010) argue that also now the result is driven by the anticipation that the tax will reduce energy use in the future, which induces consumers to increase saving now in order to gather more capital that can substitute for the lower energy input. Thus, prior the implementation, the increased capital stock increases energy input and therefore the green paradox exists. Smulders et al.(2010) and (2012) tell that implementation implies a sudden adjustment to the higher fossil energy price and there will be a discontinuous jump in the consumption and the deployed processes are adjusted to minimize the utility loss associated with the jump. The larger wealth can be used as a buffer to smooth discontinuous change in consumption when the carbon tax is implemented.

Thus, Smulders et al(2010) argue that depending on the relative cost of the investment types, a green policy announcement may lead in increased pollution during the interim period. Smulders et al.(2010)and (2012) argue that uncertainty decreases consumption but not as much as an exact implementation would. Even though, Smulders et al.(2010) and (2012) claim that this result of increased fossil energy use is strong and lasts at all times until the tax policy is executed. Smulders et al(2010) tell that this result holds both when the policy is a low tax rate which reduces fossil fuel use but does not provoke the use of alternative energy as well as when the tax rate is high enough to induce a shift to clean energy. Smulders et al.(2010) and (2012) remark that the saving comes at the expense of consumption, and the realization of the green paradox effect depends on a condition that relates the production elasticity of capital to the elasticity of marginal utility of consumption. Smulders et al.(2012) continue that since uncertainty is a common factor characterizing climate policies, this negative effect may be significant.

5.11. Increasing Unit Carbon Taxes

Sinn(2008) studies the possible responses of intertemporally profit maximizing fossil fuel owners to climate policies examining increasing ad-valorem and cash-flow taxes within a Hotelling model. In contrast to Sinn(2008), Edenhofer and Kalkuhl(2011) consider increasing unit taxes on resource extraction as the economic and political debate mainly consider carbon taxes as unit taxes which are not linked to actual prices of fossil fuel. Edenhofer and Kalkuhl(2011) add that ad-valorem tax can be transformed into an unit tax.

5.11.1. The Model of Increasing Unit Resource Taxes

Edenhofer and Kalkuhl(2011) use the model of Sinn(2008) simplifying it with constant extraction costs and competitive resource side and extending it by a formal analysis of unit taxes. The analysis of Edenhofer and Kalkuhl(2011) differs from Sinn's(2008) in that as Sinn(2008) assumes that all fossil fuel resources are exhausted, Edenhofer and Kalkuhl(2011) assume that the cumulative amount of extraction might be lower within an infinite time horizon. Sinn(2008) focuses only on a pure timing effect of policies, as Edenhofer and Kalkuhl(2011) also take into account a volume effect. Even though Hoel(2010b) calculates that a carbon tax of 179 dollars per tonne of CO2 from oil will surely decrease carbon emissions from the beginning, Edenhofer and Kalkuhl(2011) argue that due to the heterogeneity in fossil fuel extraction costs and demand, it is challenging to calculate the critical initial tax level leading to reduced cumulative extraction. Therefore, Edenhofer and Kalkuhl(2011) focus on the timing effect of carbon taxes and their effect on fossil fuel extraction.

5.11.2. Unit Carbon Tax Rate

Edenhofer and Kalkuhl(2011) distinguish three cases. In the first case, the carbon tax grows at the discount rate, in the second case the carbon tax grows at a lower rate than the discount rate and in the third case the carbon tax grows at a rate higher than the discount rate.

If the carbon tax grows at the discount rate, Edenhofer and Kalkuhl(2011) claim that the growing tax will not have an impact on the time path of the resource price and, thus, resource extraction. Edenhofer and Kalkuhl(2011) argue that if the initial tax is below or at the level where a pure tax and extraction cost would equalize cumulative demand with the total resource stock, the initial consumer price equalizes the entire resource stock with the cumulative demand over an infinitive time horizon. If the initial tax level is above that level, the consumer price will equal the tax and is at each point in time strictly higher than in the case without tax. Thus, Edenhofer and Kalkuhl(2011) claim that a unit tax increasing with the discount rate has no timing effect. However, Edenhofer and Kalkuhl(2011) argue that it may have a notable volume effect in decreasing demand and conserving the resources. Thus, with a unit tax increasing at the discount rate, a green paradox cannot exist.

Edenhofer and Kalkuhl(2011) claim that if the carbon tax grows lower than the discount rate, the resource tax will have a timing effect, as the price path is flattened and, thus, extraction is delayed. It depends on the initial tax level whether the cumulative extraction is affected. Edenhofer and Kalkuhl(2011) report that if it was set equal or below the level where cumulative demand is equalized with the total resource stock, the entire stock will be exhausted. Edenhofer and Kalkuhl(2011) continue that if the initial tax level was set above this level, the resource tax would decrease the cumulative demand, and thus the resource stock will not be fully exhausted. Thus, in this case the volume effect reduces emissions. In either case, the tax delays extraction and therefore reduces climate damages by the timing effect.

In the third case, Edenhofer and Kalkuhl(2011) assume that the carbon tax grows with a rate higher than the discount rate, and claim, that the tax will have a clear timing effect. Edenhofer and Kalkuhl(2011) argue that the price path is steepened and, thus, extraction is hastened. Again, the volume effect depends on the initial tax level. Edenhofer and Kalkuhl(2011) argue that an initial tax level that is below the level where cumulative demand is equalized with the total resource stock, does not reduce the cumulative extraction. However, as Edenhofer and Kalkuhl(2011) highlight, climate damages increase because the resources are extracted too early. Thus, the green paradox occurs. In contrast, Edenhofer and Kalkuhl(2011) report that if the tax level is above the level where cumulative demand is equalized with the total resource stock, the cumulative extraction will be reduced and the stock is not fully exhausted. In this case, as the volume effect leads to lower long term extraction, Edenhofer and Kalkuhl(2011) claim that the near term extraction could in effect increase due to the timing effect. The higher is the initial tax level, the stronger the volume effect, and, thus, the timing effect reduces more.

5.11.3. The Role of the Discount Rate

According to Edenhofer and Kalkuhl(2011) the green paradox does only occur for a special set of increasing carbon taxes, with low initial tax level and with a tax growth rate higher than the effective discount rate of the resource owners for the whole time horizon. Edenhofer and Kalkuhl(2011) emphasize that it is the discount rate resource owners use that is crucial for the green paradox, not the choice of an appropriate social discount rate. Edenhofer and Kalkuhl(2011) argue that the social discount rate is important for estimating costs and benefits of mitigation and for defining optimal mitigation targets.

Edenhofer and Kalkuhl(2011) argue that it is difficult to determine the discount rate resource owners use to discount their resource rent. Market interest rates differ between regions and in risk of financial assets and change in time. As the rate of return of UK or US government bonds has been 1.5 % in the long-run, the rates of private equity are around 6-7 %. Edenhofer and Kalkuhl(2011) report that fossil fuel owners may also add an additional risk premium if the ownership of the resources is insecure due to political instability or if future markets for fossil fuels are incomplete. Edenhofer and Kalkuhl(2011) add that estimated effective discount rates of OPEC countries might even exceed 25 % while in industrialized countries they are estimated to be around 10 %. Even though these rates might not apply today, Edenhofer and Kalkuhl(2011) argue that it is most probable that discount rates of resource owners exceed market interest rates substantially.

