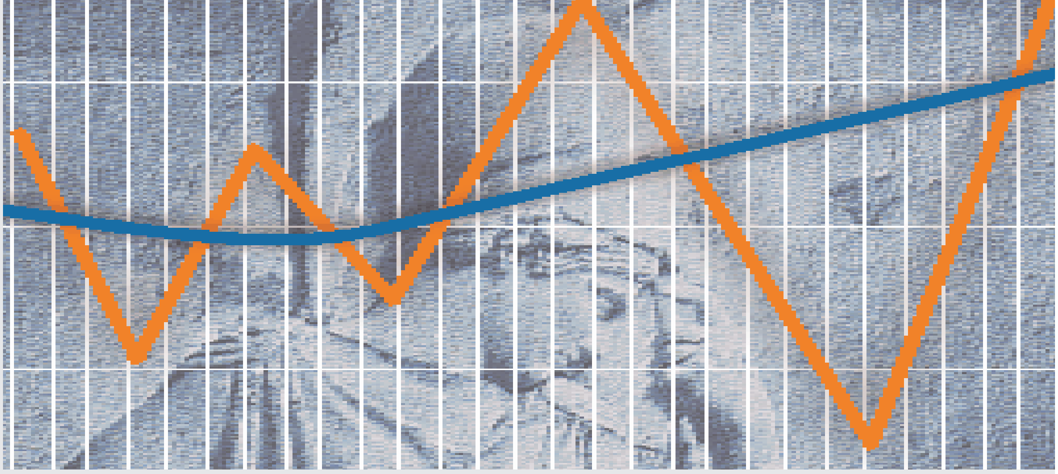

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zur Wirtschaftsforschung

62

Climate Policy and the Intertemporal Supply of Fossil Resources

Christian Beermann

ifo Institut
Leibniz-Institut für Wirtschaftsforschung
an der Universität München e.V.

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Schriftleitung: Chang Woon Nam

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PREFACE

This thesis was written by Christian Beermann while he was a research assistant at the Center for Economic Studies (CES) at the University of Munich. It was completed in December 2014 and accepted as a doctoral thesis by the Department of Economics at the University of Munich in May 2015. The thesis analyses the intertemporal supply reaction of the fossil resource supply side to demand-reducing climate policies while explicitly taking into account the global warming problem.

The interaction between a climate coalition that can either be global or incomplete, comprising only a subset of the world's countries in the latter case, and a representative competitive resource supplier is analysed in a Stackelberg differential game in which the coalition leads. Chapter 2 demonstrates that the global community should strive for the formation of a global climate coalition as this coalition would implement the Pareto efficient resource extraction path in the time-consistent solution. Chapter 3 shows that the resource consumption path chosen by an incomplete climate coalition that faces a passive fringe of other resource consuming countries as well as a competitive resource supply side slows down the speed of global resource extraction compared to the laissez-faire case in the open-loop solution if the incomplete coalition and the fringe countries exhibit the same constant price elasticity of demand, if the resource demand of the coalition and the fringe countries grows or shrinks at the same rate over time for exogenous reasons and if extraction costs are negligible. Chapter 4 demonstrates how the incomplete coalition can implement a certain intertemporal resource allocation equivalently via a price or a quantity regulation. Furthermore, it is shown how the incomplete coalition can slow down the speed of global resource extraction compared to the speed that results under its selfish open-loop policy. The overall conclusion is that the global community should regulate the world's fossil resource consumption path by constraining the global greenhouse gas emissions over time via a time-path of emission caps as this is the fool-proof instrument to fight global warming.

Keywords: carbon leakage, carbon tax, global warming, Kyoto protocol, Stackelberg differential game

JEL classification: H23, O13, Q32, Q38, Q54

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I also thank Rick van der Ploeg and Tony Venables for giving me the opportunity to conduct a very inspiring research stay at the Oxford Centre for the Analysis of Resource Rich Economies at the University of Oxford.

Finally, I am very much indebted and eternally thankful to my parents and my brother for their love and their support. I dedicate this thesis to them.

Christian Beermann Munich, July 2015

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1 INTRODUCTION

Exploiting the fossil resources that lie in the world's crust has prompted a period of unseen growth and economic prosperity since the beginning of the industrialisation in the late-18th century. Today, our global economy is addicted to fossil resources: in 2011, the joint share of petroleum, coal and natural gas in the world's total primary energy consumption was 86 per cent.[1] Fossil resources are used for highly diverse purposes and in countless production processes around the world, although exploiting the world's fossil resource stocks comes at a cost. Every fossil resource unit that is burned on earth increases the CO_2 concentration in the atmosphere and a higher CO_2 concentration induces the process that is generally referred to as anthropogenic climate change, or alternatively the global warming problem. Climate change is expected to reduce global output over time via the increasing occurrence of floods, droughts and severe weather. Moreover, society will have to devote more resources to adaptive measures such as building dikes or heating and cooling housing spaces. Regarding the combustion of fossil resources, the peculiarity is that the social costs induced by the combustion of one resource unit in an arbitrary period do not constitute a one-time cost, but rather a continuous flow of costs from the time when this resource unit is combusted onwards. The underlying reason is that each resource unit that is burned over time only marginally contributes to the CO_2 concentration in the atmosphere, albeit for a long time once it has been burned.[2] The relation between the global flow of fossil resources that is burned over time and the accumulated stock of CO_2 in the atmosphere has important implications for the speed at which society shall exploit the world's fossil resource stocks over time from an economic perspective.

Of course, the notion that the combustion of fossil resources induces global output losses via the process of climate change does not imply that society should not exploit them. As usual, it is a question of benefits and costs. As demonstrated in Sinn (2007, 2008a), exploiting the global fossil resource stock in the presence of the global warming problem implies that society should extract its fossil resources more slowly over time, compared to the current speed. The market failure occurs because individual companies and households do not

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[1] U.S. Energy Information Administration, International Energy Statistics, December 2014, http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=44&pid=44&aid=2.

[2] Cf. Archer (2005) and Archer and Brovkin (2008) for investigations of the atmospheric lifetime of CO_2. Archer (2005) concludes that for the public discourse, it would be sensible to consider a lifetime of fossil fuel CO_2 of "300 years, plus 25% that lasts forever".

internalise the global warming externality that the combustion of each fossil resource unit induces when they decide upon their resource consumption path over time. Individual households and companies do not consider the advantage that a larger future resource stock in situ generates for future generations in terms of lower output losses from global warming. Therefore, the global fossil resource stock is being depleted too quickly from an intertemporal efficiency perspective, if the extraction decision is entirely left to the competitive market. Correcting the market failure requires forcing individual households and companies to internalise the advantage of lower global output losses from global warming incurred by society in the future if the present generation hands over a larger resource stock in situ to future generations. In Sinn (2007), it is shown that by slowing down the speed of global resource extraction and thus leaving a larger resource stock in situ for future generations, at least either the present or future generation can be made better off without making the other worse off compared to the current situation. Slowing down the current speed of resource extraction increases the efficiency of the intertemporal resource allocation, whereby the additional available output can be distributed among all generations. Hence, there is a strong argument that society should slow down the speed at which the world's fossil resources are being exploited over time compared to the current speed of extraction.

Achieving this goal is easier said than done, because the decision when to extract which resource quantity over time is taken by the supply side of the fossil resource market. As Hotelling (1931) demonstrated, fossil resource owners who own a given and finite resource stock in situ maximise their discounted profits by solving an intertemporal maximisation problem. The global equilibrium resource flow that is extracted and consumed in an arbitrary period is as usually determined by demand and supply. However, the peculiarity regarding the global fossil resource flow is that it is not only determined by demand and supply prevailing in an arbitrary period, but also by demand and supply prevailing in future periods. Demand-reducing policies that the suppliers expect in the future thus affect their extraction decision today. Considering this intertemporal reaction of the resource supply side changes the notion of what can be regarded as climate policies that actually combat global warming in a significant way. The intertemporal reaction of the resource supply side to demand-reducing climate policies essentially determines the success of the policy in fighting climate change. Therefore, this supply reaction is the theme of the present thesis.

The relevance of the supply side in tackling the global warming problem has stimulated a lively scientific debate about how public policies can achieve the required reduction in the speed of global fossil resource extraction. Due to the intertemporal nature of their profit maximisation problem, what matters for the fossil resource owners is the expected climate policy path that the world's countries will pursue over time. If resource suppliers expect that the demand for their resources will be decreasing sufficiently quickly as time proceeds, for instance due to increasingly stricter climate policy measures that the public calls for as the consequences from global warming gradually come to light, the anticipation of this policy path can incentivise them to extract some resource quantities that they had originally planned to extract in the future already in the present. The argument that demand-reducing climate policies that intend to lower the extracted resource flow today might instead trigger an increase in present resource supply has been introduced in Sinn (2008a,b, 2012), who phrased this possibility the Green Paradox. Consequently, a climate policy that seeks to postpone the extraction of some resource quantities from the present to the future needs to announce a policy path that makes future extraction relatively more attractive compared to present extraction. This thesis asks the question of whether the policy path that is endogenously chosen by a climate coalition of countries, which can be global or incomplete, actually slows down the speed at which the global fossil resource stock is depleted over time compared to the laissez-faire case.

Chapter 2 firstly introduces the normative benchmark for the positive analyses. The Pareto efficient resource extraction path chosen by the social planer provides the benchmark against which the extraction paths that result in the subsequently analysed positive scenarios can be evaluated from an intertemporal efficiency perspective. As a first step towards the positive analysis, the hypothetical case of a global climate coalition that comprises all countries is analysed in Chapter 2. The global coalition purchases a resource flow over time from a representative competitive resource supplier. This setting thus depicts a situation in which all countries jointly decide on their resource consumption path while the global fossil resource stock is privately owned by competitive resource suppliers. The interaction between the global coalition and the representative competitive supplier is captured in a Stackelberg differential game approach. The coalition announces a unit tax to be levied on global resource consumption over time in the initial period of the game, which the representative supplier takes as given. The model extends the analyses conducted by Karp (1984) and Karp and Newbery (1993) for the global warming problem. These papers demonstrate that the import tariff chosen by a global coalition is dynamically inconsistent if unit extraction costs depend on the remaining level of the resource stock in situ. Tahvonen (1995) investigates the case of a global coalition in the presence of the global warming problem while assuming that extraction costs increase in the rate of extraction. This assumption leads to the result that the open-loop unit tax chosen by the global coalition is time-consistent and that the coalition implements an over-conservative extraction path from an intertemporal efficiency perspective. In the framework presented here, it is assumed that unit extraction costs depend on the remaining level of the resource stock in situ. This renders the derived open-loop solution dynamically inconsistent.

In the presented model, the global coalition has two incentives to slow down the speed of global resource extraction compared to the laissez-faire case. The first incentive arises out of the coalition's motive to manipulate the trajectory of resource rents that the coalition has to pay to the supply side over time, as discussed in Karp (1984) and Karp and Newbery (1993). The underlying reason is that in the presence of stock-dependent unit extraction costs, the resource rent that the coalition has to pay to the supply side in each period hinges on the entire remaining resource extraction path. When deciding on whether to consume the marginal resource unit in an arbitrary period, the coalition considers that consuming this unit increases the rent that it has to pay on the inframarginal units consumed before. Therefore, it benefits the coalition to slow down the speed of resource consumption compared to the competitive rate because it can thereby reduce the present value of the total rent payment to the supply side. The second incentive to slow down the extraction speed compared to the laissez-faire speed arises because the coalition suffers output losses from global warming and because the output losses occurring in an arbitrary period are smaller the larger the remaining resource stock in situ remains. It thus benefits the coalition to consume less of the resource in the present to enjoy the advantage of lower output losses from global warming in the future.[3]

The open-loop solution to the Stackelberg differential game derived here also reveals that the resulting extraction path is over-conservative from an intertemporal efficiency perspective. On the one hand, the global coalition internalises the global warming externality induced by the combustion of each resource unit over time, which is desirable from an intertemporal efficiency perspective. On the other hand, the coalition's monopsony power constitutes a market failure and the coalition's attempt to manipulate the trajectory of resource rents that it has to pay to the supply side over time is not desirable from an intertemporal efficiency perspective. Fortunately, as Karp (1984) and Karp and Newbery (1993) show in the absence of the global warming problem, the open-loop solution is dynamically inconsistent if unit

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[3] The incentive for a climate coalition to manipulate the speed of global resource extraction for environmental reasons is also discussed in Wirl (1994, 1995), Wirl and Dockner (1995), Tahvonen (1996), Rubio and Escriche (2001) and Liski and Tahvonen (2004). The closest paper to the present analysis is the one by Tahvonen (1995), where a competitive resource supply side is also assumed. In contrast to the present analysis, Tahvonen (1995) considers stock-independent unit extraction costs.

extraction costs depend on the remaining resource stock in situ. The contribution of the present analysis is to show that only the coalition’s motive to internalise the global warming externality is time-consistent and thus credible from the perspective of the resource supply side. The main result of Chapter 2 is that in the time-consistent solution, the global coalition dictates the Pareto efficient resource extraction path.

The actual situation that currently prevails in the world is subsequently analysed in Chapter 3. The chapter supplements the analyses of an incomplete coalition conducted by Maskin and Newbery (1990) and Karp and Newbery (1993) by introducing the global warming problem. In the light of the global warming problem, Chapter 3 firstly infers under which circumstances an incomplete climate coalition that comprises a stable subset of the word’s resource consuming countries is able to fight climate change by unilaterally reducing its resource consumption over time. The incomplete coalition purchases a resource flow from a representative competitive resource supplier over time while the other countries outside the coalition behave passively, taking the world market price for the resource as given. In this framework, it is demonstrated that a unit tax that is levied only on the incomplete coalition’s resource consumption is neutral for the speed of global extraction if the tax is constant in present value terms, if the incomplete coalition and the passive countries outside the coalition exhibit the same constant price elasticity of demand and if demand is independent of calendar time. Under these assumptions, it also follows that the incomplete coalition can unambiguously slow down the speed of global resource extraction compared to the laissez-faire case by levying a unit tax on its resource consumption that decreases in present value terms. These results also hold in the presence of stock-dependent unit extraction costs. Moreover, allowing for time-dependent resource demand while abstracting from extraction costs, it is shown that a unilateral unit tax on resource consumption that is constant in present value terms is neutral for the speed of global resource extraction if the incomplete coalition and the fringe countries exhibit the same constant price elasticity of demand and if the resource demand of the coalition and the fringe countries grows or shrinks at the same rate over time for exogenous reasons. A generalisation of these results to the case of a policy mix that reduces the incomplete coalition’s demand over time, including subsidies on renewable energy or bio fuels, is possible.

Subsequently, Chapter 3 analyses the decision problem of an incomplete coalition that is concerned with the global warming problem and has market power on the global resource market. The fringe countries outside the coalition behave passively, taking the world market price for the resource as given. The incomplete coalition purchases a resource flow over time from a representative competitive resource supplier. Abstracting from extraction costs, the open-loop solution to the incomplete coalition’s decision problem is derived under the assumption that the coalition members suffer a fraction of the global output losses brought about by the process of global warming in every period. The unilateral open-loop unit tax chosen by the incomplete coalition decreases in present value terms as long as the coalition’s member countries suffer output losses from global warming. How the unilateral open-loop unit tax affects the speed of global resource extraction compared to the laissez-faire case is generally not only determined by the growth rate of the tax itself. However, under the assumptions that the coalition and the fringe countries exhibit the same constant value of price elasticity of demand, that the demand of both groups grows or shrinks at the same rate over time for exogenous reasons and that extraction costs are negligible, the incomplete coalition’s open-loop unit tax unambiguously slows down the speed of global resource extraction to some extent. In this case, the representative resource supplier shifts some resource supply from the present to the future compared to the laissez-faire case and the incomplete coalition’s selfish open-loop policy increases the efficiency of the intertemporal resource allocation. Nonetheless, irrespective of how the coalition’s unilateral unit tax affects the speed of global resource extraction compared to the laissez-faire case, the world market price for the resource is lower under the tax than in the laissez-faire case whereby the countries outside the coalition increase their resource consumption in response.

Chapter 4 provides a simplified two-period interpretation of the model, also abstracting from extraction costs. Given that the European Union has a cap-and-trade system in place and not a price instrument like a carbon tax, it is shown that the intertemporal resource allocation that would result under a certain unilateral unit tax can be mimicked by a respective time-path of unilateral emission caps. Furthermore, if the incomplete coalition does not implement the unilateral open-loop policy path that maximises its discounted net output, but rather seeks to follow a unilateral policy that certainly slows down the speed of global resource extraction compared to the laissez-faire case, for example for altruistic reasons, a simple rule to achieve this goal is provided. Within the two-period partial equilibrium framework, the incomplete coalition can always trigger an intertemporal shift in supply from the present to the future compared to the laissez-faire case by unilaterally constraining its resource consumption in period 1 while not constraining it in period 2. Accordingly, the incomplete coalition triggers an intertemporal supply shift from the future to the present compared to the laissez-faire case by constraining its resource consumption below the laissez-faire level in period 2 while not constraining its consumption in period 1; namely, the Green Paradox certainly results. These results neither require the assumption that the coalition and the fringe countries exhibit the same constant price elasticity of demand nor do they require that the demand of both groups grows or shrinks over time at the same rate for exogenous reasons.

Also, given that the incomplete coalition has announced unilateral emission caps for period 1 and for period 2, it is shown that the speed of global resource extraction can always be reduced compared to the speed that would result under this benchmark equilibrium if the coalition would instead announce a less stringent cap for period 2 while keeping the period-1-cap at the benchmark level. The same is true if the coalition would tighten the period-1-cap while keeping the cap in period 2 at the benchmark level. Irrespective of whether the original benchmark caps would slow down or speed up the speed of global resource extraction compared to the laissez-faire case, loosening the period-2-cap or tightening the period-1-cap compared to the respective benchmark cap would slow down the extraction speed compared to benchmark equilibrium. In contrast, the global speed of extraction would increase compared to the benchmark equilibrium if the period-2-cap was tightened or if the period-1-cap was loosened compared to the respective benchmark cap.

Although the analysis demonstrates that an incomplete coalition comprising a subset of the world’s countries is in principle able to slow down the speed of global resource extraction compared to the laissez-faire case to some extent if that was its aim, it is also clear that from an intertemporal efficiency perspective, the final target is to reach the global coalition. In the time-consistent solution, the global coalition dictates the Pareto efficient resource extraction path and the analysis shows that this path can equivalently be implemented by regulating the price or the quantity. Both interventions can similarly implement the efficient intertemporal resource allocation. Regarding the transition process from the currently incomplete to the global coalition, it is important that the global community manages to establish the global coalition that comprises all countries as soon as possible, as emphasised in Sinn (2008a,b, 2012). If the resource suppliers fear sufficiently large reductions in future global resource demand due to a growing climate coalition, they speed up extraction today. As long as no cap on global emissions is established, the major challenge for an effective climate policy is thus not to reduce global demand too quickly over time. Furthermore, a long phase in which the resource owners around the world can sell off their resource stocks to those countries that have not yet constrained their carbon consumption needs to be avoided. To effectively fight climate change, it is necessary to establish a global climate coalition, as well as doing so quickly.

2 GLOBAL CLIMATE COALITION

As a starting point, this chapter takes the hypothetical case of a global climate coalition that comprises all countries and purchases a fossil resource flow over time on the competitive global resource market. The global coalition is called a ‘climate coalition’ to emphasise that the world’s countries suffer output losses from global warming in the present analysis. As will become apparent during the analysis, the world’s countries would also benefit from forming a global coalition in the absence of the global warming problem, because they can thereby reduce the resource rent payments to the competitive fossil resource suppliers. The interaction between the global climate coalition and the competitive resource supply side is captured in a Stackelberg differential game approach in which the coalition leads and a representative competitive supplier follows. Essentially, a situation is analysed in which all countries jointly decide on their resource consumption path while the global fossil resource stock is the private property of competitive resource suppliers. The main result of this chapter is that from an intertemporal efficiency perspective, the global community should strive for the formation of a global climate coalition because this coalition would implement the normative speed of resource extraction in the time-consistent solution. The global coalition internalises the global warming externality and it dictates the Pareto efficient resource extraction path. Before the theoretical analysis is conducted, the next section sheds light on the past and the status quo of the international climate negotiations and subsequently highlights which countries are the major polluters. At present, the declared goal of the participants of the United Nations climate conferences is to reach a global treaty for the regulation of global carbon emissions comprising all countries by 2020.[1] However ambitious this target is, it shows that a global climate coalition is at least not unthinkable.