Edenhofer and Kalkuhl(2011) report that carbon taxes are extremely sensitive to many parameters concerning the climate system, climate damages and technological progress. Edenhofer and Kalkuhl(2011) continue that even for mitigation targets as ambitious as 450 ppm most of the taxes have moderate growth rates between one and four percent and are thus lower than the risk free interest rates within these integrated assessment models. However, to avoid green paradox would need resource owners' discount rates lower than these tax growth rates. Edenhofer and Kalkuhl(2011) argue that an optimal carbon tax, which does not provoke green paradox, follows complex dynamics and requires accurate understanding of the damages of climate change. In order to calculate it, we needed to know the correct discount rate, but it is still beneficial to consider second-best taxes to get important information about the robustness of carbon taxes.

By using carbon unit taxes and Sinn’s(2008) model, Edenhofer and Kalkuhl(2011) conclude that the green paradox is restricted to specific conditions where initial tax level has to be lower than a certain limit and the tax has to always grow at a rate higher than the discount rate of fossil fuel owners. Thus, there is a broad set of carbon taxes for several mitigation targets that have a low risk to provoke green paradox. Edenhofer and Kalkuhl(2011) agree with Sinn(2008) in that the best way to exterminate the remaining risk of green paradox is to implement an emissions trading scheme with adequately set emission caps and correctly working intertemporal permit market. Edenhofer and Kalkuhl(2011) argue that if governments nevertheless rely on carbon taxes the initial tax level should be high enough and the growth rate of the tax equal or below market interest rates.

5.12. Deposit markets

The Kyoto Protocol already recognized the need to reduce global carbon dioxide emissions but it has not been able to secure full participation. The United Nations conference on climate change was able to reach the Paris Agreement 2015, which will be signed by over 160 countries. Hopefully these countries can truly commit to this agreement to mitigate climate change damages. Still, there is a possibility of a carbon leakage if the nonparticipating countries are likely to pollute too much, which may deteriorate the effort of the climate coalition. Harstad(2012) argues, that as the coalition introduces restrictions, the world prices change, market shares shift, industries relocate, and nonparticipating countries may start emitting more than they did before.

Harstad(2012) studies this by considering a coalition of countries harmed by the extraction and consumption of fossil fuel. Harstad(2012) argues that nonparticipating countries are naturally polluting too much compared to the optimum. Moreover, if the coalition reduces its demand for fossil fuel, the world price for fuel decreases and the countries outside the coalition will consume even more. Harstad(2012) adds that if the coalition cuts down its fossil fuel supply, the nonparticipants increase their supply, and if investment in renewable energy is possible, nonparticipants invest too little. Harstad(2012) points out that for the coalition, restricting consumption, production, and trade is only a second-best solution.

The paper of Harstad(2012) combines the literature of carbon leakage with the literature that argues that parties can reach efficiency by negotiating operations ex post, regardless of the allocation of property rights. Harstad(2012) continues that the coalition should then be able to negotiate with and bribe countries outside the coalition to decrease their consumption of fossil fuel.

5.12.1. The market for deposits

Harstad(2012) studies how trade in fossil fuel deposits may help a coalition mitigate climate change. Harstad(2012) assumes that there are two sets of countries, one that participates in the climate agreement while the other does not. Harstad(2012) treats the participating countries as one player and assumes that only the participating countries have environmental concerns and are experiencing harm from the pollution. Harstad(2012) argues that the equilibrium fuel price is influenced by climate treaty's policies and the participating player does take this effect into account.

Harstad(2012) allows for trade in fossil fuel deposits. The cost function is implicitly arranging deposits according to their extraction costs. Harstad(2012) assumes that in the deposit market, participating countries may purchase the right to exploit such a deposit from the nonparticipating countries. Assuming linear demand and supply curves, Harstad(2012) examines when a reduction in consumption should be accompanied by an identical decrease in supply, which may entail purchasing or leasing foreign fossil fuel deposits.

At the first stage of the game of Harstad(2012) the right to extract each deposit can be traded in the market. Harstad(2012) claims that the market clears when there is no pair of countries that would both strictly profit from trading some deposit at some price. Harstad(2012) argues, that the market equilibrium is not unique since if each of two countries exploit one deposit, they could easily swap these two deposits, which would make up another equilibrium. Nevertheless, Harstad(2012) states that in every equilibrium of the deposit market, participating player's equilibrium policy implements the first best since all the inefficiencies, free riding, consumption leakage, production leakage, and the market power of the climate agreement vanish once the deposit market has cleared.

Harstad(2012) argues that this kind of policy would be simple to implement in practice. There is no need to calculate taxes for consumption and production, instead, participating country simply purchases the deposits that are most expensive to utilize. Harstad(2012) continues that after this, participating country implements the first best by just keeping these deposits in the ground, or by using an extraction tax high enough to make them disadvantageous. Now, the market forces equalize marginal benefits and neither demand nor trade need to be regulated.

Harstad(2012) admits that creating a market for deposits is controversial, but it is not compulsory to purchase the permanent right to exploit deposits, the climate treaty can simply just pay a nonparticipating country for not extracting certain deposits.

5.12.2. Deposit market with endogenous technology

As developing new technology is central in the debate on how to mitigate climate change, Harstad(2012) extends his model to consider endogenous technologies, in which all countries can invest. Technology is a substitute to polluting and can thus represent clean energy sources. Harstad(2012) simplifies the model by assuming no spillovers or trade in technologies.

Harstad(2012) summarizes that, for a common distribution of deposits, investments in clean technology are suboptimal for all countries. Nonparticipating countries invest too little, which amplifies their already existing overpollution. Harstad(2012) argues that to enhance investments, the climate treaty would like to commit to strong supply side policies rather than demand policies. Harstad(2012) claims that, also in this case, a market for deposits solves all these problems.

5.12.3. Deposit market with multiple periods

As Harstad(2012) argues, without a deposit market, inefficiencies as intertemporal leakages arise. If the climate treaty is expected to decrease its future consumption, the expected future price declines, which makes it more desirable for the nonparticipants to consume fuel today. Thus, green paradox arises. A stronger environmental policy in the future can increase emissions today. Harstad(2012) states, that obviously, the green paradox reduces the value of an expected future demand side policy.

To depict this Harstad(2012) assumes two periods. As climate change is a long-run problem, and its true costs realize in future, Harstad(2012) lets the harm exists only in the second period. Harstad(2012) supposes harm to be a function of cumulated emissions since carbon has a long lasting impact on the climate and shows that if the climate treaty commits to future policies it's preferred policy is generally different from the equilibrium policy when it is not able to commit. Harstad(2012) argues that participating countries would prefer to rely more on supply side policies and less on demand side policies, than what is optimal in second period. Harstad(2012) continues that by doing this, participating countries avoid the intertemporal consumption leakage and the green paradox. On the other hand, if the participating countries cannot commit, the policy is not time consistent.

Harstad(2012) argues that with a deposit market at the beginning of the first period, the participating player purchases the deposits that are most costly to extract from the nonparticipating country. Once the deposit market clears, Harstad(2012) shows that the participating country relies entirely on supply side policies in both periods, and that intertemporal efficiency is ensured regardless of the commitment to future policies. Harstad(2012) states that also now, the policy is easy to implement by setting aside the costliest deposits or setting high enough extraction taxes to make the deposits unprofitable. Harstad(2012) argues that these taxes should be Pigouvian and positive in both periods. Otherwise the private suppliers would prefer to extract in period 1, to avoid paying the tax from extracting on second period. This would generate the green paradox. As Harstad(2012) argues, to avoid the green paradox, the discounted value of the tax should be the same across all periods.

Harstad(2012) reports that this also holds with more than two periods, and that a deposit market at the beginning of the game implements the first best. However, Harstad(2012) continues that, if the abating country also cared about the time at which emissions took place in addition to the aggregate emissions, things get more complicated. In reality, if we need to take into account when the emissions take place in order to mitigate climate change. Harstad(2012) argues that participating country may then have an incentive to trade deposits at the start of every period, and whether this would secure efficiency would depend on the structure of the market.

5.10.4. Deposit market with heterogeneous fuels

Harstad(2012) achieves his results by assuming that consuming one unit of fossil fuel creates one unit of emissions. In real life, different fuels differ in their carbon content. Harstad(2012) argues that also with heterogeneous fuels both within and between countries, since nonparticipating country does not internalize the environmental harm, it might exploit deposits that have higher carbon contents and higher social costs than some other deposit that it considers too costly to exploit. This is why Harstad(2012) considers a deposit market more important than ever before.

Thus, Harstad(2012) states that in every equilibrium of the deposit market, participating country's equilibrium policy implements the first best even if fuels differ in their carbon content. Harstad(2012) adds that some deposits might be cheap to exploit even if highly polluting, but in equilibrium, participating country is purchasing these deposits.

5.12.5. Results of a deposit market

Harstad(2012) states that if a climate coalition reduces its consumption of fossil fuel, the world price declines and nonparticipating countries consume more. If the coalition reduces its supply, nonparticipants extract more from their deposits. Moreover, investments to renewable energy by nonparticipants are too small.

Harstad(2012) claims that setting a market for trade in fossil fuel deposits, all these issues are resolved and the first- best outcome is realized, even though some countries remain outside the coalition. Harstad(2012) argues, that in equilibrium, the coalition acquires the right to utilize the fossil fuel stocks that are most polluting or costly to exploit. Harstad(2012) claims that the coalition only needs to conserve certain deposits, for example by setting an extraction fee high enough to make them unprofitable to extract. Harstad(2012) adds that foreign deposits need not be purchased, as a leasing arrangement may also be sufficient. As Harstad(2012) mentions, countries are in real life often selling, auctioning or licensing the right to extract fossil fuels and other minerals to international companies or to major countries such as India and China.

Thus, the coalition implements its policy simply by reducing its supply of fuel and the fuel supply of the nonparticipants becomes locally inelastic. Thus the supply side leakage is exterminated. Harstad(2012) adds that now, the coalition relies entirely on reducing its supply and not its demand, and thus no consumption leakage occurs. As a result, there is no need to regulate trade or consumption and the fossil fuel price is equalized across countries and all investments become efficient. Thus, the normative result of Harstad(2012) suggests that rather than focusing on reducing consumption of fossil fuels, climate policies should focus on the supply side, which is exactly what Sinn(2008) highlights.

5.13. Investment and capacity building decision

Gronwald et al.(2010) add the issue of capacity building to the discussion of green paradox. Gronwald et al.(2010) argue that extraction is a highly capital intensive process, and thus the size and the costs of capacity play an important role in resource extraction problems. Gronwald et al.(2010) claim that literature has not taken this into account, but rather assumed that the production capacity is large enough or that it can be build up without costs. Gronwald et al.(2010) further develop the extraction decision modelled by Sinn(2008) to have understanding of the role of capacities in extraction problems. Gronwald et al.(2010) extend the model by adding an endogenous capacity choice under the assumption of convex adjustment costs.

Gronwald et al.(2010) show that as a result an extraction path is divided in two parts. First there will be a phase of extraction capacity building and rising extraction. Gronwald et al.(2010) call this the pre-peak oil phase, and it is followed by the post-peak oil phase in which extraction is decreasing and the costly overcapacities are reduced. Gronwald et al.(2010) report that with common assumptions about the cost structure, the green paradox may not exist and thus, greener policies remain a valid instrument in mitigating climate change. Gronwald et al.(2010) derive the necessary conditions for the green policies to be effective and demonstrate that the evaluation of the green paradox differs between pre- and post-peak oil phases.

Also Ghoddusi(2009) studies the capacity building by examining investment decision of an active fossil fuel resource monopolist. Ghoddusi(2009) investigates what happens to the current extraction decision if the producer takes into account the possibility of expanding the extraction capacity in future and does change the supply side responses to demand shocks. Ghoddusi(2009) claims, that with uncertainty about demand and endogenous price dynamics, the monopolist chooses both the optimal extraction rate and the optimal time to build in an extra capacity. Moreover, Ghoddusi(2009) shows that the consideration of optimal investment decisions will lead the resource owner to choose a more conservative expansion policy and thus causes higher prices in strong demand shock periods.

5.13.1. Model of capacity building

Gronwald et al.(2010) utilize the extended Hotelling resource extraction model used by Sinn(2008) and make the relevant additional assumption that the resource owner faces a binding capacity constraint which is always fully employed but can be increased or decreased with costs. Gronwald et al.(2010) argue, that actually, Sinn's model, with zero adjustment costs, is a special case of their general model. Gronwald et al.(2010) argue that assuming total utilization of the extraction capacity is a useful simplification, and changing it would not alter the results of the occurrence of green paradox in a deterministic analysis. Gronwald et al.(2010) assume the marginal costs to be increasing with extraction. Gronwald et al.(2010) argue, that the adjustment cost function is convex and twice continuously differentiable, and has its minimum when the adjustment of capacity is zero.

Gronwald et al.(2010) assume that there are two regimes, as at first capacity has to build up so it can eventually decrease after peaking at some point in between. The resource owner begins with zero capacity after which follows a pre-peak oil regime as capacity increases. Gronwald et al.(2010) add that if marginal adjustment costs were not increasing, the peak in fossil fuel production would be reached at once. After the maximum oil production is reached, the post-peak oil regime begins and capacity starts to decrease. Gronwald et al.(2010) claim that once the post-peak regime has started, it is never optimal to switch back to higher extraction. Gronwald et al.(2010) assume a deterministic framework, and thus, after the resource owner first builds up the capacity in the first regime, he then switches once and for all to the second regime at some point in time.

On the other hand Ghoddusi(2009) considers a monopolist producer of a fossil fuel, who faces stochastic demand and fixed capacity constraint while possessing a capacity expansion option at the same time. Since the production rate is restricted by capacity factors, the optimal extraction path of the resource owner will differ from what the basic Hotelling rule suggests. Ghoddusi(2009) argues that this is simply due to a fact that an optimal extraction plan in some periods may require extraction rates which are higher than the feasible level.

Ghoddusi(2009) remarks that, the option to expand capacity provides a chance to loosen the capacity limit by bearing specific investment costs. Ghoddusi(2009) claims that these costs are irreversible and thus, the option to wait has a positive value and the capacity expansion option will be executed only when the immediate exercise is profitable enough. Ghoddusi(2009) handles the option to invest through the fact that the producer is active in both periods before and after executing the capacity option. Therefore, as there is also the level of remaining reserves, Ghoddusi(2009) considers the capacity option problem to be a two-dimensional one.

5.13.2. Results of capacity building

Sinn(2008) shows that the growth rate of marginal profits has to equal the time preference rate plus the rate of growth of the cash-flow tax. Gronwald et al.(2010) argue that therefore the introduction of an increasing tax rate results in more rapid extraction as the growth rate of marginal profits has to be higher. Thus the carbon resource will be extracted earlier which accelerates global warming.