2.1 FROM RIO DE JANEIRO TO LIMA

Under the patronage of the United Nations, the world’s countries have been negotiating which efforts should be undertaken to fight global warming over the last two decades. The history of these international negotiations is one of alternating success and failure. Probably, it is one of the most difficult international negotiations due to the substantial economic interests and the heterogeneity of the parties that are involved. The international combat against global

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[1] United Nations, Framework Convention on Climate Change, Report of the Conference of the Parties on its seventeenth session, held in Durban from 28 November to 11 December 2011. Decision adopted by the Conference of the Parties, March 2012.

warming has its origin in Rio de Janeiro where in June 1992 the United Nations Conference on Environment and Development took place. Back in that summer, the United Nations Framework Convention on Climate Change entered the picture. The convention is the first international statement that declares the common goal to obtain a “stabilization of carbon concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”[2] Although this international treaty has been negotiated in five preceding meetings of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change during 1991 and early 1992, and despite its finalisation in New York City in May 1992, the true birthplace of the international combat against global warming is the city of Rio de Janeiro, where 154 states signed the convention in June 1992. The convention subsequently entered into force in March 1994. However, the convention itself neither specifies any reduction targets for carbon emissions nor does it clarify what actually has to be considered as “dangerous anthropogenic interference”, thus leaving room for a variety of individual interpretations among the signatories. Importantly, the convention right away opened up the way for the exclusion of developing and emerging countries from binding emissions targets by pronouncing the “common but differentiated responsibilities” of the signatories in combating global warming.[3]

Progress towards actual carbon emission reductions was made with the so-called ‘Berlin mandate’, which the parties agreed upon during the first United Nations climate conference in Berlin in 1995. The conference begot a task force with the aim to negotiate legally binding emission reduction targets in the form of an additional protocol to the convention, which resulted in the Kyoto protocol. It was decided in 1997 during the third United Nations climate conference, after the parties had agreed to further push into the direction of a legally binding agreement during the second conference in Geneva. The Kyoto protocol is the first international binding agreement on the reduction of six greenhouse gases (carbon dioxide, methane, nitrous oxide, hydro fluorocarbons, per fluorocarbons and sulphur hexafluoride). It became effective in February 2005 after Russia decided to ratify the protocol in 2004. As the United States resigned from the protocol in 2001, Russia’s ratification satisfied the second condition under which the protocol could come into force, namely, that the signatories jointly represent at least 55 per cent in global CO_2 emissions. The first condition of 55 ratified members had already been met by then. By March 2014, the number of parties to ratify the Kyoto protocol had increased to 192. The protocol imposed a reduction target of 5.2 per cent

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[2] United Nations Framework Convention on Climate Change, United Nations, 1992, p. 9.

[3] United Nations Framework Convention on Climate Change, United Nations, 1992, p. 2.

in overall greenhouse gas emissions on average during the first commitment period of 2008-2012 compared to the respective 1990 levels for the industrialised countries listed in Annex B of the protocol.[4]

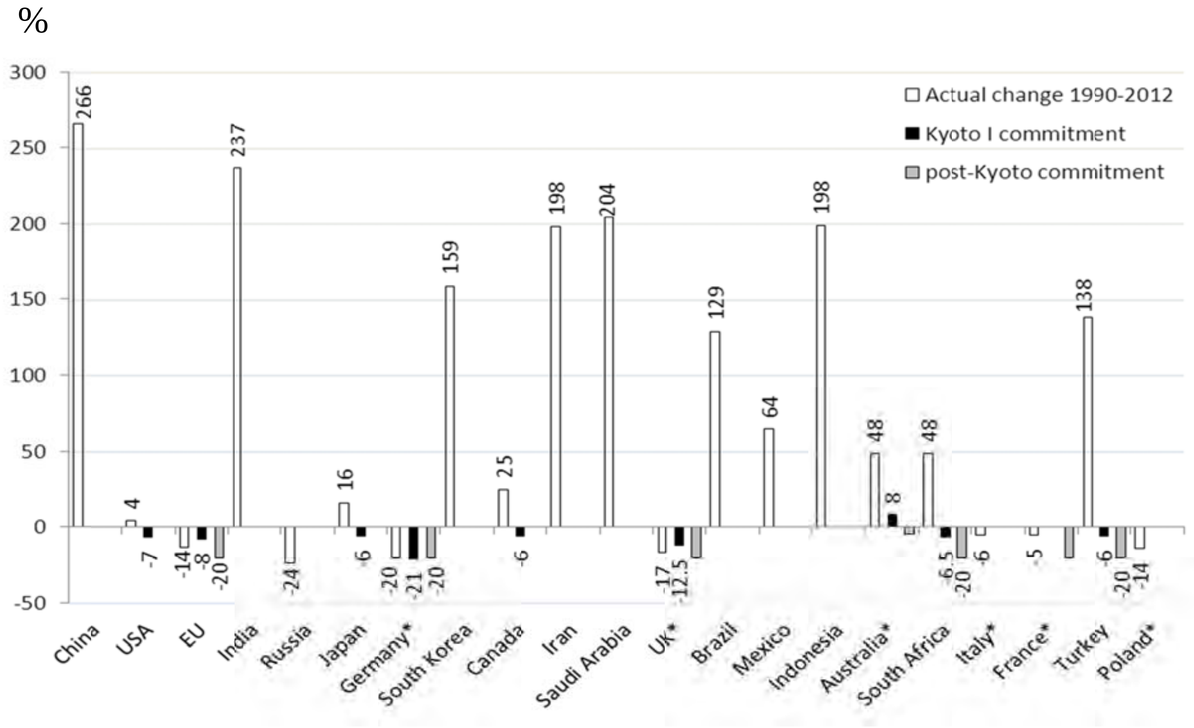

Figure 2.1: Emission reduction targets under Kyoto I (2008-2012) and post-Kyoto commitment (2013-2020), as well as actual changes in CO_2 emissions of the world's 20 largest CO_2 emitters in 2012 plus the EU (ranked by 2012 CO_2 emissions) from 1990-2012 in per cent.[5]

Sources: CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris. United Nations, Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1998, Annex B. United Nations, Doha Amendment to the Kyoto Protocol, 2012.

Originally, Annex B of the Kyoto protocol states emission caps for 38 industrialised countries. Excluding the US and including Malta and Cyprus, which are not on the original Annex B list but adopted individual reduction targets of 8 per cent when joining the EU in 2004, this group covered approximately 22 per cent of global CO_2 emissions from fossil fuel combustion in 2008.[6] The European Union pursued its common reduction target via a burden sharing agreement among its member states. Germany and Denmark had emission reduction

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[4] United Nations, Kyoto Protocol to the United Nations Framework Convention on Climate Change,1998, Article 3, p. 3, which states a reduction target of at least 5 per cent.

[5] The figure is based on those provided in Sinn (2008b, 2012).

[6] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

targets of 21 per cent compared to 1990 levels, followed by Austria with 13 per cent and Great Britain with 12.5 per cent, while France had no obligation to reduce its greenhouse gas emissions.[7] Further countries with binding emission caps included Australia (+8 per cent), Canada (-6 per cent) and Japan (-6 per cent). Russia and the Ukraine had the target of not increasing their emissions compared to 1990 levels. China, India, Brazil, and eventually also the US, which signed but did not ratify the protocol, did not impose caps on their emissions, although these four countries alone comprised 47 per cent in global CO_2 emissions in 2008.[8]

As depicted in figure 2.1, the growth in CO_2 emissions between 1990 and 2012 in China, India and Indonesia, as well as Iran and South Korea, emphasises the importance of these countries for a successful fight against global warming. Of course, these are growth rates and the global warming problem originates from the global emission concentration in the atmosphere. However, as figure 2.2 shows, China and India already rank among the world's largest CO_2 emitters in absolute levels, while South Korea, Iran and Indonesia also exhibit significant emission levels. Admittedly, the comparison would look different in per capita terms due to the comparably lower per capita CO_2 emissions in the BRICS countries compared to the industrialised countries.[9] However, the presented absolute emissions levels expose the problem: without inducing China and the US to reduce their emissions, any climate policy is significantly constrained in its effectiveness in fighting global warming as these two countries alone accounted for approximately 42 per cent in global CO_2 emissions in 2012.

During the first commitment period, the parties to the convention also set out the route for a follow-up protocol that should continue the taken path after 2012. The aim was to agree on a post-Kyoto protocol by 2009, but the respective climate conference in Copenhagen did not accomplish this goal. The subsequent negotiations in Cancun in 2010 also failed to lead to a post-Kyoto agreement, but the parties to the convention agreed for the first time on the target of limiting the average increase in global temperature to 2 °C compared to pre-industrial times. Based upon the reports of the Intergovernmental Panel on Climate Change, in 2009 the G8 countries pinned down their goal to reduce global emissions by 50 per cent by 2050 to reach the 2 °C target.[10] The G8 countries also endorse emission reductions of 80 per cent or more by 2050 compared to 1990 levels. Furthermore, the G8 states welcome the ambitions of

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[7] European Commission, Commission Decision of 15 December 2010 amending Decision 2006/944/EC determining the respective emission levels allocated to the Community and each of its Member States under the Kyoto Protocol pursuant to Council Decision 2002/358/EC.

[8] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[9] The BRICS countries are Brazil, Russia, India, China and South Africa.

[10] G8 L'Aquila Declaration 2009, L'Aquila, Italy.

the United Nations Framework Convention on Climate Change to develop a legal treatment for the global reduction of emissions comprising all parties to the convention by 2015.[11]

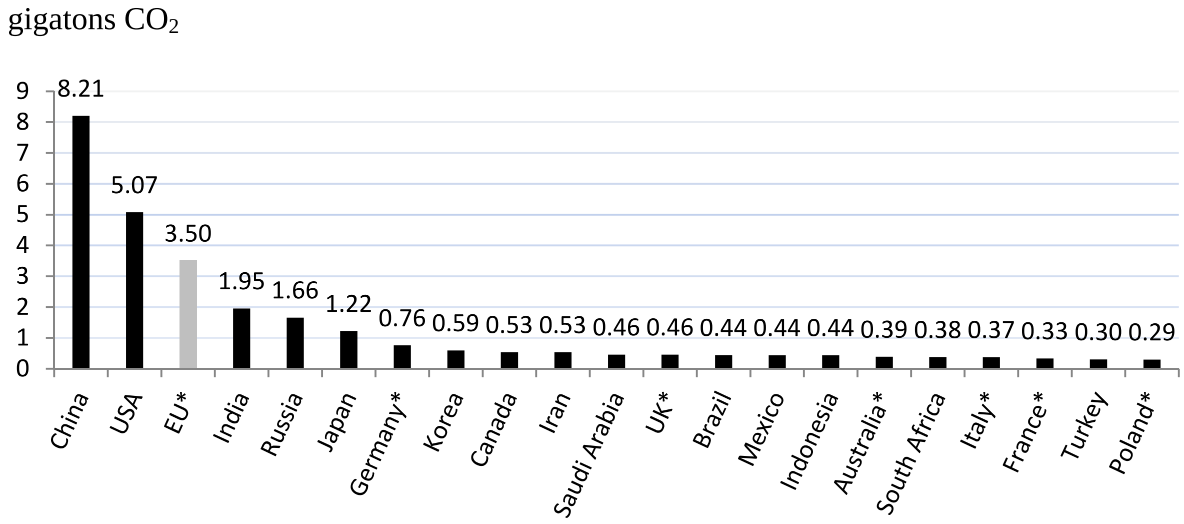

Figure 2.2: CO_2 emissions of the world's 20 largest CO_2 emitters in 2012 plus the EU in gigatons. *Has a post-Kyoto emission reduction target.

Source: CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

The approaching end of the first commitment period exerted pressure on the conferences in Durban and Doha in 2011 and 2012 to agree on a follow-up plan to the Kyoto protocol. The result was the Doha amendment, which states emission reduction targets for 37 countries for the post-Kyoto period up to 2020. However, the amendment is not yet in force, as it will only enter into force when three-quarters of the parties to have ratified the Kyoto protocol accept the amendment.[12] This currently requires that 144 parties accept the amendment. In the Doha amendment, the EU and Iceland have committed themselves to reduce their greenhouse gas emissions by 20 per cent compared to 1990 levels by 2020. Moreover, eight further countries have committed themselves to reduce their emissions by 2020 compared to 1990 levels, including Norway (-16 per cent), Switzerland (-15.8 per cent), Australia (-5 per cent), Kazakhstan (-5 per cent) and the Ukraine (-24 per cent). Australia has pledged to increase its reduction target up to 25 per cent conditional on whether the world's countries agree on an ambitious global reduction plan.[13] In addition, the European Union has pledged to increase its

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[11] G8 Camp David Declaration 2012, Camp David, USA.

[12] United Nations, Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1998, Article 20.

[13] Report of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol on its eights session, held in Doha from 26 November to 8 December 2012. United Nations, 28 February 2013. Australian Government, Department of the Environment, August 2014, http://www.climatechange.gov.au/.

target to a 30 per cent reduction if other developed countries also adopt binding targets.[14] Moreover, the EU proposed in early 2014 that it should strive for an emission reduction of 40 per cent compared to 1990 levels by 2030.[15] The European Union’s long-term objective is even to reduce emissions by 80 to 95 per cent by 2050 compared to 1990 levels in a concerted effort with other industrialised countries.[16]

The 37 countries that accepted reduction targets in the Doha amendment to the Kyoto protocol cover only one sixths of the global emissions from fuel combustion, but at least the protocol has not vanished. Furthermore, the conferences in Durban and Doha intensified the ambitions of the parties to the Framework Convention on Climate Change to establish a legally binding agreement for the global regulation of carbon emissions comprising all parties by 2015, which shall become effective in 2020. It remains to be seen whether this ambitious target can be reached. The conference held in Warsaw in November 2013 again confirmed this goal. The conference left the participating countries with the task to come up with drafts for individual greenhouse gas emission reductions or limitations by the beginning of 2015.[17] Currently, the twentieth UN climate conference is taking place in Lima, aiming to pave the way for a global treaty to be agreed in Paris next year. One can only wish that these plans will turn into action and that the parties of the convention will in deed compromise on a legal global climate agreement comprising all members in Paris in 2015, as it is planned.

The aim of the subsequent theoretical analysis is to investigate whether the global community should in fact strive for the formation of the global climate coalition from an intertemporal efficiency perspective. Therefore, in a first step, the following section characterises the normative speed of resource extraction that the social planer would chose.

2.2 NORMATIVE MODEL OF RESOURCE EXTRACTION

This section presents the social planer model that provides the normative benchmark for the subsequent positive analysis. The approach adopted follows Sinn (2007, 2008a) in assuming that the fossil resource flow is an input used in production.[18] The employed welfare criterion is the Pareto criterion, i.e. efficient depletion of the global fossil resource stock in situ requires

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[14] European Commission, 20 20 by 2020 Europe’s climate change opportunity, Brussels, January 2008. The final compromise was agreed in December 2008.

[15] European Commission, A policy framework for climate and energy in the period from 2020 to 2030, Brussels, January 2014.

[16] European Commission, Energy Roadmap 2050.

[17] UN Climate Change Conference in Warsaw keeps governments on a track towards 2015 climate agreement. Press Release, United Nations, November 2013.

[18] The optimal depletion of a fossil resource in the presence of the global warming problem is also studied in Krautkraemer (1985), Kolstad and Krautkraemer (1993), Withagen (1994), Hoel and Kverndokk (1996), Farzin (1996), Tahvonen (1997) as well as in Krautkraemer (1998).

that it is not possible to increase the present value of the net output from using a resource flow in production over time, net of the unit extraction costs, by alternating the extraction path.

Let $S(t)$ denote the remaining global fossil resource stock in situ in period t, whereby t denotes calendar time. The social planer's planning horizon starts in period $t = 0$ and the initial global fossil resource stock in situ is given by S_0 whereby $S(0) = S_0$. Furthermore, let the resource flow extracted and used in production in period t be denoted by $R(t)$. The fossil resource stock in situ develops over time according to the equation of motion for the resource stock $\dot{S}(t) = -R(t)$.[19] The output from using the resource flow $R(t)$ in an arbitrary period is determined by the production function $\phi\big(R(t)\big)$, which exhibits positive and decreasing marginal productivity. It is abstracted from technological progress whereby the production function is independent of calendar time. Moreover, it is assumed that the resource becomes infinitely productive at the margin as the employed resource flow converges to zero, i.e. $\lim_{R\to 0} \phi_R\big(R(t)\big) = \infty$. This latter assumption reflects the absence of a backstop technology that could perfectly substitute the fossil resource in all purposes of usage. Hence, there is no choke price for the resource. Dasgupta and Heal (1974) show that it is optimal not to exhaust the resource stock in finite time if the resource is essential for production. This will be true throughout the present analysis, because it is assumed that no perfect backstop technology is available.

The combustion of any fossil resource unit within the production process contributes to the CO_2 concentration in the atmosphere and triggers the process of anthropogenic global warming, via the greenhouse gas effect. Society suffers from global warming as droughts, floods and storms reduce global output. Following the formulation given in Sinn (2008a), it is assumed that the function $\omega\big(S(t)\big)$ with $\omega_S > 0$ and $\omega_{SS} < 0$ reflects the part of society's output that is not lost due to the process of global warming in an arbitrary period t, given that the prevailing fossil resource stock in situ in this period is $S(t)$. The derivative ω_S thus reflects the social output loss brought about by climate change if the resource stock in situ marginally declines. Furthermore, the assumption that $\omega_{SS} < 0$ essentially reflects convex damages from climate change associated with the advancing depletion of the global resource stock in situ. When deciding upon the optimal speed of resource extraction, the social planer anticipates that using the fossil resource in production induces the problem of global warming.

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[19] Throughout this thesis, the time derivative of a time-dependent variable $v(t)$ is denoted by $\frac{\partial v(t)}{\partial t} \equiv \dot{v}(t)$.

The unit costs of resource extraction are denoted by g and they are assumed to depend inversely on the remaining stock in situ in a given period, $S(t)$. The unit extraction costs in period t are given by the function $g\big(S(t)\big)$ with $g_S < 0$ and $g_{SS} \geq 0$. The unit extraction costs, the derivatives g_S and g_{SS}, and the social output losses from a marginal decline of the resource stock in situ are assumed to be bounded. Furthermore, the social planer discounts utility by the exogenously given and constant market rate of interest r. The social planer maximises society's discounted output net of the unit extraction costs over an infinite time horizon by choosing the fossil resource flow $R(t)$ over time. The planer's problem is to

$$max \int_0^\infty e^{-rt}\big[\phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t)\big]\, dt$$

subject to the equation of motion for the resource stock in situ

$$\dot{S}(t) = -R(t),$$

the initial condition for the global resource stock $S(0) = S_0$ and the condition that $R(t) \geq 0$. Let $\gamma(t)$ denote the co-state variable for the resource stock in situ from the perspective of the social planer. The current value Hamiltonian for this problem is subsequently given by

$$H = \phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t) - \gamma(t)R(t).$$

The necessary conditions for an optimal resource extraction plan are given by the stationary condition

$$H_R = \phi_R\big(R(t)\big) - g\big(S(t)\big) - \gamma(t) = 0 \quad (2.1)$$

and the canonical equation for the resource stock in situ

$$-H_S = \dot{\gamma}(t) - r\gamma(t) = -\omega_S\big(S(t)\big) + g_S\big(S(t)\big)R(t) \quad (2.2)$$

while the transversality condition is

$$\lim_{t\to\infty} \gamma(t)S(t)e^{-rt} = 0. \quad (2.3)$$

The asymptotic properties of the system (2.1)-(2.3) are given in Appendix A2.1 to this chapter. Essentially, as it is assumed that the marginal product of the resource is unbounded while the marginal output losses from global warming and the unit extraction costs are bounded, the global resource stock converges to zero as time proceeds to infinity. As long as some purposes of fossil resource usage exist for which no perfect substitute is available, it is optimal to distribute the fossil resource over the indefinite future and exhaust the stock, despite the global warming problem.[20]

The stationary condition (2.1) states that in each period the marginal product of the resource shall be equal to the social cost of its usage, which comprises the unit extraction costs $g(S(t))$ and the opportunity cost of resource consumption in period t, $\gamma(t)$. The condition for Pareto efficient resource extraction over time is derived by differentiating the stationary condition (2.1) with respect to time and using the canonical equation for the shadow value $\gamma(t)$, (2.2). It is given by

$$\dot{\phi}_R(R(t)) = r[\phi_R(R(t)) - g(S(t))] - \omega_S(S(t)) \quad (2.4)$$

where $\dot{\phi}_R(R(t))$ denotes the change of the marginal product of the resource over time and where $\omega_S(S(t))$ reflects the global output losses induced by a marginal decline in the resource stock in situ in period t.

In the absence of the global warming problem and with zero extraction costs, the condition for efficient resource extraction introduced by Solow (1974) and Stiglitz (1974) states that intertemporal efficiency requires that along the extraction path, the growth rate of the marginal product of the resource is equal to the marginal product of capital. Although the present partial equilibrium framework abstracts from the accumulation of capital, equation (2.4) resembles the Solow-Stiglitz efficiency condition in the case where $g(S) = \omega_S = 0$, because competitive markets imply that the marginal product of capital is equal to the market rate of interest r.

Here, the differential equation (2.4) characterises the Pareto efficient extraction path in the presence of stock-dependent unit extraction costs and the global warming problem, as derived in Sinn (2007, 2008a).[21] Equation (2.4) states that along the efficient resource extraction path, the interest that society earns on the net marginal product (net of the unit extraction costs) less the marginal output losses from global warming if it extracts another resource unit in period t, as reflected by the right-hand side of equation (2.4), must be equal to the increase in the marginal product of the resource from which society can benefit regarding this resource unit if it is extracted a period later in time due to the increased scarcity of the resource that prevails by then, as reflected by the left-hand side of equation (2.4). When deciding on whether to

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[20] Cf. Dasgupta and Heal (1974) on the general argument and Sinn (2008a) for the argument in the presence of the global warming problem.

[21] Cf. also Sinn (1981) for the extension of the Solow-Stiglitz efficiency condition to the case of stock-dependent extraction costs.

extract an additional resource unit in period t or a period later, the social planer trades off the benefit from extracting the resource unit today against the benefit from extracting it tomorrow.

Let $P\big(R(t)\big) = \phi_R\big(R(t)\big)$ denote the downward sloping global inverse demand function for the fossil resource, which is independent of calendar time. From (2.4), it then follows that

$$P_R\big(R(t)\big)\dot{R}(t) = r\big[P\big(R(t)\big) - g\big(S(t)\big)\big] - \omega_S\big(S(t)\big). \quad (2.5)$$

The normative resource extraction path can be characterised in R, S space independent of calendar time.[22] The normative extraction path must satisfy equation (2.5) and the transversality condition (2.3). Given that it holds that $dR/dS = \dot{R}/\dot{S} = -\dot{R}/R$, the slope for a point in R, S space compatible with the established normative conditions can be derived from (2.5) as

$$\frac{dR}{dS} = \varepsilon(R)\left[r\left(1 - \frac{g(S)}{P(R)}\right) - \frac{\omega_S(S)}{P(R)}\right] \quad (2.6)$$

where $\varepsilon(R) = -\frac{\partial R}{\partial P}\frac{P}{R}$ denotes the absolute value of the price elasticity of demand. For an arbitrary combination of R and S, the slope of this point in R, S space is defined by equation (2.6). Given the made boundedness assumptions regarding the price elasticity of demand, the unit extraction costs and the marginal output losses from global warming, the normative extraction path leads to the terminal point $S = 0$, as depicted in figures 2.4 and 2.6. This also implies that equation (2.6) characterises the normative resource extraction path in R, S space because there only exists one path that leads to the terminal point $S = 0$ and satisfies equation (2.6) along the way. When deciding on the speed of global resource extraction, the social planer anticipates that the global warming problem is less severe tomorrow if the resource stock in situ remains larger by then. Therefore, the social planer extracts the global stock at a lower speed over time than the competitive market, as will be demonstrated shortly.

2.3 DYNAMIC RESOURCE GAMES

Dynamic games have been frequently employed to analyse the strategic interactions taking place between the buyers and the sellers of a fossil resource. The games studied vary with respect to both the hierarchical structure and the assumptions regarding the prevailing market structure, ranging from monopsony to monopoly through to bilateral monopoly structures. In general, two motives for a monopsonistic resource buyer to regulate its resource consumption

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[22] The graphical representation of the extraction paths in R, S space follows Sinn (2008a), pp. 374-6.

are distinguished: the motive to reduce the rent payments to the supply side and the motive to fight climate change. The motive of a dominant resource buyer to reduce the rent payments to the supply side is analysed in Maskin and Newbery (1978, 1990), Kemp and Long (1980), Bergstrom (1982), Brander and Djajic (1983), Karp (1984), Karp and Newbery (1991a,b, 1992, 1993), Chou and Long (2009), Rubio (2011), as well as Fujiwara and Long (2011). Moreover, the papers by Wirl (1994, 1995), Wirl and Dockner (1995), Tahvonen (1995, 1996), Rubio and Escriche (2001), Liski and Tahvonen (2004), Dullieux et al. (2011) and Eisenack et al. (2012) also consider the monopsonistic buyer's incentive to fight climate change. A nice literature overview is given in Long (2011). The closest papers to the present analysis that also analyse the decision problem of a global coalition in a partial equilibrium Stackelberg differential game approach assuming a competitive resource supply side are those by Karp (1984), Karp and Newbery (1993) and Tahvonen (1995).

The model presented in this chapter extends the analyses conducted by Karp (1984) and Karp and Newbery (1993), where stock-dependent unit extraction cots are assumed, for the global warming problem as introduced in Sinn (2008a). Karp (1984) and Karp and Newbery (1993) investigate the optimal import tariff chosen by a monopsonist who purchases a fossil resource flow from competitive suppliers. Their analyses focus on the monopsonist‘s motive to impose an import tariff to reduce the rent payments to the supply side. Essentially, a coalition that comprises all countries could take the entire resource rent away from the supply side by announcing that it will never pay more than the unit extraction costs, as Dasgupta and Heal (1979) state. However, this only holds in the case of zero or constant unit extraction costs, or whereby the extraction costs increase in the rate of extraction, as Karp (1984) and Tahvonen (1995) point out, respectively.

With stock-dependent unit extraction costs, Karp (1984) and Karp and Newbery (1993) show that the competitive resource supply side obtains some resource rent also in the presence of a monopsonistic buyer, presuming that the monopsonist is constrained to use a single policy instrument. The role of the stock-dependent unit extraction costs for the coalition's decision problem is investigated in section 2.6.1, which derives the open-loop solution. It will turn out that besides the climate coalition's motive to fight climate change, reducing the rent payment to the supply side constitutes the coalition's second motive to regulate its resource consumption in the present analysis. Before the decision problem of the global climate coalition is investigated, the subsequent section examines the intertemporal reaction of the resource supply side to an announced unit tax path.

2.4 ROLE OF THE RESOURCE SUPPLY SIDE

A global climate coalition that purchases a resource flow on the global resource market from a representative competitive resource supplier exhibits monopsony power. This section shows that the coalition can thus manipulate the speed of resource extraction. In order to examine the intertemporal reaction of the representative competitive resource supplier to a global unit tax on resource consumption, the decision problem of the competitive supplier who takes the announced tax path as given is solved.

The assumption that the global resource market is competitive is justifiable. As Stiglitz (1976) states, in terms of exhaustible resources, the extent to which a monopolist can capitalise on its market power by constraining supply is limited. In the simple case of zero extraction costs and a constant price elasticity of demand, the competitive and the monopolistic resource supply paths even coincide. The general argument is that the monopolist could in principle constrain supply today to increase the price. Nonetheless, unless she wants to leave some of her resources untouched in situ, she will have to supply the restrained quantities in the future instead. According to Sinn (2012), the Organization of Petroleum Exporting Countries (OPEC) is a “toothless tiger” in this sense, because the OPEC might try to increase present oil prices by constraining supply today, although they will eventually have to increase supply in the future to sell their resources at some point.[23] Moreover, the OPEC, which exhibited a share in global oil production of about 43 per cent in 2013, might control the intertemporal supply of oil to some extent, although neither the supply of coal nor gas is coordinated on a global scale.[24] As the present framework implicitly considers the world’s oil, coal and gas stocks when referring to the global fossil resource stock, and for the reason given above, a competitive resource supply side is assumed throughout the analysis.

Consider now a representative competitive resource owner who extracts the global fossil resource stock with an initial size of S_0. Let $\tau(t)$ denote the unit tax levied by the climate coalition on global resource consumption in period t and let $P^C(t)$ denote the consumer price for the resource that all consumers in the world pay along the new equilibrium extraction path under the tax. The producer price along the equilibrium extraction path resulting under the tax in period t is denoted by $\underline{P}(t)$ whereby in each period it holds that $\underline{P}(t) = P^C(t) - \tau(t)$. The unit costs of extraction are captured by the function $g\big(S(t)\big)$ with $g_S < 0$ and $g_{SS} \geq 0$, whereby the derivatives are bounded by assumption and whereby $S(t)$ denotes the global

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[23] Cf. Sinn (2012), pp. 162-3 on this argument.

[24] OPEC Annual Statistical Bulletin 2014, www.opec.org.

resource stock in situ in period t. The global resource flow supplied in each period is $R(t)$ and the constant market rate of interest r is exogenously given. The representative resource supplier is aware that the global climate coalition implements a unit tax $\tau(t)$ over time and she perfectly anticipates the entire path of the unit tax over time. The representative resource owner maximises her discounted profits from supplying a resource flow $R(t)$ over time. The supplier's problem is to

$$max \int_0^\infty e^{-rt} \left[P^C(t) - \tau(t) - g\big(S(t)\big)\right] R(t) dt$$

subject to the equation of motion for the global resource stock $\dot{S}(t) = -R(t)$ and the initial condition $S(0) = S_0$. The current value Hamiltonian for this problem is

$$H = \left[P^C(t) - \tau(t) - g\big(S(t)\big)\right] R(t) - \lambda(t) R(t)$$

and the necessary conditions for optimality are given by the stationary condition

$$P^C(t) - \tau(t) = g\big(S(t)\big) + \lambda(t) \quad (2.7)$$

and the canonical equation for the resource stock

$$\dot{\lambda}(t) = r\lambda(t) + g_S(S(t))R(t) \quad (2.8)$$

while the transversality condition is

$$\lim_{t \to \infty} \lambda(t) S(t) e^{-rt} = 0. \quad (2.9)$$

The asymptotic properties of the system (2.7)-(2.9) for the considered cases of bounded unit taxes are given in Appendix A2.2 to this chapter. The stationary condition (2.7) reveals that optimality requires that the representative resource owner chooses a resource flow $R(t)$ whereby in each period the producer price that she receives for a resource unit equals the costs of supplying this unit, while the latter comprise the prevailing unit extraction costs $g\big(S(t)\big)$ and the supplier's opportunity costs of selling a resource unit in period t, $\lambda(t)$.

Differentiating the stationary condition (2.7) with respect to time and using (2.8) gives the intertemporal arbitrage condition that characterises the optimal extraction plan of the representative competitive resource supplier in the presence of a globally applied unit tax on resource consumption. It is given by

$$\dot{\underline{P}}(t) = \dot{P}^C(t) - \dot{\tau}(t) = r[P^C(t) - \tau(t) - g(S(t))] \quad (2.10)$$

where $\underline{\dot{P}}(t)$ denotes the change in the producer price over time and where $\dot{P}^C(t)$ and $\dot{\tau}(t)$ denote the changes in the consumer price and the unit tax over time, respectively. The intertemporal arbitrage condition (2.10) is the Hotelling rule extended for stock-dependent unit extraction costs.[25] The rule states that optimality requires that the representative resource owner chooses to supply a resource flow over time whereby along the extraction path she is indifferent between selling another resource unit today or tomorrow. The left-hand side of equation (2.10) depicts the increase in the producer price $\underline{\dot{P}}(t)$ from period t to the next period. Optimality requires that this increase in the producer price is at each point in time equal to the interest that the supplier can earn on the profit from selling another resource unit today, which is given by the term $r[P^C(t) - \tau(t) - g(S(t))]$ on the right-hand side of equation (2.10). The above arbitrage condition (2.10) highlights the importance of the change of the unit tax level $\dot{\tau}(t)$ over time for the intertemporal extraction decision of the resource supplier. Note that in the case in which no tax is levied, the supply side of the resource market is characterised by the intertemporal arbitrage condition

$$\dot{P}(t) = r\big[P(t) - g\big(S(t)\big)\big] \quad (2.11)$$

which follows from (2.10) for $\tau(t) = 0$ in all periods, whereby $P(t)$ denotes the laissez-faire price for the resource.

The intertemporal reaction of a competitive resource supplier to a unit tax on global resource consumption can be evaluated via the Long-Sinn invariance theorem derived in Long and Sinn (1985). The authors demonstrate that it is the wedge that a policy drives between the laissez-faire price for the resource and the hypothetical world market price that would prevail under the policy if the supply side did not react to the policy that determines the intertemporal supply reaction to the policy.[26] If the induced wedge between the laissez-faire resource price and the hypothetical world market price is constant in present value terms, i.e. if it grows at the market rate of interest over time, the supply side does in fact not react to the policy and the extraction path remains unaltered. In the case of a globally applied unit tax on resource consumption, the wedge that the unit tax induces between the laissez-faire resource price and the hypothetical world market price that would prevail under the tax did the supply side not react is given by the unit tax itself. Thus, the growth rate of the wedge between the laissez-

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[25] Cf. Hotelling (1931).

[26] The intertemporal taxation of fossil resources is also studied in Sinn (1982, 2008a), Long and Sinn (1985), Sinclair (1992, 1994), Ulph and Ulph (1994), Hoel and Kverndokk (1996), Farzin and Tahvonen (1996), Amundsen and Schöb (1999), Edenhofer and Kalkuhl (2013, 2014) as well as in van der Ploeg and Withagen (2014).

faire price and the hypothetical world market price is equal to the growth rate of the unit tax itself. Hence, it follows from the Long-Sinn theorem that one can infer the intertemporal supply reaction from the growth rate of the unit tax itself if the tax is applied globally. As will be discussed in Chapter 3, this convenient relation generally breaks down if a unit tax on resource consumption is levied by a subgroup of resource consuming countries only.

For now, suppose that the coalition levies a unit tax on global resource consumption. In this case, it depends on the growth rate of the unit tax whether the present value of the tax burden that the representative supplier has to bear regarding each extracted resource unit increases, decreases or remains constant over time. Suppose that the coalition imposes a unit tax on global resource consumption that grows at a lower rate than the market rate of interest. This implies that both the tax itself and the present value of the tax burden that the representative supplier has to bear regarding each resource unit she supplies over time decrease in present value terms. The best response of the representative supplier to this tax is to shift some resource supply from the present to the future compared to the original extraction plan.

For a graphical illustration of this result, consider figure 2.3 below where an example laissez-faire equilibrium is characterised by the path for the laissez-faire resource price path $P(t)$ in the upper graph and the corresponding laissez-faire resource extraction path $\tilde{R}(t)$ in the lower graph. In both graphs, calendar time t is depicted on the abscissa. Because demand is independent of calendar time, the equilibrium resource flow declines monotonically over time while the resource price increases over time according to the intertemporal arbitrage condition of the supply side (2.10). The unit tax levied by the coalition on global resource consumption over time is depicted by $\tau(t)$ in figure 2.3 and it is assumed that the tax is bounded. Let $\underline{\tilde{P}}(t)$ denote the hypothetical world market price that would prevail under the unit tax if the supply side did not react to the tax, i.e. given that the laissez-faire extraction path still prevails. In the case of a globally applied unit tax on resource consumption, the wedge that the unit tax $\tau(t)$ induces between the laissez-faire price $P(t)$ and the hypothetical world market price $\underline{\tilde{P}}(t)$ is in each period determined by the level of the unit tax itself. Thus, the growth rate of the wedge $P(t) - \underline{\tilde{P}}(t)$ is determined by the growth rate of the unit tax. In the case depicted, the climate coalition's policy is successful in slowing down the speed at which the resource is extracted.

Compared to the laissez-faire case, the resource flow supplied in the present is reduced while supply in the future is increased. The intertemporal arbitrage condition (2.10) implies that the representative resource supplier adjusts the resource extraction path whereby in each period she is again indifferent between selling another resource unit today or tomorrow. Because future supply is increased at the expense of present supply, the consumer price (not depicted) must at some point in time fall short of the laissez-faire resource price to guarantee full exhaustion of the resource as time proceeds to infinity. In figure 2.3, the consumer price path would lie below the laissez-faire price path from that period in time onwards in which the extraction path that results under the unit tax cuts the laissez-faire extraction path from below. Given the made boundedness assumptions regarding the price elasticity of demand, the unit extraction costs and the tax, the equilibrium extraction path prevailing under the tax requires that the global resource stock converges to zero as time proceeds to infinity, as demonstrated in Appendix A2.2 to this chapter.

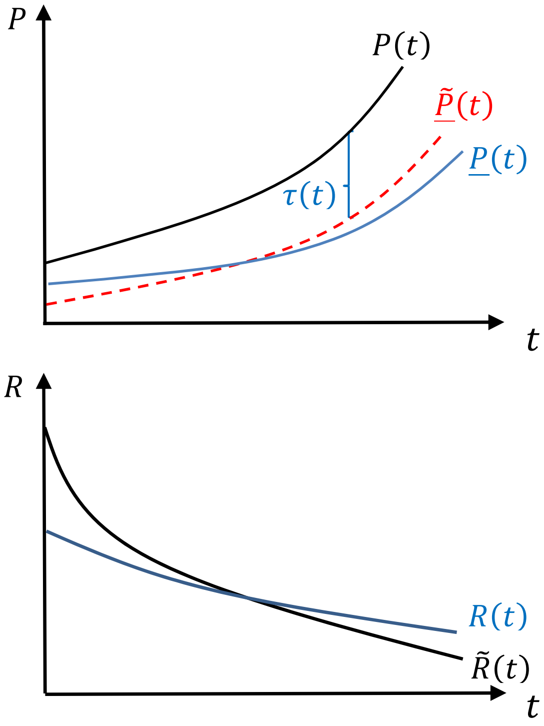

Figure 2.3: Intertemporal supply reaction to a unit tax that decreases in present value terms.

Compared to the hypothetical world market price path that would prevail if the representative resource supplier did not react to the tax, the intertemporal adjustment of the supplied resource flow allows the supplier to increase the world market price path in the early periods above the hypothetical world market price path at the expense of a lower world market price path in the future. The world market price along the new equilibrium extraction path lies everywhere below the laissez-faire price path whereby along the new extraction path the supplier arbitrage condition (2.10) is again satisfied in the presence of the tax while the global resource stock is exhausted as time proceeds to infinity. Indeed, it is this intertemporal reaction of the resource supply side that the global climate coalition anticipates when deciding upon its optimal resource consumption path.

At this point, it is important to emphasise the possibility that the implementation of a unit tax on resource consumption can also incentivise the representative resource supplier to shift some resource quantities from the future to the present compared to her laissez-faire extraction plan. This would be the case if the unit tax levied on global resource consumption increases in present value terms over time. The argument that demand-reducing climate policies imposed to combat global warming can actually accelerate the speed of resource extraction if they reduce global resource demand sufficiently quickly over time has been introduced by Sinn (2008a,b, 2012) who phrased this possibility the Green Paradox. If the global demand for the resource is reduced over time, and if this reduction induces a wedge between the laissez-faire resource price $P(t)$ and the hypothetical producer price $\underline{\tilde{P}}(t)$ over time that increases in present value terms, the representative resource supplier will speed up extraction compared to the laissez-faire case. In figure 2.3, a Green Paradox extraction path would imply a larger global resource flow extracted in the early periods compared to the laissez-faire case while in the later periods, the extracted flow would fall short of the laissez-faire flow. In the Green Paradox case, a climate policy does exactly the opposite of what is needed to fight climate change because the supplier speeds up extraction instead of slowing it down. The importance of the Green Paradox hypothesis for the actual design of an effective climate policy will be discussed in Chapter 4. In general, the analysis of the representative resource supplier's intertemporal supply reaction reveals that the speed at which the global demand for the resource is reduced over time determines a climate policy's success in fighting global warming.

2.5 RESOURCE EXTRACTION PATHS UNDER DIFFERENT GLOBAL UNIT TAXES

In this section, the laissez-faire and the normative resource extraction path as well as the extraction paths that result under different exogenous unit taxes on global resource consumption are derived. The section also confirms the Long-Sinn invariance theorem within the present framework.

Consider first the case in which no tax is levied whereby $\tau(t) = 0$ in all periods. In this case, the supply side of the resource market is characterised by the intertemporal arbitrage condition $\dot{P}(t) = r\left[P(t) - g\big(S(t)\big)\right]$ (2.11) with $P(t)$ being the laissez-faire price. Let the global demand for the resource in period t in the laissez-faire case be denoted by $R\big(P(t)\big)$, with $\partial R(P)/\partial P < 0$. Differentiating the global resource demand function with respect to time gives

$$\frac{dR(P(t))}{dt} = \dot{R}(P(t)) = \frac{\partial R}{\partial P} \cdot \dot{P}(t) \quad (2.12)$$

which characterises the change of the global resource flow demanded over time. The laissez-faire equilibrium extraction path needs to satisfy equation (2.12), the intertemporal arbitrage condition (2.11) and the transversality condition (2.9). Because $dR/dS = \dot{R}/\dot{S} = -\dot{R}/R$, it follows from (2.12) by using (2.11) that the slope for a point in R, S space in the laissez-faire case is independent of calendar time defined by

$$\frac{dR}{dS} = \varepsilon(R)r\left(1 - \frac{g(S)}{P(R)}\right) \quad (2.13)$$

where $\varepsilon(R) = -\frac{\partial R}{\partial P}\frac{P}{R}$ denotes the absolute value of the price elasticity of demand. For a given combination of R and S, equation (2.13) determines the slope for this point in R, S space. As demonstrated in Appendix A2.2 to this chapter, all equilibrium extraction paths considered in this section must lead to the terminal point $S = 0$ given the boundedness assumptions regarding the considered unit taxes, the unit extraction costs and the price elasticity of global resource demand. Therefore, the laissez-faire equilibrium extraction path is characterised by equation (2.13). Figure 2.4 depicts the laissez-faire path in R, S space. As time advances and the global resource stock in situ declines, the global resource flow gradually declines due to the assumption that the global demand for the resource is independent of calendar time. As time proceeds to infinity, both the resource stock in situ S and the resource flow R converge to zero.

Comparing equation (2.6), which characterises the normative extraction path in R, S space depicted in figure 2.4, with the respective equation for the laissez-faire case (2.13) reveals that the normative path must exhibit a lower global resource flow for a given resource stock in situ along the entire equilibrium extraction path to be compatible with the requirement that the path must lead to the terminal point $S = 0$. The reason is that the global warming externality, as reflected by the derivative $\omega_S(S)$ in (2.6), is not internalised if the extraction decision is entirely left to the competitive market. A higher resource flow for any given level of the resource stock in situ implies a quicker speed of global resource extraction. As shown in Sinn (2007, 2008a), the competitive market extracts the resource too quickly compared to the Pareto efficient speed of extraction in the sense that the present resource flow exceeds the socially efficient flow while in the future, the laissez-faire resource flow falls short of the socially efficient flow.