Gronwald et al.(2010) argue that adding the choice of capacity in the analysis might even disclaim the hypothesis of green paradox. Gronwald et al.(2010) report, that still, the increasing tax rate gives an incentive to forward extraction, but at the same it reduces the present value of the whole project so that the incentive for capacity building diminishes. Gronwald et al.(2010) state that since building-up of capacities is not that advantageous anymore, the fossil fuel owners will require higher rate of return to the marginal capacity expansion. This in turn, implies less investment in capacities, which will decrease the magnitude of the green paradox and possibly even fully dispose it.

Gronwald et al.(2010) show that with a quadratic cost function, for an increase in the carbon tax growth rate, the capacity adjustment will decrease. Gronwald et al.(2010) continue that this is positive for the struggle against climate change since in the first regime the capacity increase will be slowed down and capacity decrease will be hastened. As the total stock of resources will be fully extracted, Gronwald et al.(2010) show that since the capacity will increase slower and decrease faster with carbon tax for any given level of capacity, the production peak has to be postponed in order to the total extraction to be the same.

Gronwald et al.(2010) record that if the marginal cost function is convex in regime 1, then for any given capacity the increase in capacity will be lower after the increase of the in tax growth rate. This corresponds a slower extraction in the regime 1 and thus the green paradox is not adequate. Likewise, as Gronwald et al.(2010) claim, a concave marginal cost function in regime 2 means that for any given capacity the decrease in capacity will be higher after the increase of the growth in carbon tax rate. This is equivalent to a slower extraction in regime 2 and thus the green paradox does not occur. Therefore Gronwald et al.(2010) conclude that the green paradox may not prevail anymore if the capacity building decision is endogenous and costly instead of being free of charge. By deriving necessary conditions for the increasing taxes to be an efficient policy, Gronwald et al.(2010) argue that the existence of the green paradox changes between the pre-peak oil and the post-peak oil period.

Ghoddusi(2009) shows that if zero production costs are assumed then with isoelastic demand the optimal extraction rate is independent of demand shocks while extraction with linear demand is dependent on demand shocks. Ghoddusi(2009) argues that the capacity constraint is binding only for an early period of production path and once the resource reaches a critical level it will never bind again. Thus the value function of resource extraction is the sum of the problem for the period when the constraint is binding with a fixed rate of extraction, and the problem for the period after that. Ghoddusi(2009) argues, the first period problem is complex because the capacity expansion option is available and therefore the producer should decide on how much to produce and when to execute the option.

Ghoddusi(2009) continues that in the case of determinist growing demand, even though the change in demand does not have an effect on the immediate production rate, it still has a effect on the total value of profits. Thus, the change in demand changes the value of an extra unit of capacity remarkably. Ghoddusi(2009) argues that under linear demand optimal extraction rate is a function of stochastic demand shocks. Ghoddusi(2009) adds, that as the producer is forward looking and takes the possibility of the capacity expansion into account, may this change the optimal production rate. Thus, as Ghoddusi(2009) concludes, policies regarding extraction rate in the first period change the value of the second period problem and any investment decision affects the optimal extraction rate.

Ghoddusi(2009) claims that the producer with a possible capacity option chooses a more volatile production path compared to the producer without an expansion option. Ghoddusi(2009) continues that if there is a high demand shock the resource owner without the expansion option will react to that shock more strongly, assumed that he has enough slack capacity, than a producer with expansion option. The producer with the option can save more resources for some future periods where even higher shocks are possible.

Ghoddusi(2009) demonstrates that the existence of the capacity building option will change the optimal extraction path of the producer. Ghoddusi(2009) argues that in contrast to Hotelling rule, it is not necessary that the extraction rate declines and the price increases with interest rate because the resource owner is bounded by the capacity and wants to produce as much as possible if she expects the preserved reserves today to be valueless in future. Ghoddusi(2009) reports that prices will be more volatile if the option to build capacity is more expensive and if the remaining reverses are low. Price volatility is due to the fact that with lower reserves remaining, the probability of capacity expansion executed is lower and therefore the supply side is expected not to react so aggressively to the demand shocks.

6. Conclusions about the literature of green paradox

The coming decades are critical in terms of cumulative emissions and climate change, and Grafton, Kompas and Van Long(2010) argue that this period is likely to be important in terms of biofuels subsidies as it can be assumed that new, carbon neutral energy technologies will become more widespread. Grafton, Kompas and Van Long(2010) are seriously concerned that during this critical time period biofuel subsidies may actually encourage fossil fuel extraction and result in larger carbon emissions and increased likelihood of the severe impacts of climate change.

Hoel(2008) agrees that effective global policies for managing the climate problem are needed, or otherwise improved technology of renewable energy may increase climate costs, and the costs might even outweigh the benefits of the improved technology. Eichner and Pethig(2009) suggest that apart from specific characteristics of consumer preferences and production technologies it is the general equilibrium model with a full set of perfectly competitive markets and the account of interdependence effects of markets across countries and time which defines the allocation of resources including the magnitude of carbon leakage and green paradox.

Grafton, Kompas and Van Long(2010) argue that technological change that affects extraction costs and the net price path on non-renewables is relevant for the green paradox, especially when regarding stock-dependent extraction costs, as positive technological change should offset the impact of stock-dependent extraction. Grafton, Kompas and Van Long(2010) add that the total effect of technological change would depend on the relative changes of subsidy factor over time, the nature of stock dependent costs, on the extent to which technological progress influences the extraction costs and the costs of biofuel production. Hoel(2008) highlights that technological improvement in the production of alternative energy cannot in itself be relied on as a desirable mechanism to diminish carbon emissions. Hoel(2008) states that technological improvements of substitutes may be important for international climate cooperation, but adds that it is necessary that this cooperation also concentrates directly on emission reductions.

Chakravorty et al.(2010) claim that resource scarcity rents are negatively influenced by the learning potential, and that extraction may increase in response to the threat presented by clean energy sources. However, Chakravorty et al.(2010) argue that depending on the degree to which future gains from learning are internalized by producers today, greater learning potential may or may not lead to larger supply of clean energy. Chakravorty et al.(2010) continue that if those gains are not internalized, the oil and gas firms have greater incentive to force out clean energy suppliers through over-extraction. Chakravorty et al.(2010) add still that as extraction is increasing in learning potential, also is clean energy supply decreasing in learning potential when gains to learning are not internalized. The opposite occurs when the gains are internalized and learning implies higher clean energy supply and faster cost reduction.

Hoel(2010b) highlights that if a sufficiently high carbon tax is introduced, near-term emissions will certainly decrease, and therefore the possibility of a green paradox is not against using a carbon tax as the main climate policy instrument but rather an argument for setting the carbon tax high enough at once, instead of currently low and gradually increasing. Hoel(2010b) continues that if the government sets the near-term tax rate below its optimal level, increased concern for the climate may alter tax rates in a way that increases near-term emissions. Hoel(2010b) claims that in real life, governments cannot commit to distant future carbon rates. They only set a carbon tax for a relatively short period, and market participants form their expectations about the distant future carbon tax. Hoel(2010b) argues that with reasonable modeling of these carbon tax expectations, a higher current carbon tax will lower near-term emissions.

Hoel(2010b) points out that as climate policies are analyzed the fact that fossil fuels are scarce non-renewable resources must be taken into consideration. Otherwise analysis can give misleading conclusions. Even though Hoel(2010b) states that the principles for designing an optimal carbon tax are not altered, the consequences of departing from the optimum may be different if the scarcity is ignored.

By using carbon unit taxes and Sinn's(2008) model, Edenhofer and Kalkuhl(2011) conclude that the green paradox is restricted to specific conditions where initial tax level has to be lower than a certain limit and the tax has to always grow at a rate higher than the discount rate of fossil fuel owners. Thus, Edenhofer and

Kalkuhl(2011) claim that there is a broad set of carbon taxes for several mitigation targets that have a low risk to provoke green paradox.

6.1. Differences on assumptions

The literature reveals that the results of green paradox are extremely sensitive to assumptions made about different parameters and market structures. The cost of the clean substitute also has a crucial impact on green paradox. Eichner and Pethig(2009) argue that the magnitude of carbon leakage is determined by interaction of various parameters and elasticities. Edenhofer and Kalkuhl(2011) emphasize that it is the discount rate resource owners use that is crucial for the green paradox, not the choice of an appropriate social discount rate. Grafton, Kompas and Van Long(2010) conclude that whether the green paradox occurs or not depends on demand and supply elasticities, expected changes in subsidies, technological change in fossil fuel extraction and how extraction costs react to changes in remaining stock. The basic models of climate change usually assume zero or constant extraction costs and that fossil fuels and clean substitutes are perfect substitutes. Here we draw up some extensions to these basic assumptions. Fossil fuel owners are considered either competitive, monopoly or oligopoly.

6.1.1. Imperfect substitute

Hoel(2008) argues that his results remain valid when the substitute being imperfect and is added to the model. Hoel(2008) claims that with an imperfect substitute it seems more likely that exhaustion date will decline as a result of the reduced cost of the substitute than in the case of a perfect substitute. Hoel(2008) concludes that, if resources are managed efficiently, social welfare can always be increased with improved technology. However, with various types of market failures or regulatory failures, social welfare might even reduce with improved technology. Gerlagh(2010) proposes that with imperfect substitutes, the cheaper substitute reduces fossil fuel demand throughout the equilibrium and extends the period over which fossil fuels are used. Thus, a substitute with minimal marginal costs below the constant fossil fuel extraction costs, and increasing marginal costs, neither the weak nor the strong green paradox occurs.

6.1.2. Extraction costs increasing with accumulated extraction

Generally, the basic model of green paradox assumes zero extraction costs. Gerlagh(2010) shows that the green paradox is less likely to occur when resource extraction costs are rising with cumulative extraction levels, and when the clean substitute has decreasing returns to scale. Hoel(2008) agrees and Hoel(2010b) even claims that if the resource is limited by extraction costs increasing with accumulated extraction, total climate costs may decline even though the near-term emissions increase. Then the question would be how severe are the increased near-term emissions to climate. Hoel(2010b) continues that if there is an absolute limit on total fossil fuel extraction, and this limit is binding both with and without the carbon tax, there will be no significant difference compared to the case of constant extraction costs. The more interesting case is when the total extraction is determined endogenously, and there will be no absolute binding limit on total carbon extraction. Hoel(2010b) concludes that then total extraction is lower the higher is the level of the carbon tax path, and that the costs of the climate change may be lower when a tax is implemented, even if near-term extraction would be higher.

Hoel(2010b) argues that a rapidly rising carbon tax may result in a green paradox as near-term emissions become higher than they would be without any carbon tax. The threshold of how rapidly the tax must increase is higher when the resource is not physically limited, but as Hoel(2010b) argues, more realistically determined by extraction costs increasing with accumulated extraction. Van der Werf(2010) argues that when stock-dependent extraction costs are added, the results are not affected. Van der Werf(2010) claims that stock-dependent extraction costs only matter if initial fossil fuel stocks differ, and a second asymmetry between the countries is introduced.

6.1.3. Market structure

As Sinn(2008,2009) argues that the green paradox is the consequence of rational speculative behavior of resource owners under perfect competition. Van der Ploeg and Withagen(2010) argue, that imperfect competition is the case most studied in the literature of nonrenewable resources. The reason for that is that either the oil market dominated by OPEC or the gas market dominated by Russia, Iran, Qatar and Venezuela cannot be determined as competitive. Thus, Van der Ploeg and Withagen(2010) consider the case of a resource-owning monopolist to incorporate the occurrence of limit pricing, showing that exhaustion under a monopolist will be slower, and moreover, if the backstop is relatively cheap, a green paradox need not exist.

Grafton, Kompas and Van Long(2010) claim that under monopoly extraction, if extraction costs are zero, an increase in the biofuel subsidy factor will have no impact on the date of exhaustion of fossil fuel. If extraction costs are positive, an increase in the biofuel subsidy factor will postpone the time of exhaustion of the fossil fuel resource stock. With a monopolist fossil fuel owner, Van der Ploeg and Withagen(2010) argue, that the effect on green welfare is ambiguous and depends crucially on the price of the backstop and the rate of pure time preference.

Chakravorty et al.(2010) argue that the oligopolists are slowing down the progress of clean energy. As a monopoly owns resources, rents are maximized, and high energy prices will enhance more production and learning by doing in the substitute. Prices under monopoly are lower when learning is possible, but still much higher than under oligopoly. Under monopoly, Chakravorty et al.(2010) argue that production from both energy sources are increasing in learning even though clean energy production does not grow by as much as it would if rents were invariant to learning.

6.2. Additional extensions

No model of green paradox is perfect to reflect the real world. Grafton, Kompas and Van Long(2010) add that their model should be developed further so that they would take into consideration issues of game theory, the impacts of technological change on extraction costs, the effects of atmospheric carbon concentrations and the rates of decay, and the emission reductions from direct substitution from fossil fuels to biofuel.

Edenhofer and Kalkuhl(2010) claim that leaving the optimal timing to the market requires complete information about future markets if we want to avoid the costs of missallocation. The future markets suffer from volatile prices originating from uncertainties. Thus, Edenhofer and Kalkuhl(2010) highlight that models of green paradox should be extended to contain uncertainty about costs and damages as over time, market agents learn more about reducing mitigation costs and on the impact of climate change. However, this requires a description of agent's behavior and uncertainties e.g. damage curves, substitutes, economic growth, and discount rates, which cannot be incorporated by static marginal cost and benefit curves. Second, Edenhofer and Kalkuhl(2010) argue that closer analysis on additional market failures in the markets for permits and goods are needed, and also an endogenous treatment of information asymmetries. Chakravorty et al.(2010) suggest that climate policy models including the potential for endogenous technological progress should also include endogenous resource pricing responses. Otherwise, these models may underestimate resource extraction and emissions and thus underestimate the optimal carbon tax.

Van der Ploeg and Withagen(2010) consider it worthwhile to extend the analysis to concerns security of energy supplies, diversification or intermittence of backstops such as wind and solar energy and simultaneous use of fossil fuels and the backstop, and simultaneous use of several types of backstop at the same time. Van der Ploeg and Withagen(2010) add that one possible extension would be to investigate the issues within the context of a Ramsey model with capital formation and pollution.

6.2.1. Empirical research

Researchers should next focus on how the green paradox could be studied empirically, as so far, there does not exist any empirical research on the subject. It would be important to extend the debate of green paradox to empirical research, as Martin et al.(2014) have done with carbon leakage. Martin et al.(2014) have studied the efficiency of a climate policy and carbon leakage under the EU Emissions Trading Scheme, EU ETS, which is the world's largest cap-and-trade system imposing an overall cap on CO2 emissions from stationary sources in 30 countries. Martin et al.(2014) analyze the implications of industry compensation rules established under the EU ETS, and argue that since the beginning of the EU ETS in 2005, industrial emitters have been compensated for the cost of compliance by receiving generous allocations of free permits based on their historical CO2 emissions.