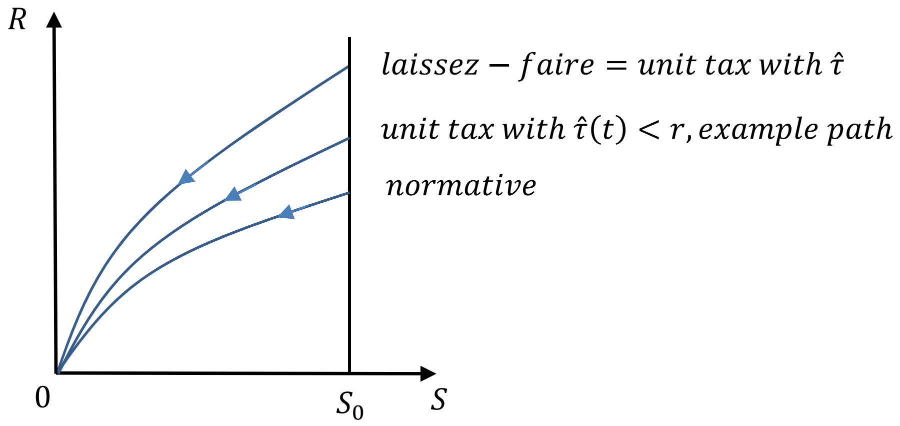

Figure 2.4: Resource extraction paths: laissez-faire, global unit tax and normative scenario.

Consider next the case in which a unit tax $\tau(t)$, which might change over time, is levied on global resource consumption and assume that the tax is bounded. Under the unit tax, the global demand for the resource in an arbitrary period t is given by the demand function $R\left(\underline{P}(t) + \tau(t)\right)$, where $\underline{P}(t)$ is the producer, or, world market price that prevails under the tax. With $P^C(t)$ denoting the consumer price, it thus holds that $P^C(t) = \underline{P}(t) + \tau(t)$ in every period. The change of the global resource flow demanded over time follows by taking the time derivative of the demand function as

$$\frac{dR\left(\underline{P}(t)+\tau(t)\right)}{dt} = \dot{R}\left(\underline{P}(t) + \tau(t)\right) = \frac{\partial R}{\partial P^C} \cdot \left[\dot{\underline{P}}(t) + \dot{\tau}(t)\right] \quad (2.14)$$

which reveals that the development of the demanded resource flow now depends on the development of the producer price, $\dot{\underline{P}}(t)$, and the development of the unit tax, $\dot{\tau}(t)$, over time. The development of the producer price along the equilibrium extraction path is characterised by the representative supplier's arbitrage condition (2.10). Along an equilibrium extraction path, equation (2.14), the intertemporal arbitrage condition of the supply side (2.10) and the respective equation of motion that characterises the development of the considered unit tax over time have to be fulfilled. Furthermore, under the assumptions made, the transversality condition (2.9) implies that the equilibrium path must imply exhaustion of the stock in any case, as is shown in Appendix A2.2 to this chapter.

Presume first that the unit tax grows at the market rate of interest whereby its development over time is characterised by the differential equation $\dot{\tau}(t) = r\tau(t)$. Substituting this equation as well as the intertemporal arbitrage condition (2.10) into (2.14) gives the change of the global equilibrium resource flow $\dot{R}(t)$ under the unit tax as

$$\dot{R}(t) = \frac{\partial R}{\partial P^C} \cdot r\left[\underline{P}(t) - g\big(S(t)\big) + \tau(t)\right] = \frac{\partial R}{\partial P^C} \cdot r\left[P^C(t) - g\big(S(t)\big)\right]. \quad (2.15)$$

Note that the global resource flow $R(t)$ consumed by the world's countries along an equilibrium extraction path in the presence of the unit tax satisfies $P\big(R(t)\big) = P^C(t)$ in each period, whereby $P\big(R(t)\big)$ is the downward sloping global inverse demand function, as introduced before. With $dR/dS = \dot{R}/\dot{S} = -\dot{R}/R$ and by using $P\big(R(t)\big) = P^C(t)$, it follows from (2.15) that the slope for a point in R, S space under a unit tax that grows at the market rate of interest is again defined by equation (2.13). The laissez-faire and the unit tax scenario define the same slope for a point in R, S space if the unit tax grows at the market rate of interest. As also the equilibrium extraction path under the unit tax must lead to the terminal point $S = 0$ in figure 2.4, the laissez-faire equilibrium extraction path and the equilibrium extraction path under the unit tax, which is constant in present value terms, coincide. Hence, the global resource flow extracted for a given stock in situ is the same in both scenarios. The speed of global resource extraction is unaltered by the tax because the unit tax is levied on global resource extraction and because the tax grows at the market rate of interest. This confirms the Long-Sinn invariance theorem.

Suppose next that a unit tax is levied on global resource consumption that declines in present value terms, i.e. which grows at a rate lower than the market rate of interest. Let the development of the unit tax over time be characterised by the differential equation $\dot{\tau}(t) = r\tau(t) - X$ where X is a positive, constant and finite number. As before, substitution of the intertemporal arbitrage condition of the representative supplier (2.10) and the equation of motion $\dot{\tau}(t) = r\tau(t) - X$ into (2.14) gives the change of the equilibrium resource flow $\dot{R}(t)$ over time as

$$\dot{R}(t) = \frac{\partial R}{\partial P^C} \cdot \left[r\left[\underline{P}(t) - g\big(S(t)\big) + \tau(t)\right] - X\right] = \frac{\partial R}{\partial P^C} \cdot \left[r\left[P^C(t) - g\big(S(t)\big)\right] - X\right]. \quad (2.16)$$

Independent of calendar time, the slope for a point in R, S space under the unit tax that declines in present value terms follows from (2.16) and it is defined by

$$\frac{dR}{dS} = \varepsilon(R)\left[r\left(1 - \frac{g(S)}{P(R)}\right) - \frac{X}{P(R)}\right]. \quad (2.17)$$

Equation (2.17) defines a lower slope for each point in R, S space compared to the laissez-faire slope (2.13). Thus, for a given level of the global resource stock in situ, the global resource flow extracted under a unit tax that declines in present value terms must fall short of the respective laissez-faire level because the global resource stock must converge to zero, as shown in Appendix A2.2. Hence, a unit tax that grows at a rate lower than the market rate of interest reduces the speed of global resource extraction compared to the laissez-faire case, as is required to increase the efficiency of the intertemporal resource allocation. In terms of calendar time, it holds that the extracted global laissez-faire flow exceeds the flow that prevails under a unit tax that decreases in present value terms in the early periods, while it must fall short of the flow prevailing under the tax from some point in time onwards.

From an intertemporal efficiency perspective, the question to be answered in the following sections is whether the unit tax path that the global climate coalition chooses will flatten the resource extraction path in the direction of or even to the normative level.

2.6 GLOBAL CLIMATE COALITION AS A STACKELBERG LEADER

In the following, the interaction between a global climate coalition that comprises all countries and a representative competitive resource supplier is captured in a Stackelberg differential game approach. The coalition leads the game, it purchases a resource flow from the representative supplier and it is assumed that the coalition cannot discriminate the price of the single resource unit. The coalition levies a unit tax on resource consumption to implement its preferred resource consumption path. The supplier takes the announced tax path as given and she adjusts her resource extraction path in response if necessary. The coalition anticipates the intertemporal reaction of the representative supplier when deciding on its tax path in the initial period of the game. Furthermore, it is assumed that the representative competitive resource supplier does not consume the resource herself and that all parties have perfect foresight. In essence, the model depicts the hypothetical situation in which all governments in the world would implement a uniform unit tax on global resource consumption while the global fossil resource stock is privately owned by competitive resource owners. The open-loop solution to the coalition’s decision problem is derived first. Because this solution proves to be dynamically inconsistent, the time-consistent solution is subsequently given.

2.6.1 OPEN-LOOP SOLUTION

In order to derive the open-loop solution to the Stackelberg differential game in which the global climate coalition leads and the representative resource supplier follows, this section extends the analyses conducted by Karp (1984) and Karp and Newbery (1993) for the global warming problem as introduced in Sinn (2008a). The coalition chooses its optimal resource consumption path over time and it enforces this path by levying a unit tax on resource consumption. The open-loop unit tax path depends on calendar time and it is announced in the initial period of the game.

The global climate coalition produces output via the production function $\phi(R(t))$ by using the global resource flow $R(t)$ in period t as input. Production exhibits positive and decreasing marginal productivity in the employed resource flow. As in the social planer model introduced in section 2.2, the combustion of the fossil resource triggers the process of anthropogenic global warming, which reduces the coalition's output for the reasons provided above. As before, the function $\omega(S(t))$ denotes the part of global output that is not needed to compensate for the damages from global warming, whereby the derivatives $\omega_S > 0$ and $\omega_{SS} < 0$ imply increasing marginal damages brought about by climate change. Because the coalition has monopsony power, it is aware that its resource consumption affects the development of the global resource stock in situ over time. Therefore, it considers that the global resource stock in situ develops according to the equation of motion $\dot{S}(t) = -R(t)$ when deciding on its optimal resource consumption path.

In addition, the coalition is aware that its resource consumption affects the resource rent that it has to pay to the supply side. Because the unit extraction costs depend on the remaining resource stock in situ and because it is assumed that the coalition cannot discriminate the price of the single resource unit that it purchases, the coalition cannot drive the entire resource rent trajectory to zero. Therefore, the coalition considers the equation of motion (2.8), which characterises the development of the resource rent over time, as an additional state variable in its maximisation problem.[27] Under the unit tax, the coalition purchases the fossil resource from the representative competitive resource supplier at the prevailing producer price $\underline{P}(t)$ in each period. The coalition's problem is to choose a resource flow $R(t)$ over time that maximises its discounted output net of the payments to the supply side in the presence of the global warming problem. The problem of the global climate coalition is to

$$max \int_0^\infty e^{-rt}\left[\phi(R(t)) + \omega(S(t)) - \underline{P}(t)R(t)\right] dt \quad (2.18a)$$

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[27] Simaan and Cruz (1973) provide the theoretical grounding to derive the open-loop solution to Stackelberg differential games using optimal control theory, which is also employed in Karp (1984), Karp and Newbery (1993) and Tahvonen (1995).

subject to the equation of motion for the global resource stock in situ

$$\dot{S}(t) = -R(t),$$

the equation of motion that characterises the development of the resource rent (2.8)

$$\dot{\lambda}(t) = r\lambda(t) + g_S(S(t))R(t)$$

and the initial condition for the global resource stock in situ $S(0) = S_0$, as well as the condition that $R(t) \geq 0$. As in Karp (1984), the differential equation for the state $\lambda(t)$ will be eliminated here as a constraint by integrating the differential equation (2.8) and directly substituting the rent into the coalition's objective. This is possible because, as follows from the representative supplier's stationary condition (2.7), the producer price is in each period equal to the sum of the resource rent and the unit extraction costs, i.e. in each period it holds that $\underline{P}(t) = \lambda(t) + g\big(S(t)\big)$.

Integration of equation (2.8) gives the laissez-faire resource rent in period t as

$$\lambda(t) = e^{rt} \cdot c - \int_t^\infty e^{-r(x-t)}\, g_S\big(S(x)\big)R(x)dx \quad (2.19)$$

where $c = \lim_{t\to\infty} e^{-rt}\lambda(t)$ (2.20). Equation (2.19) gives the resource rent that prevails in the laissez-faire case in period t. Notably, this implies that in the case of stock-dependent unit extraction costs, the resource rent that the coalition has to pay to the supply side in each period t depends on the entire remaining extraction path. In the case of stock-dependent unit extraction costs, the rent comprises two components. The first component of the laissez-faire rent is the Hotelling rent, which occurs due to the scarcity of the resource, as reflected by the first term on the right-hand side of (2.19). The second rent component is the differential rent, which occurs due to the stock-dependency of the unit extraction costs.[28] If the unit extraction costs were constant (or zero), the second rent component would be zero and $\lambda(t)$ would comprise only the Hotelling rent. This would be the case in which the coalition could extract the entire resource rent by announcing that it will not pay more for the terminal resource unit than the unit extraction costs.[29] The supplier would be indifferent and sell the last resource unit at the unit extraction costs, thus making zero profit on the last unit, which would imply that $c = 0$ in equation (2.19). Hence, if the unit extraction costs were constant (or zero), the differential rent component would be zero and the coalition could drive the entire rent

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[28] Cf. Krautkraemer (1998), p. 2069. The differential rent component is also referred to as 'Ricardian stock rent'.

[29] Cf. Dasgupta and Heal (1979) and Karp (1984) for the general argument.

trajectory to zero by announcing that it will not pay more than the extraction costs for the terminal resource unit. In contrast, with stock-dependent unit extraction costs, equation (2.19) shows that the coalition cannot drive the entire resource rent trajectory to zero because it has to pay the differential rent to induce positive supply. Therefore, the differential equation (2.8), which characterises the development of the resource rent over time, constitutes a binding constraint for the coalition's decision problem.[30]

The representative supplier's stationary condition (2.7) shows that in each period it holds that $\underline{P}(t) = g\big(S(t)\big) + \lambda(t)$, which, upon substitution of the resource rent (2.19), gives

$$\underline{P}(t) = g\big(S(t)\big) + e^{rt} \cdot c - \int_t^\infty e^{-r(x-t)}\, g_S\big(S(x)\big)R(x)dx.$$

Now substituting the right-hand side of the above equation for $\underline{P}(t)$ in the coalition's objective (2.18a) allows re-writing the coalition's objective whereby its problem becomes to

$$max \int_0^\infty e^{-rt}\big[\phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t) - e^{rt} \cdot c \cdot R(t) + \\ R(t) \int_t^\infty e^{-r(x-t)}\, g_S\big(S(x)\big)R(x)dx\big]\, dt. \quad \text{(2.18b)}$$

This formulation makes it obvious that the coalition considers that is has to pay a resource rent to the supply side along the extraction path in addition to the unit extraction costs. The coalition would prefer not to pay any resource rent at all, but it cannot drive the entire rent trajectory to zero due to the stock-dependency of the unit extraction costs. However, as previously mentioned, the coalition can drive the rent that it pays on the terminal resource unit to zero. Given that it is optimal for the coalition to drive the terminal rent to zero, which implies that $c = 0$ in its objective (2.18b), the coalition's decision problem can be further simplified. Following Karp (1984) and reversing the order of integration of the last component

$$\int_0^\infty R(t) \int_t^\infty e^{-rx}\, g_S\big(S(x)\big)R(x)dxdt$$

of the coalition's objective (2.18b) by applying Fubini's theorem gives

$$\int_0^\infty e^{-rx}\, g_S\big(S(x)\big)R(x) \int_0^x R(t)dt\, dx = \int_0^\infty e^{-rx}\, g_S\big(S(x)\big)R(x) \cdot [S_0 - S(x)]dx$$

whereby, with $c = 0$, the coalition's objective (2.18b) can be written as

$$max \int_0^\infty e^{-rt}\left[\phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t) + g_S\big(S(t)\big)R(t) \cdot [S_0 - S(t)]\right] dt. \quad \text{(2.18c)}$$

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[30] Cf. Karp (1984), p. 81, and Karp and Newbery (1993), p. 895.

The coalition maximises the objective (2.18c) subject to the equation of motion for the global stock, $\dot{S}(t) = -R(t)$ and the conditions $S(0) = S_0$ and $R(t) \geq 0$. The coalition's decision problem can be solved by applying Pontryagin's maximum principle. Let the climate coalition's co-state variable for the resource stock in situ in period t be denoted by $\mu(t)$. The current value Hamiltonian for the above problem is subsequently given by

$$H = \phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t) + g_S\big(S(t)\big)R(t)[S_0 - S(t)] - \mu(t)R(t). \quad (2.21)$$

The necessary conditions for an optimal resource consumption plan are given by the stationary condition

$$H_R = \phi_R\big(R(t)\big) - g\big(S(t)\big) + g_S\big(S(t)\big)[S_0 - S(t)] - \mu(t) = 0 \quad (2.22)$$

and the canonical equation for the resource stock in situ,

$$-H_S = \dot{\mu}(t) - r\mu(t) = -\omega_S\big(S(t)\big) + 2g_S\big(S(t)\big)R(t) - g_{SS}\big(S(t)\big)R(t)[S_0 - S(t)] \quad (2.23)$$

while the transversality condition is

$$\lim_{t \to \infty} \mu(t)S(t)e^{-rt} = 0. \quad (2.24)$$

The asymptotic properties of the system (2.22)-(2.24) are given in Appendix A2.3 to this chapter. Differentiating the stationary condition (2.22) with respect to time and using the canonical equation (2.23) gives the differential equation

$$\dot{\phi}_R\big(R(t)\big) = r\left[\phi_R\big(R(t)\big) - g\big(S(t)\big) + g_S\big(S(t)\big)[S_0 - S(t)]\right] - \omega_S\big(S(t)\big) \quad (2.25)$$

which characterises the development of the coalition's optimal resource consumption flow over time. The equation looks the same as the corresponding equation 2.4 in the social planer case derived in section 2.2, apart from the term $rg_S\big(S(t)\big)[S_0 - S(t)] < 0$ on the right-hand side of (2.25).

Just as the social planer, the global climate coalition trades off the benefit from consuming another resource unit in period t against the benefit from consuming this unit one period later. The right-hand side of equation (2.25) depicts the interest that the coalition can earn on the net marginal product of the resource less the marginal output losses from global warming if it purchases another resource unit today. The left-hand side of the equation reflects the increase in the marginal product of the resource from which the coalition can benefit if it purchases the resource unit one period later due to the increased scarcity of the resource that prevails by then. Along the optimal consumption path, these two benefits must be equal, just as in the social planer case. However, the difference from the social planer solution lies in the net marginal product that the coalition considers. The global coalition not only subtracts the unit extraction costs from the marginal product of the resource, but also the term $g_S\big(S(t)\big)[S_0 - S(t)]$. The term occurs due to the coalition's monopsony power. It can be interpreted as the coalition's inframarginal rent payment on those resource units already consumed up to period t that the consumption of another resource unit in period t would bring about.

As becomes apparent from the representative supplier's resource rent (2.19), the resource rent that the coalition has to pay to the supply side in each period hinges on the entire remaining extraction path because the unit extraction costs depend on the remaining stock in situ. From the coalition's perspective in the initial period (that is when it decides on its entire optimal consumption plan), consuming another resource unit in period t increases the resource rents that it has to pay on those resource units, which it consumes before period t. Therefore, when deciding whether it should purchase another resource unit in period t or a period later, the coalition not only subtracts the unit extraction costs from the marginal product of the resource in period t, but also the costs that would occur in the form of additional rent payments on those resource units that it consumes before period t if it purchases another resource unit in period t. The net marginal product from purchasing another resource unit in period t and thus the interest that the coalition earns on this net marginal product is reduced compared to the social planer case. In comparison to the social planer case, consumption in period t is thus less attractive for the global coalition due to its monopsony power. Hence, from the perspective of the global coalition, it is optimal to exhaust the global stock at a lower speed compared to the Pareto efficient extraction path. This will be confirmed in section 2.7, which derives the actual open-loop equilibrium extraction path.

Suppose that in order to implement the optimal resource consumption path that satisfies equation (2.25), the coalition levies a unit tax on resource consumption. Let this unit tax be denoted by $\tau_{OL}(t)$ where the subscript OL identifies the open-loop tax to distinguish it from the time-consistent tax, which is derived later. Moreover, let $P\big(R(t)\big) = \phi_R\big(R(t)\big)$ denote the global inverse demand function, which is downward sloping and let $P^C(t)$ denote the consumer price that the consumers have to pay. The consumer price is in each period given by the sum of the producer price $\underline{P}(t)$ and the tax, i.e. it holds that $P^C(t) = \underline{P}(t) + \tau_{OL}(t)$. Note furthermore that differentiating $P^C(t)$ with respect to time then gives $\dot{P}^C(t) = \underline{\dot{P}}(t) + \dot{\tau}_{OL}(t)$

and that along the equilibrium extraction path under the tax it holds that $\dot{\phi}_R\big(R(t)\big) = \dot{P}^C(t)$. The differential equation that characterises the development of the open-loop unit tax over time is subsequently found by substituting $\underline{P}(t) + \tau_{OL}(t)$ for $\phi_R\big(R(t)\big)$ and substituting $\underline{\dot{P}}(t) + \dot{\tau}_{OL}(t)$ for $\dot{\phi}_R\big(R(t)\big)$ in (2.25). It is given by

$$\dot{\tau}_{OL}(t) = r\tau_{OL}(t) - \omega_S\big(S(t)\big) + rg_S\big(S(t)\big)[S_0 - S(t)]. \quad (2.26)$$

As was demonstrated in section 2.4, it is the change of the unit tax over time rather than its level that drives the intertemporal supplier reaction. From (2.26) it follows that the open-loop unit tax grows at a rate

$$\hat{\tau}_{OL}(t) = r - \frac{\omega_S(S(t))}{\tau_{OL}(t)} + \frac{rg_S(S(t))[S_0 - S(t)]}{\tau_{OL}(t)} \quad (2.27)$$

which is below the market rate of interest because $\omega_S\big(S(t)\big) > 0$ and $g_S\big(S(t)\big) < 0$. According to the invariance theorem derived in Long and Sinn (1985), this implies that the speed of global resource extraction is slowed down compared to the laissez-faire rate whereby future supply is increased at the expense of present supply. The boundary condition for the open-loop tax is found by taking the limit of the representative supplier's stationary condition (2.7) as time proceeds to infinity. The boundary condition for the open-loop tax is

$$\lim_{t\to\infty} \tau_{OL}(t) = \lim_{t\to\infty}\big[P^C(t) - g\big(S(t)\big) - \lambda(t)\big] = \infty. \quad (2.28)$$

Because the price elasticity of global resource demand and the unit extraction costs are bounded by assumption and because it holds that $\lim\limits_{t\to\infty} \lambda(t) = 0$ as the coalition drives the terminal resource rent to zero, the open-loop unit tax goes to infinity as time proceeds to infinity.

Regarding the evolution of the open-loop unit tax over time, consider first the case of a zero interest rate whereby $r = 0$. In this case, equation (2.26) reduces to $\dot{\tau}_{OL}(t) = -\omega_S\big(S(t)\big)$, which implies that the unit tax will be falling in absolute terms over time. With a zero interest rate, only the coalition's motive to manipulate the speed of resource extraction because its member countries suffer output losses from global warming remains active while future output losses are not discounted. Because the tax in an arbitrary period reflects the output losses that the combustion of a resource unit in the considered period induces from the period of combustion onwards in this case, the tax falls over time in absolute terms as those resource units that are burned later in time induce damages for a shorter time span only.[31]

With a positive and finite market rate of interest r, the open-loop unit tax decreases in present value terms. Because the price elasticity of demand and the unit extraction costs are bounded by assumption, the global resource stock is exhausted under the open-loop tax as time proceeds to infinity. The consumer price goes to infinity and the producer price converges to the unit extraction cost of the last resource unit as time proceeds to infinity, because the coalition drives the rent on the terminal resource unit to zero. In each period along the new equilibrium extraction path under the open-loop unit tax, the tax drives a wedge between the consumer price and the producer price. Because it holds that $\phi_R\big(R(t)\big) = P^C(t)$ along the new equilibrium extraction path, the development of the consumer price over time is characterised by equation (2.25). The producer price develops according to the intertemporal arbitrage condition of the representative competitive supplier (2.10).

If the representative supplier would not react to the tax, the open-loop unit tax would drive a wedge between the laissez-faire resource price and the hypothetically prevailing producer price that would decrease in present value terms. From the perspective of the supplier, the present value of the tax burden that she has to bear regarding a resource unit if she would not react to the tax is thus declining over time, which incentivises the supplier to delay extraction from the present to the future compared to the original extraction plan. Thereby, she can reduce the total tax burden that she has to bear in present value terms. Because the open-loop unit tax triggers an intertemporal supply shift from the present to the future compared to the laissez-faire case, the consumer price under the open-loop unit tax lies first above but must at some later point in time lie below the laissez-faire resource price to guarantee exhaustion of the resource stock.

The producer price along the new equilibrium extraction path under the open-loop unit tax lies everywhere below the laissez-faire resource price whereby it satisfies the intertemporal arbitrage condition of the representative resource supplier (2.10). The resource rent obtained by the supply side in each period only comprises the differential rent component, which is given by equation (2.19), while letting $c = 0$. By levying the open-loop unit tax, the climate coalition maximises its discounted net output in the presence of stock-dependent unit

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[31] Hoel and Kverndokk (1996) study the optimal carbon tax chosen by a social planner, finding the same result for a zero interest rate.

extraction costs and the global warming problem. The next section explains why the derived open-loop solution is dynamically inconsistent.

2.6.2 DYNAMIC INCONSISTENCY OF OPEN-LOOP SOLUTION

A prerequisite that the representative resource supplier actually reacts to the coalition’s open-loop policy by shifting her supply in time is that the coalition’s announcement is credible from the supplier perspective. The supplier must believe that the coalition will actually follow its announced open-loop consumption path. This section explains why the derived open-loop solution is not credible from the perspective of the resource supplier because it is dynamically inconsistent. In dynamic games, the type of the strategy used by the players is crucial for the outcome of the game. Open-loop strategies typically depend on calendar time. They are announced by the players in the initial period for the entire time horizon of the game. The prerequisite for an open-loop strategy to be optimal in each period, in which case it is time-consistent, is that none of the players has an incentive to deviate from her originally announced strategy at any point in time. If any player deviates from her announced open-loop strategy at some point in time, the open-loop strategy is dynamically inconsistent.

The problem of dynamically inconsistent open-loop policies chosen by a dominant resource importer has been emphasised in Kemp and Long (1980), Karp (1984), Maskin and Newbery (1990) and Karp and Newbery (1993). Generally, the existence of a choke price for the resource renders the open-loop tariff chosen by a dominant resource importer dynamically inconsistent, as demonstrated in Kemp and Long (1980). The underlying intuition is that in the case of an import tariff levied by the importer, for instance, once the sum of the import tariff and the producer price reaches the importer’s choke price, the importer would lower the tariff below the announced open-loop level to continue consumption. As the supply side will foresee this behaviour, the open-loop tariff is dynamically inconsistent. Also, as Karp (1984) and Karp and Newbery (1993) demonstrate, the open-loop tariff chosen by a dominant importer is dynamically inconsistent if the unit costs of extraction depend on the remaining level of the resource stock in situ. In the present framework, the price elasticity of global resource demand is bounded, which implies that there is no choke price. Thus, it is only the stock-dependency of the unit extraction costs that renders the derived open-loop solution dynamically inconsistent.

In order to understand why the problem of dynamic inconsistency arises with respect to the derived open-loop solution, it is important to distinguish the two motives of the coalition to manipulate the speed of resource extraction in the present framework, because only the coalition's motive to slow down the extraction speed to manipulate the trajectory of the differential resource rent that it has to pay over time to the supply side is dynamically inconsistent. Its motive to internalise the global warming externality does not suffer from this problem. As emphasised in Karp (1984) and Karp and Newbery (1993), it is the initial resource stock level S_0 in the coalition's objective (2.18c) that renders the open-loop solution dynamically inconsistent once extraction has started. The coalition decides on its entire resource consumption path and the respective open-loop unit tax that enforces this path in the initial period of the game. As previously mentioned, the objective (2.18c) depends on the initial period via the initial resource stock S_0. Now suppose that extraction has started and presume that the coalition has the possibility to renege its announced consumption path in period $\bar{t} > 0$, which, in the absence of a commitment device, is naturally possible to do for the coalition. The coalition would then consider period $\bar{t}$ as the new initial period of its planning horizon, because everything that has happened before period $\bar{t}$ is now irrelevant, it can no longer be affected. This also implies that the coalition considers the stock $S(\bar{t})$ instead of S_0 as the initial stock in its objective (2.18c). Once the game has started and some resource units have been extracted and consumed, the coalition reneges its original consumption and hence its tax path, because it now prefers a different consumption path. The representative resource supplier foresees this dynamic inconsistency regarding the coalition's behaviour. Therefore, the announced open-loop consumption path that the open-loop unit tax enforces is not credible from her perspective. Only if the coalition could credibly commit itself to the originally announced open-loop consumption path would the supplier react accordingly to this announcement.

In order to nevertheless implement the open-loop solution, the coalition would thus need to have a credible commitment device at hand. One famous example for a successful commitment to an announced time-dependent action is the story of Ulysses. In order to evade the lure of the singing sirens, he asked his men to bind him onto the ship mast so that it was impossible for him to give in to the singing when the sirens came within earshot. Although Ulysses wanted to follow the sirens once he could hear them, his commitment did not allow him to deviate from what he planned to do initially, namely, to resist. If the global climate coalition had a credible commitment device at hand whereby the resource supply side would believe that the open-loop consumption path announced in the initial period would actually be followed, the coalition would be able to manipulate the differential resource rent trajectory to its advantage. However, despite the fact that it is unlikely that the global community will be able to persuade the resource supply side of its commitment to the announced open-loop policy by any conventional means, the problem is that both the coalition and the supply side would prefer a deviation from the open-loop solution once extraction has started. In this respect, Karp and Newbery (1993) distinguish between making a promise and posing a threat.[32] Regarding a promise, at least one party would want the open-loop plan to be followed whereas in the case of a threat in the form of the open-loop policy considered here, it can be in the interests of both the threatening and the threatened parties not to pursue the open-loop plan once the game has started. The necessity to coordinate many countries over a long political and calendar time horizon and make them bind themselves to the open-loop policy is a difficult task, which makes the open-loop solution less relevant in terms of implementing a real world policy.

2.6.3 TIME-CONSISTENT SOLUTION

In order to overcome the problem of the dynamic inconsistency, one has to find a time-consistent solution. The requirement of time-consistency excludes those strategies from which the climate coalition would want to deviate at some point in time during the game. Given perfect foresight, the time-consistent solution must satisfy Bellman's Principle of Optimality. The principle states that: "An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision".[33] Regarding the global climate coalition, this implies that the originally announced resource consumption path must remain optimal; including once the future becomes the present. This section provides a dynamically consistent solution to the considered game.

The following approach to obtain the time-consistent solution for the decision problem of the global climate coalition is due to Karp (1984). Intuitively, the author demonstrates that the coalition's chosen consumption path, which is for instance enforced by a respective unit tax path, is time-consistent if the coalition ignores that its consumption decision affects the rent that it has to pay to the supply side. In order for the solution concept to be applicable, it must be possible to bring the coalition's objective into the form

$$max \int_0^\infty e^{-rt}\left[f\big(R(t),S(t)\big) - hR(t)\lambda(t)\right] dt$$

subject to the equation of motion for the resource rent $\dot{\lambda}(t) = r\lambda(t) + g_S(S(t))R(t)$ (2.8), the equation of motion for the global stock $\dot{S}(t) = -R(t)$ as well as subject to the conditions

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[32] Cf. Karp and Newbery (1993), p. 899.

[33] Cf. Bellman (1957), p. 83.

$S(0) = S_0$, $R(t) \geq 0$ and $\lambda(t) \geq 0$, whereby h is a non-negative constant.[34] With $f\big(R(t), S(t)\big) = \phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t)$, the coalition's objective (2.18b) has this form for $h = 1$.

Karp (1984) then shows that the time-consistent solution to the coalition's decision problem is found by maximising the objective

$$max \int_0^\infty e^{-rt} f\big(R(t), S(t)\big)\, dt$$

subject to $\dot{S}(t) = -R(t)$, $S(0) = S_0$ and $R(t) \geq 0$, i.e. the coalition ignores that its consumption decision affects the differential resource rent that it has to pay over time.[35] With $f\big(R(t), S(t)\big) = \phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t)$, the time-consistent solution to the coalition's decision problem is in the present framework thus found by choosing a resource consumption path that satisfies the coalition's objective to

$$max \int_0^\infty e^{-rt} \big[\phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t)\big]\, dt \quad (2.29)$$

subject to $\dot{S}(t) = -R(t)$, $S(0) = S_0$ and $R(t) \geq 0$.

As Karp (1984) explains, the intuition behind this method to obtain a time-consistent solution for the coalition's decision problem can be best understood by considering the hypothetical case in which the coalition could continuously revise its control problem. Suppose that the coalition would revise its control problem in period $\bar{t} > 0$, which implies that the initial period of its revised control problem is subsequently $\bar{t}$ and no longer $t = 0$. Hence, the coalition would replace the initial stock S_0 in its (open-loop) objective (2.18c) with the stock $S(\bar{t})$. Intuitively, giving the coalition the hypothetical possibility to continuously revise its control problem implies that the last term $g_S\big(S(t)\big)R(t) \cdot [S_0 - S(t)]$ in its (open-loop) objective (2.18c) vanishes, which reduces its objective to (2.29).

Letting $\mu(t)$ denote the coalition's co-state variable for the resource stock in situ, the current value Hamiltonian for the above problem is

$$H = \phi\big(R(t)\big) + \omega\big(S(t)\big) - g\big(S(t)\big)R(t) - \mu(t)R(t) \quad (2.30)$$

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[34] Cf. Karp (1984), p. 87, equations (25), (26a) and (26b). The notation is changed here according to the present framework.

[35] Cf. Karp (1984), pp. 87-8, especially Proposition 2, p. 87.

subject to $\dot{S}(t) = -R(t)$, $S(0) = S_0$ and $R(t) \geq 0$. The conditions for optimality are the stationary condition

$$H_R = \phi_R\big(R(t)\big) - g\big(S(t)\big) - \mu(t) = 0 \quad (2.31)$$

and the canonical equation for the resource stock in situ

$$-H_S = \dot{\mu}(t) - r\mu(t) = -\omega_S\big(S(t)\big) \quad (2.32)$$

while the transversality condition is

$$\lim_{t\to\infty} \mu(t)S(t)e^{-rt} = 0. \quad (2.24)$$

The asymptotic properties of the system (2.31), (2.32) and (2.24) are given in Appendix A2.3 to this chapter.

The differential equation that characterises the development of the coalition's time-consistent optimal resource consumption flow over time is again found by differentiating the stationary condition (2.31) with respect to time and using (2.32). It is given by

$$\dot{\phi}_R\big(R(t)\big) = r\big[\phi_R\big(R(t)\big) - g\big(S(t)\big)\big] - \omega_S\big(S(t)\big). \quad (2.33)$$

Comparing equation (2.33) with the respective differential equation that characterises the social planer solution (2.4) reveals that both coincide. When deciding on whether to purchase another resource unit in period t or a period later, the coalition trades off the benefit from purchasing another resource unit today against the benefit from purchasing it tomorrow, as before. However, in the time-consistent solution, the global climate coalition ignores the effect that consuming another resource unit in an arbitrary period increases the rent payments on the inframarginal units that it has consumed up to this period. The coalition only internalises the global warming externality. Along the optimal resource consumption path, the interest that the coalition earns on the net marginal product (net of the unit extraction costs) when purchasing another resource unit in period t less the marginal output losses from global warming $\omega_S\big(S(t)\big)$, as depicted by the right-hand side of equation (2.33), must be equal to the increase in the marginal product of the resource from which the coalition would benefit if it purchases the unit a period later instead due to the increased scarcity of the resource that prevails by then. Along the time-consistent consumption path, the coalition behaves as if it would not have to pay the differential rent to the supply side.

Suppose that the coalition enforces its time-consistent consumption path via a unit tax on resource consumption and let this tax be denoted by $\tau_{TC}(t)$ where the subscript TC identifies the time-consistent unit tax. Recall that the global downward sloping inverse demand function is given by $P\big(R(t)\big) = \phi_R\big(R(t)\big)$ whereby along the equilibrium extraction path under the time-consistent tax it holds that $\phi_R\big(R(t)\big) = P^C(t) = \underline{P}(t) + \tau_{TC}(t)$ and accordingly that $\dot{\phi}_R\big(R(t)\big) = \dot{P}^C(t) = \underline{\dot{P}}(t) + \dot{\tau}_{TC}(t)$. Substituting $\underline{P}(t) + \tau_{TC}(t)$ for $\phi_R\big(R(t)\big)$ and substituting $\underline{\dot{P}}(t) + \dot{\tau}_{TC}(t)$ for $\dot{\phi}_R\big(R(t)\big)$ in the differential equation (2.33) allows deriving the equation of motion that characterises the time-consistent unit tax. It is given by

$$\dot{\tau}_{TC}(t) = r\tau_{TC}(t) - \omega_S\big(S(t)\big). \quad (2.34)$$

The growth rate of the time-consistent unit tax is thus

$$\hat{\tau}_{TC}(t) = r - \frac{\omega_S\big(S(t)\big)}{\tau_{TC}(t)}$$

which shows that the tax decreases in present value terms over time and thus incentivises the representative resource supplier to postpone some resource extraction to the future. In fact, the next section demonstrates that this implies that the coalition dictates the Pareto efficient speed of resource extraction if it is constrained to the time-consistent solution.

The boundary condition for the time-consistent unit tax is again found by taking the limit of the supplier's stationary condition as time proceeds to infinity whereby

$$\lim\nolimits_{t\to\infty} \tau_{TC}(t) = \lim\nolimits_{t\to\infty}\big[P^C(t) - g\big(S(t)\big) - \lambda(t)\big] = \infty. \quad (2.35)$$

As in the open-loop solution, it remains optimal for the coalition to drive the resource rent on the terminal unit to zero, which implies that $\lim\limits_{t\to\infty} \lambda(t) = 0$ whereby via $c = \lim\limits_{t\to\infty} e^{-rt}\lambda(t)$ (2.20) it also follows that $c = 0$ in (2.19). Also in the time-consistent solution, the coalition only pays the differential resource rent to the supply side. The time-consistent unit tax goes to infinity as time proceeds to infinity because the price elasticity of demand and the unit extraction costs are bounded by assumption, which also implies that the consumer price goes to infinity as time proceeds to infinity.[36] Because it holds that $\phi_R\big(R(t)\big) = P^C(t)$ along the equilibrium extraction path under the time-consistent tax, the development of the consumer price over time is characterised by the differential equation (2.33). The producer price

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[36] Hoel and Kverndokk (1996) study the development of the optimal carbon unit tax chosen by a social planner in a framework where the CO_2 emission concentration in the atmosphere decays. In contrast to the present analysis, in their case the CO_2 emission concentration in the atmosphere therefore declines from some time onwards, whereby the optimal carbon tax also declines in absolute terms from some time onwards.

satisfies the representative supplier's intertemporal arbitrage condition (2.10), as usual. As the coalition drives the resource rent on the terminal unit to zero, the producer price still converges to the unit extraction costs of the terminal resource unit as time proceeds to infinity.

Because the coalition reduces the global demand below the laissez-faire level in every period by levying the time-consistent unit tax, the supplier has to accept a lower price in every period to be able to exhaust the resource stock, which is an equilibrium condition, as demonstrated in Appendix 2.3. Because the time-consistent unit tax increases future supply at the expense of present supply, the consumer price must fall short of the laissez-faire price from some point in time onwards. As verified in the next section, the intertemporal supply shift is less pronounced in the time-consistent solution compared to the open-loop case. This implies that the consumer price in the time-consistent solution lies between the laissez-faire price and the open-loop consumer price in the early periods and that it also lies between these two prices from some future period in time onwards. Notably, in the time-consistent solution, the coalition only pays the differential rent to the supply side while it internalises the global warming externality at the same time. Hence, also in the time-consistent solution, the climate policy brings about the advantage of lower rent payments to the supply side compared to the laissez-faire case.

2.7 GLOBAL COALITION AND EFFICIENCY OF INTERTEMPORAL RESOURCE ALLOCATION

This section derives the equilibrium extraction paths that result in the open-loop and the time-consistent solution and compares them against the normative and the laissez-faire paths that have been derived before in sections 2.2 and 2.5, respectively. Although the solution is dynamically inconsistent, the extraction path that results in the open-loop case is also derived because it reveals that from an intertemporal efficiency perspective, it is not desirable to implement the open-loop solution, although the global climate coalition would prefer it.

With $P\big(R(t)\big) = \phi_R\big(R(t)\big)$ as the global inverse demand function for the resource that is assumed to be downward sloping as usual, the differential equations (2.25) and (2.33) that characterise the coalition's open-loop and time-consistent resource consumption path, respectively, can be written as

$$P_R\big(R(t)\big)\dot{R}(t) = r\left[P\big(R(t)\big) - g\big(S(t)\big) + g_S\big(S(t)\big)[S_0 - S(t)]\right] - \omega_S\big(S(t)\big) \quad (2.25a)$$

for the open-loop case and as

$$P_R\big(R(t)\big)\dot{R}(t) = r\big[P\big(R(t)\big) - g\big(S(t)\big)\big] - \omega_S\big(S(t)\big) \quad (2.33a)$$

for the time-consistent case. As demonstrated in Appendix A2.3, an equilibrium extraction path must lead to the terminal point $S = 0$ in figure 2.5 to meet the transversality condition of the coalition, which is $\lim_{t\to\infty} \mu(t)S(t)e^{-rt} = 0$ (2.24). Moreover, an equilibrium path must satisfy the respective differential equation, i.e. equation (2.25a) in the open-loop case and equation (2.33a) in the time-consistent solution.

With $dR/dS = \dot{R}/\dot{S} = -\dot{R}/R$, the slope for a point in R, S space in the open-loop solution follows from (2.25a) and it is defined by

$$\frac{dR}{dS} = \varepsilon(R)\left[r\left(1 - \frac{g(S) - g_S(S)[S_0 - S]}{P(R)}\right) - \frac{\omega_S(S)}{P(R)}\right] \quad (2.36)$$

where $\varepsilon(R) = -\frac{\partial R}{\partial P}\frac{P}{R}$ denotes the absolute value of the price elasticity of demand as before. Independent of calendar time, the slope for a point in R, S space that is compatible with the open-loop equilibrium conditions is defined by equation (2.36). Respectively, the slope for a point in R, S space that is compatible with the time-consistent equilibrium conditions is derived from the differential equation (2.33a) as

$$\frac{dR}{dS} = \varepsilon(R)\left[r\left(1 - \frac{g(S)}{P(R)}\right) - \frac{\omega_S(S)}{P(R)}\right]. \quad (2.37)$$

Recall that the slopes for a point in R, S space that are compatible with the respective equilibrium conditions in the laissez-faire and the normative case are defined by equations (2.13) and (2.6) as derived in sections 2.2 and 2.5, respectively. Given the boundedness assumptions made regarding the price elasticity of demand, the unit extraction costs, and the marginal output losses, all four considered equilibrium extraction paths lead to the terminal point $S = 0$. As time goes by, the global resource stock in situ is depleted and the extracted resource flow converges to zero at time proceeds to infinity in any scenario. Furthermore, the extracted resource flows decline monotonically in all cases because demand is assumed to be independent of calendar time.