In the beginning of 2013, EU was aiming to radically increase the share of permits auctioned off, thereby transferring the ownership of emissions from polluters back to governments. Martin et al.(2014) argue that this aim was strongly opposed by the affected industry, claiming that full auctioning of permits would exacerbate the injurious impact of the EU ETS on their competitiveness. If profits fall by too much, firms have an incentive to relocate to an unregulated country, and take with them the emissions targeted by the regulation. Consequently, carbon leakage will occur. Thus, industry compensation is given as free permit allocations, with the objective to prevent relocation and carbon leakage. Martin et al.(2014) suggest that compensation should be given first to firms where it leads to the highest marginal improvement of the government’s objective function associated with the climate policy, which differs from compensating the firms with the highest tendency to relocate.

The empirical study of Martin et al.(2014) combines three sources of data into a firm-level data set designed for analyzing the relation between permit allocation and carbon leakage. First, Martin et al.(2014) collected data on vulnerability to carbon pricing by interviewing managers of 761 manufacturing firms in Belgium, France, Germany, Hungary, Poland and the UK. Martin et al.(2014) asked managers if they expect that government efforts to price carbon emissions will force them to outsource some of the production site in the foreseeable future or to close down completely. Next, Martin et al.(2014) augmented this information from the manager survey with data on economic performance from the ORBIS database maintained by Bureau Van Dijk. Third, Martin et al.(2014) acquired data on CO2 emissions from the official EU ETS registry, the Community Independent Transactions Log (CITL). Martin et al.(2014) report that the data on carbon emissions and permit allocations for all EU ETS firms in the sample are calculated as the average of verified emissions and allocated permits between 2005 and 2008.

Martin et al.(2014) claim that in all countries and in most industries, the average downsizing risk remains below a 10% cut in production, and in none of the industries will the average firm close down entirely and relocate to a non-European country. However, Martin et al.(2014) continue that there is, substantial variation in the vulnerability between sectors and individual firms. Martin et al.(2014) argue that the large heterogeneity in relocation risk indicates that efficiency gains could be achieved by allocating free permits at the firm level. Martin et al.(2014) suggest that free permits should be given to those firms where they have the highest marginal impact on aggregate carbon leakage risk. With the data from the interviews, Martin et al.(2014) show that this marginal impact varies substantially across firms and sectors, and that it is not necessarily correlated with the impact level. Martin et al.(2014) argue that optimal allocation of free permits dramatically reduces the aggregate risk of CO2 leakage for a given amount of permits, even when compared to the situation where all permits are handed out for free. Martin et al.(2014) state that the aggregate risk of carbon leakage resulting from an application of the current EU permit criteria could be achieved with just a fraction of the amount of permits that will be handed out for free. The current criteria to establish the risk of carbon leakage give rise to very inefficient allocations. Martin et al.(2014) argue that optimal allocations cause drastic improvements in relocation risk and, thus in carbon leakage risk. Analogous study could be made examining green paradox.

Sinn(2008) and other economists have warned policy makers about the green paradox that may occur with some choices of policy instruments. On the other hand, for example Gerlagh(2010) argues that, because the fossil fuel reserves are too wide to be completely exhausted, one type of green paradox is less likely to arise. Gerlagh(2010) argues that under imperfect carbon pricing policies, development of a clean substitute, resulting in lower costs, will most likely to decrease cumulative fossil fuel use. In addition, Gerlagh(2010) claims that as lower costs for renewable energy will also accelerate the current use of renewables, due to decreasing returns to scale and imperfect substitution between energy sources, present fossil fuel use may also reduce. Thus, the green paradox does not necessarily arise.

Still, in the climate change debate, many economists along with Sinn(2008) have pointed out to a green paradox, which means that climate change policies may increase current emissions. As policy makers with good intentions present an implementation of a future carbon tax, or subsidizing the development of low carbon energy sources to substitute fossil fuels in the future, oil markets may anticipate a future reduction in demand and increase current supply.

7. Policy suggestions

Planning climate policies is complex because costs and benefits are uncertain, arise at different points of time, and strike different countries and generations differently. There is an aspect in literature that a demand policy that attempts to influence supply through price signals will ever make a contribution towards restraining climate change. While these demand reducing measures emphasized in the public debate may be useless or even hazardous to fight the global warming, Sinn(2008) claims that there still exist some effective policies against the global warming. According to Sinn(2008) useful policy measures are those that succeed in flattening the carbon supply path in the world energy markets. As Benchekroun and Chaudhuri(2009) argue that only developing green technologies does not solve the problem, but that international cooperation is also needed. The general view is that the best policy would be an inclusive international agreement on climate policies. Sinn(2008) claims that this complete world-wide system of emissions trading combines the consuming countries to a monopsony. This system would be able to drive a more conservative carbon consumption path and in addition providing these countries monopsony rents. Edenhofer and Kalkuhl(2010) argue that there is a need for an central bank like carbon bank enabling a intertemporal management of the climate rent and exhaustible resources. This carbon bank could enhance the commitment to a fixed budget of permits and lead markets to an optimal intertemporal path. In this chapter we introduce some of these optional policies to mitigate the global warming.

As Sinn(2008) concludes, taxes on fossil fuel consumption and the development of alternative energy sources will not mitigate the problem of global warming. Hoel(2008) emphasizes that it is much too optimistic to believe that technological progress in itself can help solve the problem of climate change. Useful policies according to Sinn(2008) entail sequestration, afforestation, stabilization of property rights and emissions trading. Best of the public finance measures to flatten the supply path would be constant unit carbon taxes and source taxes on capital income for resource owners. Gerlagh(2010) ranks measures to reduce emissions from cheap to expensive ones, and from short-term to long-term, and these are structural transition towards less energy intensive industries, energy savings, substitution from coal to gas and from fossil fuels to clean energy sources, and carbon capture and sequestration. Gerlagh(2010) adds that we should first focus on the short-term options, and not mainly on the long-term solutions. An expected reduction in future fossil fuel demand may increase current supply, and thus emissions, if measures that also reduce present demand are not considered. Grimaud, Lafforgue and Magné(2009) argue that simultaneous use of carbon tax and subsidies to research of clean technologies reinforces the individual effects of these policies.

7.1. Public finance measures

Solution to the green paradox according to Sinn(2008) could be a green policy that would have higher pressure on prices at the beginning but would loosen gradually over time. A decreasing ad-valorem tax would have the effect of quickly dropping world market price to a rather low level only to rise afterwards at a steadily increasing rate. Thus the resource owners no longer have incentive to accelerate extraction of their fossil fuels and the climate change would be slowed down. Unfortunately, as Sinn(2008) point out, this is only a theoretical solution that is almost impossible to achieve, as this steadily less greener policy would have difficulties gaining credibility among the resource owners. Sinn(2008) add that it would also lead to a negative tax rate in finite time so that the government would have to subsidize resource use. Politicians do not want to put forward policies that would enforce immediate reductions as it would scare of their voters. Sinn(2008) continues that rising environmental concern of the public will make a gradually reducing tax rate hard to implement.

Sinn(2008) suggests a constant unit tax on carbon extraction that would slow down extraction and could be more credibly defended. The absolute tax wedge would be constant and thus extraction would be slowed down if the discounted tax wedge declines in time. Sinn(2008) admits that a unit tax could also be distorted to accelerate global warming by increasing its rate sufficiently fast, but the danger is much smaller than in the case of ad-valorem tax on resource consumption. However, Sinn(2008) argues that a unit tax would not decelerate global warming because it internalizes a marginal externality of similar size but because its present value declines in time. Sinn(2008) adds that the unit tax on carbon extraction needs to be levied world wide, because otherwise the non-taxing countries could profit from the decreasing prices the tax creates and consume more than they otherwise would have consumed.

Sinn(2008) proposes subsidizing the stock in situ as a way to internalize the negative externality of the accumulated stock of carbon dioxide in the air. If the consuming countries would each year pay a fee to the fossil fuel owners to keep their stocks in ground, the externality would be internalized. As a political proposal this would be impossible to implement because those countries that already pay high oil prices would certainly not be willing to bribe the oil owners to reduce their oil supply and charge even higher prices.

Another possibility to curb the climate change could be taxing heavily the resource owners’ interest income. Sinn(2008) argues that this would not alter the tax on interest in consumer nations but would only levy higher taxes on interest income for the resource owners, which would make converting resources into financial wealth unattractive. Sinn(2008) adds that downside is that interest income taxation pushes down the rate of capital accumulation so that eventually, the tax may increase the gross interest rate, leaving the net-of-tax interest rate constant. Consequently, Edenhofer and Kalkuhl(2011) claim that this instrument is not sufficient to achieve ambitious mitigation target, while capital tax rates cannot be set very high as they will result in distortions in investment decisions implying decreasing welfare. Therefore, Sinn(2008) claims that given that only a fraction of the financial saving comes from the fossil fuel owners, governments should not tax the income from resource ownership in similar way capital income is taxed. Sinn(2008) adds that the capital income earned by resource owners in the international markets should be taxed in a same way they tax capital income by other people. Governments could try to close the tax havens and this way ensure that all interest income is subjected to a minimum source tax.

7.2. Stabilization of property rights

Sinn(2008) reports that securing the property rights of resource owners would be a simple way to mitigate global warming. Sinn(2008) claims that if the transitional expropriation probability is set equal to zero, one of the main reasons for overextraction would be eliminated as the extraction path would become flatter. Sinn(2008) adds that this would not be enough to reach the Pareto optimum but it might be a great move in the right direction. Though Sinn(2008) reminds that the practical implementation is not that simple.

7.3. Quantity constraints and emissions trading

Sinn(2008) points out that the dilemma with the public finance solution suggested by Stern(2007) is that it is of a static nature while the problem is essentially dynamic. Thus it is not possible to find the appropriate level of the carbon tax that Stern(2007) seeks because it is the change of that tax rather than the level that counts. Sinn(2008) claims that the solution is to stop speculating about the economy's quantity reactions to price signals and start to control the quantities, which is the alternative to carbon taxation. Sinn(2008) argues that the best way to do this is with emissions license trading, which is the approach of the Kyoto Protocol. Sinn(2008) argues that this would work, because the aggregate extraction path is controlled by political decisions, and the market only has to allocate the restraint in carbon consumption efficiently among firms and countries. Also Edenhofer and Kalkuhl(2011) claim that as a mal-adjusted tax can accelerate extraction, an emissions trading scheme might be the superior alternative.

Sinn(2008) states that as implementing the quantity constraints on CO2 production, the consuming countries form a worldwide monopsony for carbon that reduces demand and lowers the producer price of carbon at the same time. This creates a monopsony profit at the expense of the extracting countries and mitigates global warming. Sinn(2008) argues that consumption caps could be build up through a global certificate trading system arranged by United Nations. The UN would become the joint owner of the fossil fuel resources and set the extraction path but it would still be a market system that allocates carbon volumes to the individual countries. Individual consumers would have higher energy costs because they would have to buy the certificates, but the state would have more revenue and citizens would benefit for example from lower taxes. Sinn(2008) adds that the consumer countries as a whole would pay less for fossil fuels because their demand will be reduced, thus driving down the world market prices. The revenue that governments achieve comes at the expense of the resource owning countries and would lower the market value of the resources.

There are still downsides to this solution as well, and Sinn(2008) argues that one of them is X-inefficiency. Governments may lack the knowledge necessary to define the optimal intertemporal time path of carbon emissions, and thus the Pareto efficient extraction path might not be reached. According to Sinn(2008), another downside is the completeness of the trading system. Also Eichner and Pethig(2009) argue that when more countries join the coalition of abating countries less carbon tends to leak into the non-abating countries. This as well as the other demand reducing policies are aimless if all important countries of the world are included because otherwise they will only operate through price signals and are likely to cause the green paradox. Sinn(2008) argues that the trading system reduces the demand of the participating countries and hence lowers the world market price and thus the non-participating countries will use up the quantities that are left from the participating countries and also the extra resources that suppliers bring to market fearing for gradually tightening constraints and weakening prices. Thus, the supply path gets steeper and the problem of global warming exacerbates.

Harstad(2012) highlights that environmental policy is not efficient when some polluting countries do not cooperate. The Kyoto Protocol constrained only a minority of countries. The now reached Paris Agreement involves nearly 200 countries including also the important countries USA, Australia, China and India. This covers over 95% of total worldwide emissions and hopefully countries truly commit to these emission reduction targets and make the necessary reductions achievable. At least the Paris Agreement shows that worldwide cooperative agreements are possible. However, Sinn(2008, 2009) reminds that there are problems also with this worldwide agreement. The power of the UN bureaucracy will strengthen and countries will begin to compete with each other over who is to be favored in the allocation of the certificates. Potentially a black market for carbon will arise. Sinn(2008) argues that most certainly the resource owning countries will do everything they can to prevent this demand cartel from realizing and possibly will try to form a counter cartel. Sinn(2008,2009) concludes that these policies and counter policies will increase the potential for conflicts.

Sinn(2008,2009) adds that only with an immediate completion of the demand cartel the resource owners will not have the time to react by hastening the extraction, as if countries are joining the demand cartel gradually, the more rapidly the owners will extract their resources, and the more rapidly will the climate warm up.

Gersbach and Hummel(2009) promote a refunding scheme designed to mitigate climate change instead of a complete emissions trading scheme. Gersbach and Hummel(2009) state that first, industrial countries pay a fee to a global fund. Then each country decides its national carbon tax. Gersbach and Hummel(2009) argue that a fraction of the fund is refunded to developing and industrial countries, in proportion to the relative emission reduction they achieve. Countries are refunded net of tax revenues. Gersbach and Hummel(2009) claim that this system reduces emissions and achieves equity, as developing countries abate voluntarily, do not have to pay the fee and are fund receivers. However, Gersbach and Hummel(2009) admit that such a system still needs coordination among industrial countries to pay the fees into the fund, but that in a smaller scale than a Paris Agreement requires.

7.4. Sequestration and afforestation

Sinn(2008) argues that sequestration and afforestation are the only exceptions to the rule that carbon extraction is proportional to the accumulation of carbon dioxide in the atmosphere. Sequestration is the process of removing carbon from the atmosphere and depositing it in a reservoir into the ground. Even though sequestration sounds promising Sinn(2008) remarks that it has its practical limitations. Because a substantial fraction of the carbon comes from strip mining it does not leave any suitable storage space in the ground and the volume of CO2 that would have to be stored is much greater than the volume of fossil fuel burned. For example one cubic meter of crude oil generates 3,6 m3 of carbon dioxide. Sinn(2008) continues that the storage of the carbon is risky since CO2 is a heavy gas that would stay close to the surface and crowd out oxygen if released. Storage also captures a significant part of the energy produced. Thus,sequestration is a possibility but difficult to execute due to the gigantic quantities involved. Sinn(2008) claims that it still is worth trying, and that governments should use the funds currently consumed as subsidies for windmills and bio diesel for sequestration.