Notably, equation (2.13), which characterises the laissez-faire extraction path, defines a steeper slope for each point in R, S space compared to all other scenarios, which implies a larger global resource flow for a given resource stock in situ and thus a quicker speed of global extraction than in any other scenario. Hence, the laissez-faire path starts with the highest initial resource flow. However, this does not imply that at each point in time the quantity in the laissez-faire case exceeds the quantities in the other scenarios. As the resource stock is finite, an extraction path that exhibits a larger resource flow than another path in early periods must exhibit a smaller flow than the other path at some future point in time. Along the normative path, the extracted resource flow for a given stock in situ falls short of the laissez-faire resource flow. This is compatible with the lower slope for each point in R, S space as defined by equation (2.6). Intertemporal efficiency requires that the speed of global resource extraction is reduced compared to the laissez-faire case. As demonstrated in Sinn (2007, 2008a), the competitive market does not internalise the global warming externality whereby the global resource stock is extracted too quickly compared to the Pareto efficient speed of resource extraction.

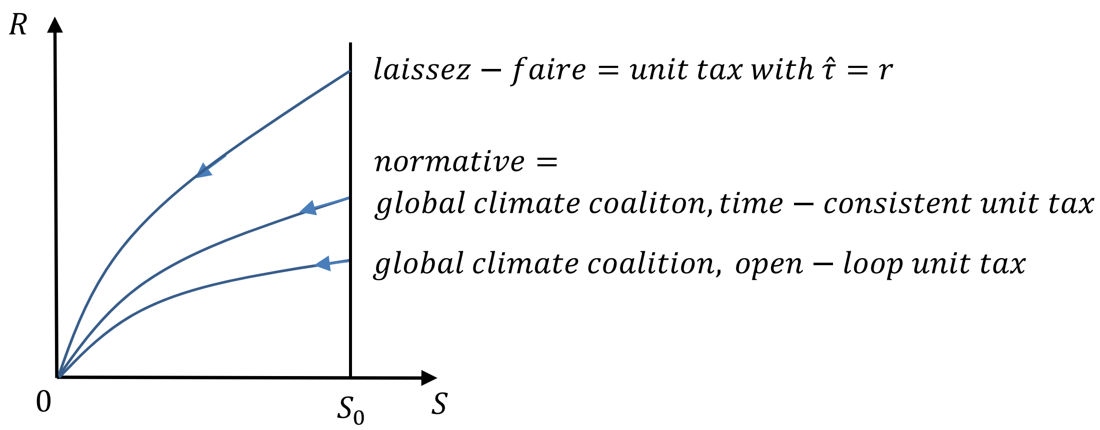

Figure 2.5: Resource extraction paths: laissez-faire, normative as well as time-consistent and open-loop scenario.

Moreover, figure 2.5 reveals that the global climate coalition reduces the speed of global resource extraction below the efficient speed in the open-loop solution. From an intertemporal efficiency perspective, the coalition dictates an over-conservative extraction path in terms of the extraction speed if it can credibly commit itself to its open-loop consumption path. The lower resource flow in the open-loop solution is required by equation (2.36), which defines a lower slope for each point in R, S space compared to the normative case. The coalition's motive to slow down the speed of global resource extraction to manipulate the differential resource rent trajectory in addition to its desire to internalise the global warming externality makes it optimal to enforce an even lower speed of resource extraction than the social planer would choose.[37] The coalition's monopsony power implies a market failure, which expresses itself in the open-loop solution via the overly conservative open-loop extraction path. However, as was demonstrated, the open-loop solution is dynamically inconsistent. Fortunately, regarding the efficiency of the intertemporal resource allocation, this implies that this solution is of minor practical relevance.

Only the climate coalition's motive to internalise the global warming externality is credible from the perspective of the supply side. Importantly, figure 2.5 shows that the extraction path resulting in the time-consistent solution coincides with the normative extraction path because equation (2.37) defines the same slope for a point in R, S space as the normative equation (2.6). Because the global climate coalition internalises the global warming externality in the time-consistent solution, the coalition dictates the Pareto efficient speed of resource extraction. Under the boundedness assumptions made regarding the price elasticity of demand, the unit extraction costs, and the marginal output losses from global warming, it is sufficient to reduce the speed of global resource extraction to achieve Pareto efficiency regarding the intertemporal resource allocation.

Although these results are less surprising given the assumption that the global climate coalition comprises all countries, implying that the global warming externality is internalised in the time-consistent solution, they provide the justification for the aim to strive for a global climate coalition as discussed in the beginning of this chapter. In the time-consistent solution, the coalition dictates the normative speed of global resource extraction. Put differently, if, for instance, the United Nations were to decide on the global climate coalition's optimal resource consumption path on behalf of all countries, the global resource stock would be depleted at the Pareto efficient speed in the time-consistent solution. In this regard, there is a strong case to aim for a globally coordinated climate policy supported by the global community. However, as will be demonstrated in the next chapters, the chosen way towards a global climate coalition will crucially determine the speed at which the resource suppliers deplete their resource stocks in the meantime and thereby the severity of the global warming problem.

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[37] Tahvonen (1995), p. 267, finds a similar result in a linear-quadratic framework, whereby, in contrast to the case considered here, the open-loop solution is dynamically consistent because stock-independent unit extraction costs are assumed. The author also states that the socially efficient extraction path is implemented if extraction costs are constant.

APPENDIX 2

A2.1 NORMATIVE MODEL (ADOPTED FROM SINN (2008a))

The asymptotic properties of the system (2.1)-(2.3) given here are based on those provided in Sinn (2008a), pp. 390-1. The solution to the system is restricted to feasible extraction paths. Because the resource stock in situ is finite, feasibility requires that $R(t) \to 0$ as $t \to \infty$. Given the assumptions that the unit extraction costs are bounded from above and that $\lim_{R\to 0} \phi_R\big(R(t)\big) = \infty$, it follows from the planner's stationary condition (2.1) that

$$\phi_R\big(R(t)\big) - g\big(S(t)\big) = \gamma(t) \quad (2.1a)$$

which reveals that $\gamma(t) \to \infty$ as $t \to \infty$ because it must hold that $R(t) \to 0$ for $t \to \infty$. Moreover, from the planner's canonical equation (2.2) it follows that

$$\hat{\gamma}(t) = r - \frac{\omega_S\big(S(t)\big)}{\gamma(t)} + \frac{g_S\big(S(t)\big)R(t)}{\gamma(t)}. \quad (2.2a)$$

As $\gamma(t) \to \infty$ for $t \to \infty$, equation (2.2a) reveals that $\hat{\gamma}(t) \to r$ as $t \to \infty$ due to the assumptions that the marginal output losses and the derivative g_S are bounded and because it must hold that $R(t) \to 0$ as $t \to \infty$. As $\hat{\gamma}(t) \to r$ for $t \to \infty$ it then follows that $\gamma(t)e^{-rt} > 0$ as $t \to \infty$ and hence the resource stock must converge to zero as time proceeds to infinity whereby the transversality condition $\lim_{t\to\infty} \gamma(t)S(t)e^{-rt} = 0$ (2.3) is met.

A2.2 MAXIMISATION PROBLEM OF REPRESENTATIVE RESOURCE SUPPLIER

Given are the asymptotic properties of the system (2.7)-(2.9) for the cases of the bounded unit taxes and given the downward sloping global inverse demand function $P\big(R(t)\big)$ as considered in section 2.5. As the resource stock in situ is finite, feasibility of the solution requires that $R(t) \to 0$ as $t \to \infty$. Note that along an equilibrium extraction path under a global unit tax on resource consumption it holds that $P^C(t) = P\big(R(t)\big)$. Because the price elasticity of global demand, the considered unit taxes and the unit extraction costs are bounded by assumption, it follows from the stationary condition of the representative supplier

$$P^C(t) - \tau(t) = g\big(S(t)\big) + \lambda(t) \quad (2.7)$$

that $\lambda(t) \to \infty$ as $t \to \infty$ because the boundedness assumption regarding the price elasticity of demand implies that $\lim_{R\to 0} P\big(R(t)\big) = \infty$, i.e. $P^C(t) \to \infty$ as $R(t) \to 0$ for $t \to \infty$. Moreover, from the supplier's canonical equation (2.8) it follows that

$$\hat{\lambda}(t) = r + \frac{g_S(S(t))R(t)}{\lambda(t)}. \quad (2.8a)$$

As $\lambda(t) \to \infty$ for $t \to \infty$ it follows from equation (2.8a) that $\hat{\lambda}(t) \to r$ for $t \to \infty$ because it must hold that $R(t) \to 0$ as $t \to \infty$ and because the derivative g_S is bounded by assumption. This implies that $\lambda(t)e^{-rt}$ is bounded away from zero as $t \to \infty$ whereby the transversality condition $\lim_{t\to\infty} \lambda(t)S(t)e^{-rt} = 0$ (2.9) is only met if $S(t) \to 0$ as $t \to \infty$. The global stock converges to zero as time proceeds to infinity under the considered global unit taxes.

The asymptotic properties for the laissez-faire case follow accordingly by letting $\tau(t) = 0$ and if it is noted that along the laissez-faire equilibrium path it holds that $P(t) = P(R(t))$.

A2.3 GLOBAL CLIMATE COALITION

Given are the asymptotic properties of the open-loop and the time-consistent solution. From the coalition's stationary condition in the open-loop case (2.22) it follows that

$$\phi_R(R(t)) - g(S(t)) + g_S(S(t))[S_0 - S(t)] = \mu(t) \quad (2.22a)$$

while from the coalition's stationary condition in the time-consistent solution (2.31) it follows that

$$\phi_R(R(t)) - g(S(t)) = \mu(t). \quad (2.31a)$$

Feasibility of both solutions requires that $R(t) \to 0$ as $t \to \infty$ due to the finiteness of the resource stock. Thus, in both the open-loop and in the time-consistent solution it follows that $\mu(t) \to \infty$ as $t \to \infty$ due to the assumption that $\lim_{R\to 0} \phi_R(R(t)) = \infty$ and because the unit extraction costs as well as the derivative g_S are bounded by assumption. Moreover, it respectively follows from the coalition's canonical equations in the open-loop (2.23) and the time-consistent (2.32) solution that in the open-loop case it holds that

$$\hat{\mu}(t) = r - \frac{\omega_S(S(t))}{\mu(t)} + \frac{2g_S(S(t))R(t)}{\mu(t)} - \frac{g_{SS}(S(t))R(t)[S_0 - S(t)]}{\mu(t)} \quad (2.23a)$$

while in the time-consistent case it holds that

$$\hat{\mu}(t) = r - \frac{\omega_S(S(t))}{\mu(t)}. \quad (2.32a)$$

Equations (2.23a) and (2.32a) reveal that in the open-loop and in the time-consistent solution it equally holds that $\hat{\mu}(t) \rightarrow r$ as $t \rightarrow \infty$ because $\mu(t) \rightarrow \infty$ and $R(t) \rightarrow 0$ for $t \rightarrow \infty$ and because the marginal output losses and the derivatives g_S and g_{SS} are bounded by assumption. Hence, as in both cases $\mu(t)e^{-rt}$ does not converge to zero as $t \rightarrow \infty$, it must be the case in both solutions that $S(t) \rightarrow 0$ as $t \rightarrow \infty$, whereby the coalition's transversality condition $\lim_{t\rightarrow\infty} \mu(t)S(t)e^{-rt} = 0$ (2.24) is satisfied. The present values of both the Hamiltonian (2.21) and the Hamiltonian (2.30) converge to zero as time proceeds to infinity.

3 INCOMPLETE CLIMATE COALITION

While the notion that the global climate coalition implements the normative resource extraction path in the time-consistent solution is promising, this result naturally hinges on the assumption that the coalition comprises all countries, which is far from reality at present. In fact, a small number of countries have been at the forefront of the combat against global warming since the introduction of the United Nations Framework Convention on Climate Change in 1992. Despite the difficulties in agreeing upon a successor to the Kyoto protocol for the time after the first commitment period, which ended in 2012, the EU underlined its ambitions to reduce its CO_2 emissions also from 2012 onwards already in 2008. Back then, the EU lined out its target of a 20 per cent reduction in CO_2 emissions compared to 1990 levels by 2012 in its EU climate and energy package.[1] Furthermore, the European Commission proposed in early 2014 that its member countries should strive for a 40 per cent reduction in CO_2 emissions by 2030 compared to 1990 levels.[2] The EU's long-term goal to reduce its CO_2 emissions by 80 per cent by 2050 compared to 1990 levels is pinned down in its Energy Roadmap 2050.[3]

Given the prevailing situation, this chapter firstly asks the question under which premises a unilateral reduction in fossil resource consumption can actually slow down the speed of global resource extraction. As in the case of the global climate coalition, the considered incomplete coalition, which comprises a subset of the world's countries, is again called a 'climate coalition' to emphasise that the member countries of the coalition suffer output losses from global warming. However, it will be demonstrated that, irrespective of the global warming problem, the member countries benefit from the formation of the incomplete coalition if the established coalition can commit itself to its optimal resource consumption path.

As is well known by now, the major drawback of a unilateral climate policy that seeks to postpone extraction from the present to the future for the good of the environment is that, given that the incomplete climate coalition exhibits some degree of market power, reducing the demand for the resource in one world region depresses the world market price for the

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[1] European Commission, 20 20 by 2020 Europe's climate change opportunity, Brussels, 2008. The final compromise was agreed in December 2008.

[2] European Commission, A policy framework for climate and energy in the period from 2020 to 2030, Brussels, January 2014.

[3] European Commission, Energy Roadmap 2050, Brussels, 2011.

resource that the resource owners obtain on the global resource market. This decline in the world market price triggers an increase in resource consumption in those world regions where no climate policy is implemented.[4] The term ‘carbon leakage’ describes this mechanism. If only a subgroup of the world’s resource consuming countries reduces its fossil resource consumption compared to its laissez-faire consumption level, the refrained resource quantities will, at least to some extent, be consumed in the non-policy countries at the lower world market price. Unfortunately, for the global warming problem it is irrelevant where fossil resources are burned in the world as long as they are burned in the same period.

To answer the question under which circumstances a unilateral reduction in fossil resource consumption does slow down the speed of global extraction, an incomplete climate coalition is considered that comprises a subgroup of the world’s resource consuming countries. The incomplete coalition has some degree of market power and it purchases a fossil resource flow from a representative competitive resource supplier over time. The countries outside the coalition, hereafter also referred to as the fringe countries, take the world market price for the resource as given and they do not implement any policy whatsoever. In a first step, the policy path pursued by the incomplete coalition is assumed to be exogenously given. It is demonstrated that a unilateral unit tax levied on resource consumption within the incomplete coalition is neutral for the speed of global resource extraction if the coalition and the fringe countries exhibit the same constant price elasticity of demand and if demand is independent of calendar time. This holds also with stock-dependent unit extraction costs. If the unilateral unit tax increases (decreases) in present value terms it speeds up (slows down) global extraction compared to the laissez-faire case. Allowing for time-dependent demand while abstracting from extraction costs, a unilateral unit tax that grows at the market rate of interest remains neutral for the global speed of extraction if the demand of the coalition and the fringe countries grows or shrinks at the same rate over time for exogenous reasons and if both groups have the same constant price elasticity of demand.

The present chapter also analyses the decision problem of an incomplete climate coalition. It is assumed that the incomplete climate coalition exhibits some degree of market power on the global resource market and that its member countries suffer output losses over time due to climate change. The incomplete coalition leads in a Stackelberg differential game in which a representative competitive resource supplier and the passive fringe countries outside the coalition are the followers. The open-loop solution to the incomplete coalition’s decision

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[4] Cf. Hoel (1991), Bohm (1993), Sinn (2008a,b, 2012) as well as Eichner and Pethig (2011) and Ritter and Schopf (2013) on this mechanism commonly referred to as ‘carbon leakage’.

problem is derived by extending the Stackelberg differential game introduced in Chapter 2 for a passive fringe of countries that have no policy in place. It emerges that the incomplete coalition implements a unilateral unit tax that decreases in present value terms. Abstracting from extraction costs, the unilateral open-loop policy thus unambiguously slows down the speed of global extraction compared to the laissez-faire case under the assumptions that the demand of the coalition and the fringe countries grows or shrinks for exogenous reasons over time at the same rate and that both groups exhibit the same constant price elasticity of demand. Although the coalition is incomplete and although the fringe countries increase their resource consumption in response to the policy-induced decline in the world market price for the resource, the coalition thus fights global warming in the open-loop solution under the assumptions made. If the assumptions made fail to be valid, the effect that the incomplete coalition's unilateral open-loop policy has on the speed of global resource extraction is more complex.

3.1 MARKET POWER AS A PREREQUISITE

An incomplete coalition comprising a subset of the world's countries can only affect the speed of global resource extraction if it exhibits some degree of market power on the global resource market. If this was not the case, any unilateral demand reduction would not alter the laissez-faire resource price path and hence there would be no intertemporal supply reaction to the policy. Thus, market power is the essential prerequisite for a unilateral climate policy that aims to fight global warming. In the case of the European Union, the assumption of some degree of market power is, to some extent, plausible.

Figure 3.1 depicts the development of the CO_2 emissions of the four largest emitters in 2012, as well as those of the European Union and the rest of the world (ROW) over the last two decades. Calendar time is depicted on the abscissa. During the last two decades, the global annual CO_2 emissions from fuel combustion have increased from 21 gigatons of CO_2 in 1990 to 31.7 gigatons in 2012. Actually, China alone accounts for more than half of this global increase in CO_2 emissions and its total energy consumption is forecasted to further increase by 71 per cent until 2035 compared to the level that prevailed in 2012.[5] Together, the four countries depicted in figure 3.1 plus the EU increased their common CO_2 emissions from 13.9 gigatons CO_2 in 1990 to 20.4 gigatons CO_2 in 2012.

Because CO_2 emissions can be regarded as the mirror image of the amount of fossil fuels combusted in these countries, they serve as an indicator for a country's market power on the

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[5] BP Energy Outlook 2035, January 2014.

fossil resource markets in terms of its share in global fossil resource consumption. The EU's share in global CO_2 emissions has declined over the years, from 19.4 per cent in 1990 to 11 per cent in 2012. In addition, the emission shares of the US and Russia decreased between 1990 and 2012, namely from 23.2 to 16 per cent and from 10.4 to 5.2 per cent, respectively. The joint emission share of the EU, the US and Russia fell from 53 per cent in 1990 to 32.3 per cent in 2012 while China and India's joint emission share rose from 13.5 to 32 per cent during the same period. India's share in global CO_2 emissions increased from 2.8 per cent in 1990 to 6.2 per cent in 2012 and China's share increased from 10.7 per cent in 2010 to 25.9 per cent in 2012. If one considers the changes in the emission shares between 1990 and 2012 of the emitters ranking behind the top five group of emitters in percentage points (in brackets), namely Japan (-1.2), South Korea (+0.8), Canada (-0.4), Iran (+0.8) and Saudi Arabia (+0.7), it becomes clear that the shift in global CO_2 emission shares over the last two decades occurred mainly from the US, the EU and Russia to China and India.

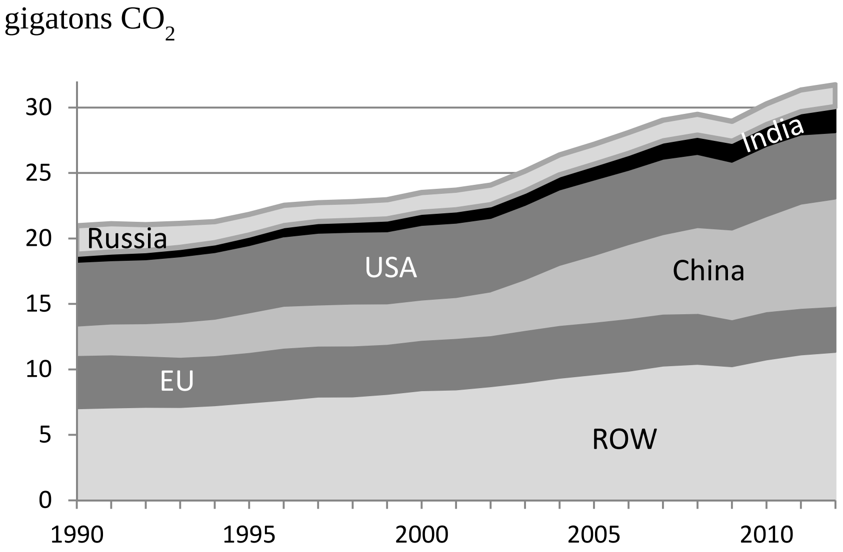

Figure 3.1: Development of CO_2 emissions from fuel combustion of the world's four largest CO_2 emitters in 2012, the European Union and the rest of the world (ROW) from 1990 to 2012 in gigatons.