Afforestation is the establishment of a forest or stand of trees in an area where the preceding land use was not forest. Sinn(2008) argues that trees are able to store substantial amounts of biomass on the ground, and as biomass is largely reduced carbon, trees clean the atmosphere from this most significant greenhouse gas. Unfortunately, currently the world's stock of forests is declining rapidly and therefore afforestation is not likely to solve the problem of global warming at least in the near future. Countries should try to reach agreements to protect their forests and stop the deforestation process immediately. Sinn(2008) suggests that the UN should lead this process and also lead the rich countries to bribe the emerging countries, where most of the forests are located, into extensive afforestation programs.

Even though every solution seems to have downsides, the risks of global warming are so extensive that immediate action needs to be taken. The Paris climate agreement gives hope to reaching successful global climate solution.

8. Conclusions

Formerly, it was fear for oil exhaustion and its effects for economic growth that drove the literature on exhaustible resources, which studied the feasibility and optimality of sustainable growth as production depends on an exhaustible resource. Today, our view on the world's most valuable exhaustible resource, has significantly changed. The main concern is no longer the scarcity of resources, but on the fact that there is too much oil and other fossil fuels in the world, which are causing climate change damages when extracted.

The following decades will be crucial for the world to decide on the structures of future energy supply. It is extremely important that the Stern Review launched a major debate on the problem of global warming. According to Sinn(2008) the downside is that neither the public discourse nor the Stern Review do combine the economics of exhaustible resources with the economics of climate change. These two could not be more closely intertwined, since the problem of global warming is the problem of piecemeal translating the exhaustible stock of carbon from underground into the atmosphere. Sinn(2008) continues that unfortunately, markets are unable to solve the optimal path for this double stock-adjustment problem since insecure property rights and the externality of global warming distort the private incentives, both leading to overextraction of fossil fuels relative to the intertemporal Pareto optimality.

Currently governments are trying to solve the problem of climate change by a number of different measures aimed at reducing CO2 emissions. These measures include everything from taxes on fossil fuel consumption to the development of alternative energy sources. However, Sinn(2008) argues that these are measures aimed at reducing carbon demand, and will not diminish the problem of global warming, as they have no flattening impact on the carbon supply path that wealth maximizing resource owners choose. Sinn(2008) argues that if the measures decrease the price path of carbon that would result from a given extraction path such that the discounted value of the price reduction is constant for all points in time, resource owners will indeed keep the extraction path unchanged. Sinn(2008) claims that it is even possible that the measures reduce the discounted value of the carbon price in the future more than in the present, and the problem of global warming will even be exacerbated, because resource owners will have an incentive to anticipate the price reductions by extracting the carbon earlier. This is the essence of green paradox. In order to defeat the green paradox, Sinn(2008) argues that we should focus on supply-side policies. Also Gronwald et al.(2010) claim that the general problem of the environmental policies is the inability to effectively restrict the supply of fossil fuel resources since all policies intervene only the demand side.

Thus, Sinn(2008) argues that current climate policies that turn greener and greener over time steer resource owners to accelerate extraction of their fossil fuels, which in turn precipitates the warming of the planet. By saving more energy and developing alternative energy sources we are raising the fear of the future fossil fuel prices among the resource owners and leading them to boost the extraction rate. If we want to slow down the global warming, we must slow down the carbon extraction rates and for that reason the resource owners must be encouraged to temporarily leave more fossil fuels unused. As an example, Sinn(2008) argues that the climate efforts of Europe have not been able to cause any delay on the world's carbon dioxide emissions, but has caused lower energy prices. The countries outside the Kyoto agreement have enjoyed these lower energy prices and raised their consumption by even more than Europeans have reduced theirs. Sinn(2008) claims, that this shows that slowing down global warming cannot be achieved with green policies taking place only in Europe.

The main goal for this thesis was to find out, whether the green paradox is a possible outcome of current climate policies. Several studies agree with Sinn(2008) in that the green paradox truly is a potential result of carbon taxes or clean energy subsidies. For example, Grafton, Kompas and Van Long(2010) examine several possible cases under which a green paradox may hold as a result of policies of biofuel subsidies, as the supply side reaction by fossil fuel producers more than offsets the benefits from substitution to biofuels. Grafton, Kompas and Van Long(2010) strongly argue, that a green paradox arising from biofuel subsidies designed to diminish greenhouse gas emissions, is a genuine possibility. However, this outcome seems to be extremely sensitive to assumptions made about different parameters, and market structures. Thus, there also exist a group of scientists arguing that that green paradox is not likely to occur. For instance, the results of Eichner and Pethig(2009) do not unambiguously support the proposition that tightening the second period emissions cap necessarily leads to the green paradox. As a conclusion, it can be said that the occurrence of the green paradox is ambiguous, and extremely sensitive to assumptions.

The literature of green paradox generally draws a conclusion that a binding global certificate system covering all carbon sources is the only substantial solution to the climate change problem. Current attempts of implementing greener policies are either ineffective or even counterproductive, and consequences are severe for the nature as more and more countries developing their greener technologies will reinforce the green paradox. Nevertheless, Grafton, Kompas and Van Long(2010) agree with Sinn(2008) that, at the very least, policy makers should carefully evaluate the supply side effects of demand reducing public policies, such as biofuel subsidies, on the extraction of fossil fuels. It is better safe than sorry, as the loss of human lives, many ecosystems and animal species cannot be quantified properly in monetary terms, and thus, if there is a slightest possibility of green paradox, we should rethink our current climate policies.

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Appendix

Tables from Grafton, Kompas and Van Long(2010)

T	50	75	**100**	150	200
$\frac{dT}{dz}$	-1.75	-2.04	$\mathbf{-2.09}$	-2.110	-2.113

Table 1: Effect of a Biofuel Subsidy on Exhaustion Date for Different Fossil Fuel Reserve Sizes

z	0.5	0.75	1	1.5	2
$\frac{dT}{dz}$	-6.6	-3.43	$\mathbf{-2.09}$	-0.99	-0.56

Table 2: Effect of a Biofuel Subsidy on Exhaustion Date for Different Initial Subsidy Levels

ε	0.1	0.5	1	2	3
$\frac{dT}{dz}$	-0.35	-1.34	$\mathbf{-2.09}$	-2.89	-3.32

Table 3: Effect of a Biofuel Subsidy on Exhaustion Date for Different Demand Elasticities of the Manufactured Good

μ	0.5	0.75	1	1.5	2
$\frac{dT}{dz}$	**1.45**	-2.07	$\mathbf{-2.09}$	-3.88	-3.75

Table 4: Effect of a Biofuel Subsidy on Exhaustion Date for Different Supply Elasticities of Biofuel

Cost sensitivity parameter	Marginal extraction cost of the 'last drop'	Choke price of fuel when z=1.2/z=1	ΔT	$\Delta T/\Delta z$	Paradox/ No Paradox
0	0.005	0.54/0.618	-0.270	-1.35	Paradox
0.0001	0.013	0.54/0.618	-0.176	-0.88	Paradox
0.0002	0.021	0.54/0.618	-0.077	-0.39	Paradox
0.0003	0.029	0.54/0.618	0.025	+0.13	No Paradox
0.0005	0.045	0.54/0.618	0.244	+1.22	No Paradox

Table 5: Parameter Values for the Weak Green Paradox