Source: CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

In the model presented in this chapter, an incomplete climate coalition will be considered that exhibits a share in global resource consumption that is sufficiently large to imply market power on the global resource market to some extent. Furthermore, the incomplete coalition is assumed to be of a stable size in terms of its member countries over time, i.e. the analysis abstracts from any coalition formation issues. A game theoretical literature has been established that analyses the underlying rationale for countries to participate in a climate coalition. A basic result of this literature is that the size of a self-enforcing climate coalition is the larger the smaller that the global potential net gains are when one moves from the non-cooperative case to full cooperation.[6] The essential mechanism that triggers the incentive to participate in a climate coalition in many of the studied games is that the mitigation effort of the coalition members increases if other countries join. The stable size of the coalition is reached when no coalition member wants to leave and when no country outside the coalition wants to join. However, as the focus of the present chapter lies on the effect that unilateral reductions in resource consumption have on the intertemporal resource allocation, the subsequent analysis takes the size of the incomplete coalition in terms of its member countries as exogenously given and constant over time.

3.2 CARBON LEAKAGE

The analysis of an incomplete climate coalition is different compared to that of a global climate coalition because carbon leakage occurs. The term describes the mechanism whereby part of the resource flow that the incomplete coalition refrains from in an arbitrary period is not delayed to the future, but is rather consumed somewhere else in the world within the same period. In an early paper, Hoel (1991) emphasises the possibility that pursuing a unilateral climate policy might in fact increase instead of decrease global emissions because the policy decreases the benefit that the non-policy countries have from reducing their emissions. In the light of the unilateral climate policy advances of the EU, this would imply that if the EU is in fact able to slow down the speed of global resource extraction via its unilateral demand reductions in resource consumption, the incentive for the countries outside the coalition to cut their emissions is reduced. Bohm (1993) also provides an early notion of carbon leakage by stating that a unilateral policy reduces the global resource price, which increases demand in the non-policy regions of the world, thereby offsetting the effect of the unilateral policy.

The literature on carbon leakage essentially distinguishes two channels via which carbon leakage occurs, namely via the trade in carbon intensive goods and the international resource market itself.[7] The first channel emphasises the idea that a unilateral climate policy in one world region leads to a decrease in the output of carbon intensive goods in this policy region while the output of carbon intensive goods in the non-policy region increases, given a certain

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[6] Cf. for instance Barrett (1994, 2001) on this basic result as well as Hoel (1992), Carraro and Siniscalco (1993) and Hoel and Schneider (1997) on the analysis of the formation of climate coalitions.

[7] Cf., for instance, Felder and Rutherford (1993) and Gerlagh and Kuik (2007) on the distinction of both subsequently discussed channels.

global demand for carbon intensive goods.[8] In this respect, the so-called ‘pollution haven hypothesis’ should also be mentioned, which states that a unilateral climate policy can trigger emigration of particularly carbon intensive industries to other regions in the world that exhibit no or laxer environmental policies.[9] From the perspective of a carbon intensive industry located in the policy region, the price for the input factor carbon is comparably lower in the laissez-faire region and this triggers the emigration decision. Accordingly, the increase in the output of carbon intensive goods in the non-policy regions is produced by both domestic firms that have always been there and by foreign firms that came in response to the policy that has been implemented in their home country. Literally speaking, the carbon intensive goods channel captures the idea that with globally integrated markets, carbon intensive goods formerly produced in Europe are now produced in the non-policy regions of the world and are subsequently exported to Europe.

The second carbon leakage channel works via the global fossil resource market itself, as considered in Bohm (1993) and Sinn (2008a,b, 2012), for instance. As previously mentioned, the underlying mechanism is that given that the incomplete coalition exhibits market power on the global resource market, the coalition’s unilateral reductions in resource consumption reduce the global demand for the resource over time, thereby pushing down the world market price below the laissez-faire price. This decrease in the world market price increases the resource consumption of the non-policy countries compared to their laissez-faire consumption level in the reasonable scenario in which these countries exhibit a downward sloping demand curve. Carbon leakage thus occurs via the global resource market as long as a unilateral consumption reduction undertaken by a subgroup of the world’s countries reduces the world market price for the resource compared to the laissez-faire scenario.

In reality, both channels of carbon leakage are related and likely occur as a mix. The implementation of a unilateral climate policy will decrease the global demand for the resource and thus the world market price for the resource compared to the laissez-faire scenario. Furthermore, given a certain global demand for carbon intensive goods, the unilateral policy might simultaneously trigger a shift in the production of carbon intensive goods from the policy region to the non-policy regions. However, this chapter focuses on the interactions taking place on the global resource market and thus considers carbon leakage occurring via this channel only.

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[8] Cf. Perroni and Rutherford (1993), Copeland and Taylor (1994, 2005), Kuik and Gerlagh (2003), Di Maria and van der Werf (2008) as well as Aichele and Felbermayr (2012).

[9] Cf. Taylor (2004), Umanskaya and Barbier (2008) and Levinson (2009).

Literature analysing carbon leakage in dynamic models of fossil resource extraction in the context of the global warming problem is fairly rare. In the presence of resource suppliers that solve an intertemporal optimisation problem, the mechanism of carbon leakage is, to the author's knowledge, analysed in Sinn (2008a,b, 2012), Eichner and Pethig (2011), Hoel (2011b) and Ritter and Schopf (2013). Eichner and Pethig (2011) investigate carbon leakage in a two-period general equilibrium model considering a dynamically optimising resource supply side. In their analysis, in which the incomplete coalition implements an exogenously given cap on its emissions, the price elasticity of demand for the fossil resource and the intertemporal elasticity of substitution with respect to the consumption good turn out to be the crucial determinants for the intertemporal supply reaction to the unilateral policy. Ritter and Schopf (2013) extend the framework for stock-dependent extraction costs, thereby endogenising cumulative extraction. Another author who investigates carbon leakage in the presence of a dynamically optimising resource supply side is Hoel (2011b). The author analyses the case of heterogeneous countries exhibiting different, but constant and exogenously given tax levels in a partial equilibrium resource market model with a dynamically optimising resource supply side. Assuming zero extraction costs and a perfect substitute for the fossil resource that is available at a constant marginal cost, Hoel (2011b) shows that a unilateral increase of the tax level in that country with the initially lower tax might accelerate resource extraction. The aim of the present analysis is to derive general conditions under which a unilateral climate policy unambiguously fights climate change in a partial equilibrium model that captures the global resource market. Moreover, the policy choice of an incomplete coalition that is concerned with the global warming problem is endogenised.

The quantification of carbon leakage is difficult but a few estimates regarding the magnitude of the effect exist. Felder and Rutherford (1993) find that 25 per cent of the marginal emission unit abated in the OECD countries is consumed somewhere else in the world. Static computable general equilibrium models as employed in Burniaux and Oliveira Martins (2000) and Paltsev (2001) have indicated that the carbon leakage rate crucially depends on the fossil source under consideration and particularly the respective supply elasticity. Paltsev (2001) finds a leakage rate of 10.5 per cent, to which the chemical, iron and steel industries contribute most. For coal supply elasticities below two, Burniaux and Oliveira Martins (2000) find a carbon leakage rate of at least 20 per cent. Babiker (2005) focuses on the relocation of energy-intensive industries in response to the Kyoto process, i.e. the pollution haven hypothesis, and finds a wide range of possible leakage rates between 50 and 130 per cent. A carbon leakage rate of more than 100 per cent is in fact a hint that an intertemporal supply response in the form of an anticipation of resource quantities from the future to the present might have been triggered, i.e. the forces of the Green Paradox would be at work.

Figure 3.1 in the former section already revealed that during the last two decades, a significant shift in CO_2 emission shares has taken place from the US, the EU and Russia mainly to China and India. Figure 3.2 shows that China and India not only exhibit increasing shares in the rising global CO_2 emissions path, but also that their energy consumption mix has become more fossil fuel-intensive over the last two decades. The graph depicts the development of the fossil fuel share in total primary energy consumption of the four largest CO_2 emitters in 2012 and the EU for the period from 1990 to 2011.

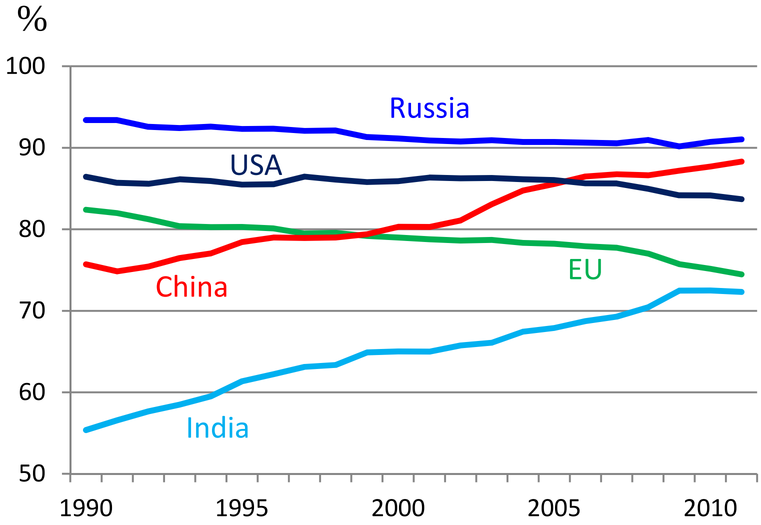

Figure 3.2: Development of fossil fuel share in total primary energy consumption in kilotons of oil equivalent of the four largest CO_2 emitters in 2012 and the EU from 1990 to 2011. Fossil fuel comprises coal, oil, petroleum and natural gas products.

Source: World Bank, World Development Indicators, August 2014, http://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS.

In China, the share of fossil fuels in total primary energy consumption has increased from 75.7 per cent in 1990 to 88.3 per cent in 2011 while within the EU the share declined from 82.4 per cent to 74.5 per cent during the same period. Within these two decades, the EU reduced its annual CO_2 emissions from 4.1 gigatons in 1990 to 3.6 gigatons in 2011 while China at the same time increased its emissions from 2.2 to almost 8 gigatons CO_2. India's total emissions rose from 0.58 gigatons in 1990 to 1.8 gigatons in 2011 and the share of fossil fuels in total primary energy consumption has increased from 55.4 per cent in 1990 to 72.3 per cent in 2011. Note, however, that the graph does not reveal whether carbon leakage is actually a responsible factor for these changes because it is unknown how the Chinese and Indian primary energy consumption mixes would have looked like without any climate policy advances in the form of the Kyoto process in the past. However, it is sensible to hypothesise that a shift towards a dirtier energy consumption mix in China and India is favoured by the unilateral consumption reductions undertaken by those countries that have binding emission reduction targets under the Kyoto protocol, presuming that these reductions actually lower the world market prices for fossil resources. However, as previously mentioned, only knowing that one world region decreases its fossil resource consumption while another country increases its consumption does not prove that this increase is actually due to carbon leakage because the counterfactual CO_2 emissions or resource consumption path that would have prevailed in the absence of the Kyoto process is unknown. This constitutes a major problem regarding the quantification of carbon leakage.

However, that a unilateral climate policy reduces the global demand for fossil resources and thereby depresses their world market prices compared to the laissez-faire prices whereby the non-policy countries increase their resource consumption in response to this price reduction is a theoretically convincing argument that cannot be ignored. As will be demonstrated in the theoretical framework presented below, the reaction of the non-policy countries is important to consider for the understanding of how a unilaterally pursued climate policy actually affects the speed of global fossil resource extraction.

3.3 SUPPLIER REACTION TO A UNILATERAL UNIT TAX

The intertemporal reaction of the resource supply side to a unit tax on resource consumption is determined by the growth rate of the unit tax itself if the tax is levied globally, as follows from the Long-Sinn invariance theorem.[10] The reason is that in the case of a global unit tax on resource consumption, the wedge that the unit tax drives in an arbitrary period between the laissez-faire world market price for the resource and the hypothetical world market price that would prevail if the representative supplier did not react to the tax is equal to the level of the unit tax itself. Hence, the growth rate of the wedge that the tax drives between the laissez-faire price and the hypothetical world market price and the growth rate of the tax coincide. This convenient relation breaks down in the case of a unilateral unit tax on resource consumption that is only levied by a subgroup of the world's countries.

Due to the existence of the fringe countries, the growth rate of a unilateral unit tax on resource consumption and the growth rate of the wedge that this tax induces between the laissez-faire

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[10] Cf. Long and Sinn (1985).

resource price and the hypothetical world market price that would prevail under the tax if the supply side did not react to the tax are no longer the same. However, it is still the growth rate of this wedge that determines the intertemporal supply reaction. If the induced wedge is constant in present value terms, the extraction path is unaltered by the unilateral consumption tax, as follows from the Long-Sinn invariance theorem.[11] To make progress towards the understanding of how a unilateral unit tax on resource consumption affects the intertemporal supply decision of a representative competitive resource supplier, this section in a first step investigates how the introduction of such a tax affects the international resource distribution within an arbitrary period assuming that the supply side does not react to the tax.[12]

Let the resource demand function of the considered incomplete coalition be $R_i\big(P(t)\big)$ with $\partial R_i(P)/\partial P < 0$ where subscript i identifies the coalition and where $P(t)$ is the laissez-faire price in the considered period t. The absolute value of the constant price elasticity of demand of the coalition is given by $\varepsilon_i = -\frac{\partial R_i}{\partial P}\frac{P}{R_i}$ and is assumed to be bounded. To justify this assumption, only the absence of a truly perfect substitute for all purposes of fossil resource usage is necessary. The downward sloping inverse demand function of the incomplete coalition is denoted by $P_i\big(R_i(t)\big)$ where the resource flow consumed by the coalition in period t is $R_i(t)$. Furthermore, the aggregate demand of the fringe countries in the laissez-faire case is given by $R_{-i}\big(P(t)\big)$ with $\partial R_{-i}(P)\,/\partial P < 0$ where subscript $-i$ identifies the fringe countries outside the coalition. The downward sloping inverse demand function of the fringe countries is respectively given by $P_{-i}\big(R_{-i}(t)\big)$ whereby $R_{-i}(t)$ denotes the resource flow consumed by the fringe countries in period t. The absolute value of the price elasticity of the fringe demand is denoted by $\varepsilon_{-i} = -\frac{\partial R_{-i}}{\partial P}\frac{P}{R_{-i}}$ and is also bounded by assumption.

The situation on the global resource market in an arbitrary period is depicted in figure 3.3. Because this section focuses on one period only, the principle time-dependence of the concerned variables is suppressed. The width of the box is given by the global laissez-faire resource flow R that is supplied in the considered period and for now this flow is assumed to be fixed. In the graph, the inverse demand functions of the incomplete climate coalition and the fringe countries are depicted by $P_i(R_i)$ and $P_{-i}(R_{-i})$, respectively. The global laissez-faire resource flow is distributed among the coalition and the fringe countries whereby the resource

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[11] Cf. Sinn (2008a,b, 2012) on the Long-Sinn invariance theorem and its application to the intertemporal supply reaction to a unilateral climate policy.

[12] The following analysis of carbon leakage in the hypothetical case of a fixed resource supply flow is based upon Sinn (2008), pp. 342-9 and Sinn (2012), pp. 143-6.

flow consumed in the coalition is depicted on the abscissa from the left to the right. Correspondingly, the resource flow consumed in the fringe countries is depicted on the abscissa from the right to the left. The equilibrium on the global resource market in the laissez-faire case is characterised by the intersection of the groups' inverse demand curves and the resulting international resource allocation is characterised by point 0. The laissez-faire resource flow consumed by the incomplete climate coalition is $R_{i,0}$ and the residual resource flow consumed by the passive fringe countries is $R_{-i,0} = R - R_{i,0}$. The world market price for the resource in the laissez-faire case is P. In fact, there are similar graphs as the one depicted for the periods before and after the considered period where the period-specific inverse demand functions determine the international distribution of the global resource flow that is supplied over time.

Now consider the case of a unilateral unit tax τ_i levied on resource consumption within the incomplete climate coalition in the considered period. Let the consumer and the world market price that would prevail under the unilateral unit tax in the hypothetical case in which the supply side did not react to the tax be denoted by $\tilde{P}^C$ and $\underline{\tilde{P}}$, respectively. The unilateral unit tax decreases the resource demand within the climate coalition because the consumers now have to pay the hypothetical world market price $\underline{\tilde{P}}$ plus the unit tax τ_i. The inverse demand curve of the incomplete climate coalition in the presence of the unilateral unit tax is depicted by the dashed inverse demand curve left to the original curve $P_i(R_i)$. The intersection of the dashed inverse demand curve of the coalition and the inverse demand curve of the fringe countries determines the new equilibrium on the resource market depicted by point A for the hypothetical case of a fixed supply flow. The climate coalition reduces its consumption from $R_{i,0}$ to $R_{i,A}$ while the fringe countries increase their consumption from $R_{-i,0} = R - R_{i,0}$ to $R_{-i,A} = R - R_{i,A}$. In the hypothetical case of a fixed resource supply path, every resource unit that the coalition members refrain from in an arbitrary period is consumed in the fringe countries instead in the same period. As shown in Sinn (2008b, 2012), if the intertemporal supply schedule was indeed fixed, the unilateral policy would be entirely ineffective in fighting climate change. The same would be true if the incomplete coalition had no market power at all, in which case the laissez-faire price path would remain unchanged, despite the unilateral policy. However, the intertemporal supply schedule of the supply side is not fixed and it is assumed that the incomplete coalition has market power to some degree.

What holds relevance for the reaction of the supply side is the wedge that the unilateral tax drives between the laissez-faire resource price P and the hypothetical world market price $\underline{\tilde{P}}$

over time. Precisely, as follows from the Long-Sinn invariance theorem, it is the growth rate of the wedge $P - \underline{\tilde{P}}$ over time that determines the intertemporal supply reaction to the unilateral policy. If the wedge increases in present value terms extraction speeds up and if it decreases in present value terms extraction is slowed down compared to the laissez-faire case.

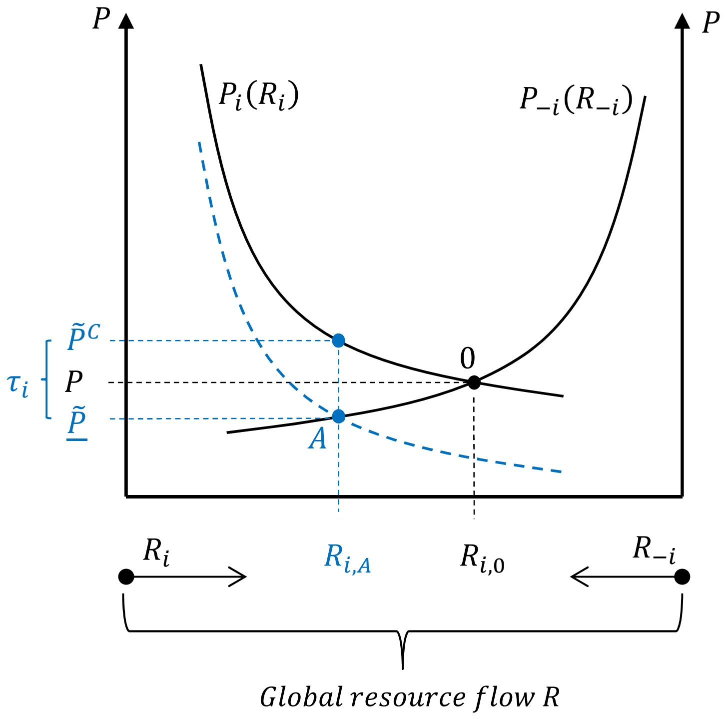

Figure 3.3: Effect from a unilateral unit tax on the international resource distribution given a fixed resource supply flow. Figure based on Sinn (2008b, 2012).

As previously mentioned, there is a graph similar to figure 3.3 for every period, and given a pair of inverse demand functions in every period, the unilateral unit tax induces a hypothetical wedge $P - \underline{\tilde{P}}$, which would result if the supply side did not react to the tax. The wedge $P - \underline{\tilde{P}}$ thus depends on calendar time. The following differential tax incidence experiment shall clarify the difference between a global and a unilateral unit tax on resource consumption regarding the intertemporal supply reaction. It asks the question of how the introduction of an arbitrarily small unilateral unit tax that the incomplete coalition levies on its resource consumption in an arbitrary period t translates into a wedge $P(t) - \underline{\tilde{P}}(t)$ in this period. While being aware of the limitation of the differential tax incidence analysis to an arbitrarily small tax, the experiment is nevertheless helpful to emphasise the importance of the role that the price elasticities of demand of the incomplete coalition and the fringe countries play for the reaction of the supply side to the considered unilateral unit tax.

Consider again the hypothetical case in which the resource supply side would not react to the unilateral tax whereby the laissez-faire resource supply path is fixed. Furthermore, presume that the incomplete coalition levies the arbitrarily small unit tax $\tau_i(t)$ on its resource consumption in period t. As before, let $\underline{\tilde{P}}(t)$ denote the hypothetical world market price that would prevail under the unit tax in period t, but given the global laissez-faire resource supply flow. Moreover, let $\tilde{P}^C(t)$ denote the corresponding hypothetical consumer price whereby it holds that $\tilde{P}^C(t) = \underline{\tilde{P}}(t) + \tau_i(t)$ in period t. Given a fixed intertemporal supply path, the incomplete coalition's demand for the resource under the unilateral unit tax is in period t given by $R_i\left(\underline{\tilde{P}}(t) + \tau_i(t)\right)$ with $\partial R_i\left(\tilde{P}^C\right)/\partial\, \tilde{P}^C < 0$. Furthermore, in the considered case of a fixed supply flow, the demand of the fringe countries is given by $R_{-i}\left(\underline{\tilde{P}}(t)\right)$ with $\partial R_{-i}\left(\underline{\tilde{P}}\right)/\partial\, \underline{\tilde{P}} < 0$. If the supply side would not react to the unilateral unit tax, the hypothetical equilibrium on the global resource market in the considered period t is characterised by the equality of global resource demand and supply, i.e. it holds that

$$R_i\left(\underline{\tilde{P}}(t) + \tau_i(t)\right) + R_{-i}\left(\underline{\tilde{P}}(t)\right) = R(t) \quad (3.1)$$

where the supplied fixed laissez-faire resource flow in the considered period is $R(t)$. Totally differentiating (3.1) while holding the supplied resource flow $R(t)$ fixed gives

$$\frac{d\underline{\tilde{P}}(t)}{d\tau_i(t)} = -\frac{\frac{\partial R_i}{\partial \tilde{P}^C}}{\frac{\partial R_i}{\partial \tilde{P}^C} + \frac{\partial R_{-i}}{\partial \underline{\tilde{P}}}}. \quad (3.2)$$

By evaluating equation (3.2) in the laissez-faire scenario where it holds that $\tilde{P}^C(t) = P(t)$ and where $\tau_i(t) = 0$, equation (3.2) can be written as

$$\left.\frac{d\underline{\tilde{P}}(t)}{d\tau_i(t)}\right|_{\tau_i(t)=0} = -\frac{\frac{\partial R_i}{\partial P}}{\frac{\partial R_i}{\partial P} + \frac{\partial R_{-i}}{\partial P}}. \quad (3.3)$$

Define $\beta(t) \equiv R_i(t)/R(t)$ as the incomplete coalition‘s share in global resource consumption that would prevail in the period considered along the laissez-faire equilibrium extraction path in the absence of any policy, whereby $R_i(t)$ is the laissez-faire flow consumed by the coalition and where $R(t)$ is the global laissez-faire equilibrium resource flow in the absence of any policy. Accordingly, the equilibrium share of the fringe countries in global resource consumption in the absence of any policy is defined as $\left(1-\beta(t)\right) \equiv R_{-i}(t)/R(t)$, whereby $R_{-i}(t)$ is the laissez-faire flow consumed by the fringe countries. Moreover, define $dP(t) \equiv \left|d\underline{\tilde{P}}(t)\right|$ as the absolute value of the wedge that the introduction of an arbitrarily small unilateral unit tax induces in period t between the laissez-faire world market price for the resource and the hypothetical world market price that would prevail under the tax if the supply side did not react to the policy. Equation (3.3) can subsequently be written as

$$dP(t) = \frac{\beta(t)\varepsilon_i}{\beta(t)\varepsilon_i + \left(1-\beta(t)\right)\varepsilon_{-i}} \cdot d\tau_i(t) > 0 \quad (3.4)$$

where ε_i and ε_{-i} are the absolute values of the price elasticity of demand of the incomplete coalition and the fringe countries, as introduced above. Equation (3.4) reveals how the introduction of an arbitrarily small unilateral unit tax changes the world market price for the resource that the supply side receives in the considered period, as reflected by $dP(t)$, in the hypothetical case in which the supply side did not react to the tax. Equation (3.4) indicates that the introduction of the tax decreases the world market price for the resource and that the extent to which this is the case hinges on the incomplete coalition's share in laissez-faire resource consumption before the tax is introduced, $\beta(t)$, as well as both the absolute value of the price elasticity of demand of the coalition, ε_i, and the fringe countries, ε_{-i}.

Importantly, if one assumes that both resource consuming groups have the same possibilities available to substitute away from the resource, i.e. if one assumes that the coalition and the fringe countries exhibit the same constant value of price elasticity of demand ε, whereby it holds that $\varepsilon = \varepsilon_i = \varepsilon_{-i}$, equation (3.4) reduces to

$$dP(t) = \beta(t) \cdot d\tau_i(t) \quad (3.5).$$

Equation (3.5) suggests that in the case of an identical and constant price elasticity of demand regarding both resource consuming groups, the pressure that the unilateral unit tax exerts on the world market price for the resource in an arbitrary period, given that the supply side did not react to the tax, hinges on the coalition's share in global resource consumption, $\beta(t)$, which would have prevailed in the absence of any policy. This gives an important notion of how a unilateral unit tax affects the intertemporal supply reaction. As is known from the Long-Sinn invariance theorem, it is the pressure that a demand-reducing policy exerts on the world market price for the resource over time, given that the representative supplier would stick to the laissez-faire extraction path, which actually drives the intertemporal supply reaction. In the case of a global unit tax, this pressure is in each period determined by the level of the unit tax itself. As equation (3.5) suggests, this is different in the case of a unilateral unit tax levied on resource consumption by a subgroup of the world's countries. In this case, equation (3.5) suggests that the pressure which the unilateral unit tax exerts in each period on the world market price, given that the supplier would stick to the laissez-faire extraction path, is not only determined by the tax itself, but also by the incomplete coalition's share in global resource consumption that would prevail in the absence of any policy. The subsequent section 3.4 derives the conditions under which one can unambiguously infer the intertemporal supply reaction to a unilateral unit tax levied on resource consumption from the growth rate of the unilateral unit tax alone. Expectably, in the considered cases in which this is possible, the incomplete coalition's share in global resource consumption is constant along the extraction path in the absence of any policy. Before this is verified, the decision problem of the representative resource supplier who anticipates that the incomplete coalition levies a unilateral unit tax on resource consumption is investigated.

Consider a representative competitive resource owner who extracts the global resource stock in situ of an initial size S_0. The unit extraction costs g are inversely related to the remaining resource stock in situ in period t, $S(t)$. Hence, the unit extraction costs in period t are given by the function $g\big(S(t)\big)$ with $g_S < 0$, whereby the derivative g_S is bounded by assumption. The global resource stock in situ develops over time according to the equation of motion $\dot{S}(t) = -R(t)$. The incomplete climate coalition levies a unilateral unit tax $\tau_i(t)$ on those resource units that are consumed by its member countries. The tax might change over time and $\dot{\tau}_i(t)$ characterises its change over time. All consumers within the coalition pay the consumer price $P^C(t)$ along the new equilibrium extraction path under the unilateral tax. The new equilibrium world market price under the tax is $\underline{P}(t)$ whereby in each period it holds that $\underline{P}(t) = P^C(t) - \tau_i(t)$. The resource owner receives the world market price $\underline{P}(t)$ that prevails along the new equilibrium extraction path under the unilateral tax, regardless of whether a resource unit is consumed within or outside the coalition. As before, the exogenous and constant market rate of interest is given by r. The representative resource owner maximises her discounted future profits by choosing the resource flow $R(t)$ over time. The problem of the representative resource owner is thus to

$$max \int_0^{\infty} e^{-rt} \left[P^C(t) - \tau_i(t) - g\big(S(t)\big)\right] R(t) dt \quad (3.6)$$

subject to the equation of motion for the resource stock $\dot{S}(t) = -R(t)$ and the conditions $S(0) = S_0$ and $R(t) \geq 0$. Let $\lambda(t)$ denote the supplier's co-state variable for the global resource stock in period t. The current value Hamiltonian for the above problem is then given by

$$H = \left[P^C(t) - \tau_i(t) - g\big(S(t)\big)\right]R(t) - \lambda(t)R(t). \quad (3.7)$$

The stationary optimality condition is

$$P^C(t) - \tau_i(t) = g\big(S(t)\big) + \lambda(t) \quad (3.8)$$

and the canonical equation for the resource stock is

$$\dot{\lambda}(t) = r\lambda(t) + g_S\big(S(t)\big)R(t) \quad (3.9)$$

while the transversality condition is

$$\lim_{t\to\infty} \lambda(t)S(t)e^{-rt} = 0. \quad (3.10)$$

The asymptotic properties of the system (3.8)-(3.10) are given in Appendix A3.1 to this chapter. Differentiation of the stationary condition (3.8) with respect to time and substitution of the canonical equation for the resource rent (3.9) gives the intertemporal arbitrage condition that describes the development of the producer price, which is the new world market price for the resource in the presence of the unilateral unit tax, as

$$\underline{\dot{P}}(t) = \dot{P}^C(t) - \dot{\tau}_i(t) = r\left[P^C(t) - \tau_i(t) - g\big(S(t)\big)\right]. \quad (3.11)$$

Equation (3.11) is the Hotelling rule in the presence of a unilateral unit tax on resource consumption and stock-dependent unit extraction costs. As usual, the representative resource supplier supplies a resource flow over time whereby in each period the change of the producer, or, world market price from period t to the period after, as reflected by $\underline{\dot{P}}(t)$, which is equal to the change of the consumer price $\dot{P}^C(t)$ less the change of the unit tax $\dot{\tau}_i(t)$, is equal to the interest that she can earn on the net profit when selling another resource unit in period t . The latter is given by the term $r\left[P^C(t) - \tau_i(t) - g\big(S(t)\big)\right]$ on the right-hand side of (3.11). For the representative resource supplier, it is the world market price that matters, irrespective of whether a unit tax on resource consumption is levied globally or unilaterally. Hence, the intertemporal arbitrage condition that characterises the global resource market looks the same as in the presence of a global unit tax.

From the arbitrage condition (3.11) it also follows that in the laissez-faire case, the arbitrage condition of the supplier is given by $\dot{P}(t) = r\left[P(t) - g\big(S(t)\big)\right]$ (3.12) where $P(t)$ is the laissez-faire resource price. Having derived the intertemporal arbitrage condition of the representative competitive resource supplier, the next sections study the effect of different unilateral unit taxes on the speed of global resource extraction.

3.4 RESOURCE EXTRACTION PATHS UNDER DIFFERENT UNILATERAL UNIT TAXES

The subsequent two sections derive the extraction paths resulting under an exogenously given unilateral unit tax that is constant in present value terms in one case and decreases in present value terms in the other. However, the results derived are not limited to the specific example of a unilateral unit tax, but rather can easily be extended to any demand-side policy that reduces the demand for the fossil resource within the incomplete coalition. In section 3.4.1, it is assumed in a first step that demand is independent of calendar time. This assumption will be relaxed in section 3.4.2, where time-dependent demand functions for both groups are considered while it is assumed that extraction costs are negligible.

3.4.1 TIME-INDEPENDENT RESOURCE DEMAND

This section analyses the effect of a unilateral unit tax on the speed of global resource extraction if demand is independent of calendar time, while keeping the assumption that the unit extraction costs depend on the remaining stock in situ. With $R_i(t)$ and $R_{-i}(t)$ denoting the equilibrium resource flows consumed by the coalition and the fringe countries and with $R(t)$ being the global equilibrium flow, it holds in each period t that $R(t) = R_i(t) + R_{-i}(t)$ (3.13). The development of the global equilibrium resource flow over time thus satisfies

$$\dot{R}(t) = \dot{R}_i(t) + \dot{R}_{-i}(t) \quad (3.14)$$

which follows by differentiating (3.13) with respect to time. In the laissez-faire case, both the coalition and the fringe countries purchase the resource at the laissez-faire price $P(t)$. Hence, the resource demand function of the coalition in the laissez-faire case is given by $R_i\big(P(t)\big)$ and the respective demand function of the fringe countries is given by $R_{-i}\big(P(t)\big)$. Both functions are downward sloping. Taking the time derivative of both demand functions gives, respectively,

$$\frac{d\Big(R_i\big(P(t)\big)\Big)}{dt} = \dot{R}_i\big(P(t)\big) = \frac{\partial R_i}{\partial P} \cdot \dot{P}(t) \quad (3.15)$$

and

$$\frac{d\Big(R_{-i}\big(P(t)\big)\Big)}{dt} = \dot{R}_{-i}\big(P(t)\big) = \frac{\partial R_{-i}}{\partial P} \cdot \dot{P}(t). \quad (3.16)$$

Substitution of (3.15) and (3.16) into (3.14) and using the laissez-faire arbitrage condition $\dot{P}(t) = r\big[P(t) - g\big(S(t)\big)\big]$ (3.12) gives the change of the aggregate laissez-faire resource flow over time as

$$\dot{R}(t) = \left[\frac{\partial R_i}{\partial P} + \frac{\partial R_{-i}}{\partial P}\right] \cdot r\big[P(t) - g\big(S(t)\big)\big]. \quad (3.17)$$

Along the laissez-faire equilibrium extraction path, equation (3.17) has to be met while the equilibrium path must lead to the terminal point $S = 0$, as shown in Appendix A3.1. With $dR/dS = \dot{R}/\dot{S} = -\ \big(\dot{R}_i + \dot{R}_{-i}\big)/R$, it follows from (3.17) that

$$\frac{dR}{dS} = r\left[\beta\varepsilon_i\left(1 - \frac{g(S)}{P_i(R_i)}\right) + (1-\beta)\varepsilon_{-i}\left(1 - \frac{g(S)}{P_{-i}(R_{-i})}\right)\right] \quad (3.18)$$

whereby β in (3.18) is the coalition's share in global resource consumption along the laissez-faire equilibrium path for the case in which both groups exhibit a different price elasticity of demand, i.e. it holds that $\varepsilon_i \neq \varepsilon_{-i}$. By assuming that the coalition and the fringe countries exhibit the same constant value of price elasticity of demand ε, equation (3.18) reduces to

$$\frac{dR}{dS} = \varepsilon r\left[\beta\left(1 - \frac{g(S)}{P_i(R_i)}\right) + (1-\beta)\left(1 - \frac{g(S)}{P_{-i}(R_{-i})}\right)\right] \quad (3.19)$$

whereby β in (3.19) is now the coalition's share along the laissez-faire path given that $\varepsilon = \varepsilon_i = \varepsilon_{-i}$. Furthermore, because along the laissez-faire equilibrium extraction path the resource flow consumed by the coalition, the flow consumed by the fringe countries and the global resource flow respectively satisfy the equation $P_i(R_i) = P_{-i}(R_{-i}) = P(R) = P$, equation (3.19) can be further simplified to

$$\frac{dR}{dS} = \varepsilon r\left(1 - \frac{g(S)}{P(R)}\right) \quad (3.20)$$

where $P(R)$ is the downward sloping global inverse demand function for the resource and where ε is the absolute value of the price elasticity of global demand.

Both equation (3.18) and (3.19) define a direction of movement for each point in R_i, R_{-i}, S space that is compatible with the equilibrium conditions in the respective laissez-faire case. Independent of calendar time, the direction of movement for a point in R_i, R_{-i}, S space is jointly determined by its move in R_i, S space and its move in R_{-i}, S space. For a given combination of the resource flow consumed within the coalition, R_i, the resource flow consumed in the fringe countries, R_{-i}, and the resource stock in situ, S, equations (3.18) and

(3.19) determine a direction of movement for this point in R_i, R_{-i}, S space. Importantly, equation (3.20) reveals that in the case in which the coalition and the fringe countries exhibit the same constant price elasticity of demand, the same global laissez-faire resource flow prevails for a given stock level in situ, irrespective of the groups' shares in global resource consumption. That is, the laissez-faire speed of resource extraction is independent of the coalition's share in global laissez-faire consumption. As demonstrated in Appendix A3.1, the global resource stock is exhausted in all considered cases.

For a graphical representation of the laissez-faire extraction path, consider the case in which both groups exhibit the same constant price elasticity of demand. Because the laissez-faire equilibrium path must lead to the terminal point $S = 0$, the equilibrium path is characterised by equation (3.19), or, equivalently, by (3.20). The corresponding starting point of the laissez-faire path is depicted by point A in figure 3.4 (on p. 73). Starting from the initial resource stock level depicted by S_0, the global resource flow declines monotonically as time goes by because demand is assumed to be independent of calendar time. Importantly, in the case in which the coalition and the fringe countries exhibit a different price elasticity of demand, the global laissez-faire equilibrium extraction path, which is characterised in this case by equation (3.18), could be different from the path depicted.

Expectably, in the case in which the coalition and the fringe countries exhibit the same constant price elasticity of demand while demand is independent of calendar time, the coalition's equilibrium share in global resource consumption is constant along the equilibrium extraction path that results in the absence of any policy. This can be verified by taking the time derivative of the coalition's share in global resource consumption $\beta(t) = R_i(t)/R(t)$, which gives

$$\frac{d\beta(t)}{dt} = \dot{\beta}(t) = \frac{\dot{R}_i(t)}{R(t)} - \frac{R_i(t)\hat{R}(t)}{R(t)}.$$

The growth rate of the coalition's consumption share along any equilibrium extraction path follows by dividing the above equation by $\beta(t) = R_i(t)/R(t)$ as

$$\hat{\beta}(t) = \hat{R}_i(t) - \hat{R}(t). \quad (3.21)$$

Naturally, equation (3.21) shows that in any case the coalition exhibits a constant share in global resource consumption over time if its consumed flow grows at the same rate as the global resource flow. In the absence of any policy, the growth rate of the equilibrium resource flow consumed within the incomplete coalition can be derived from equation (3.15) as

$$\hat{R}_i(t) = \frac{\dot{R}_i(t)}{R_i(t)} = -\varepsilon_i r \left(1 - \frac{g(S)}{P_i(R_i)}\right) \quad (3.22)$$

while the growth rate of the global equilibrium resource flow in the absence of any policy can be derived from equation (3.17) as

$$\hat{R}(t) = \frac{\dot{R}(t)}{R(t)} = -r\big[\beta(t) \cdot \varepsilon_i + \big(1 - \beta(t)\big) \cdot \varepsilon_{-i}\big] \left(1 - \frac{g(S)}{P(R)}\right). \quad (3.23)$$

Substitution of (3.22) and (3.23) into (3.21) subsequently gives the growth rate of the coalition’s equilibrium consumption share in the absence of any policy as

$$\hat{\beta}(t) = -r\big(1 - \beta(t)\big)(\varepsilon_i - \varepsilon_{-i}) \left(1 - \frac{g(S)}{P(R)}\right). \quad (3.24)$$

If both the coalition and the fringe countries exhibit the same constant price elasticity of demand ε whereby it holds that $\varepsilon = \varepsilon_i = \varepsilon_{-i}$ and if demand is independent of calendar time, it holds that $\hat{\beta}(t) = 0$. The coalition and the fringe countries exhibit a constant share in global resource consumption over time in the absence of any policy. The intuition is that as the price for the resource rises over time, both the coalition and the fringe countries reduce their consumption at the same rate because they have the same possibilities available to substitute away from the fossil resource. If the coalition was more price elastic than the fringe countries, i.e. if $\varepsilon_i > \varepsilon_{-i}$, the coalition’s share in global resource consumption in the absence of any policy would decline over time, given that demand is independent of calendar time. Intuitively, the coalition’s share declines because it can substitute away from the fossil resource more easily than the fringe countries can. In the opposite case, its consumption share would correspondingly increase over time.

In order to study how unilateral demand reductions undertaken by the incomplete coalition over time affect the intertemporal resource supply path, consider an exogenously given unilateral unit tax $\tau_i(t)$ that the coalition levies on the resource flow consumed by its member countries. As before, the tax might change over time while this change is denoted by $\dot{\tau}_i(t)$. Recall that the consumer price within the coalition and the world market price along the new equilibrium extraction path under the tax are denoted by $P^C(t)$ and $\underline{P}(t)$, respectively, whereby it holds that $P^C(t) = \underline{P}(t) + \tau_i(t)$ in each period. In the presence of the unilateral unit tax, the coalition’s downward sloping resource demand function in an arbitrary period is given by $R_i\left(\underline{P}(t) + \tau_i(t)\right)$ and the downward sloping demand function of the fringe countries is given by $R_{-i}\left(\underline{P}(t)\right)$. Differentiating both demand functions with respect to time respectively gives

$$\frac{d\left(R_i\left(\underline{P}(t)+\tau_i(t)\right)\right)}{dt} = \dot{R}_i\left(\underline{P}(t)+\tau_i(t)\right) = \frac{\partial R_i}{\partial P^C} \cdot \left[\dot{\underline{P}}(t)+\dot{\tau}_i(t)\right] \quad (3.25)$$

and

$$\frac{d\left(R_{-i}\left(\underline{P}(t)\right)\right)}{dt} = \dot{R}_{-i}\left(\underline{P}(t)\right) = \frac{\partial R_{-i}}{\partial \underline{P}} \cdot \dot{\underline{P}}(t). \quad (3.26)$$

Furthermore, substitution of (3.25) and (3.26) into the equilibrium condition $\dot{R}(t) = \dot{R}_i(t) + \dot{R}_{-i}(t)$ (3.14) gives

$$\dot{R}(t) = \frac{\partial R_i}{\partial P^C} \cdot \left[\dot{\underline{P}}(t)+\dot{\tau}_i(t)\right] + \frac{\partial R_{-i}}{\partial \underline{P}} \cdot \dot{\underline{P}}(t). \quad (3.27)$$

From the maximisation problem of the representative resource supplier discussed in section 3.3 it is known that the development of the world market price in the presence of a unit tax on resource consumption is characterised by the arbitrage condition $\dot{\underline{P}}(t) = r\left[\underline{P}(t) - g\left(S(t)\right)\right]$ (3.11). An equilibrium extraction path in the presence of a unilateral unit tax $\tau_i(t)$ must satisfy the above equation (3.27), the intertemporal arbitrage condition of the representative supplier (3.11) and the respective equation of motion $\dot{\tau}_i(t)$, which characterises the development of the unilateral unit tax under consideration over time. In addition, the supplier's transversality condition (3.10) implies that the path must lead to the terminal point $S = 0$, as shown in Appendix A3.1.

Suppose first that the incomplete coalition levies a unilateral unit tax on resource consumption that grows at the market rate of interest whereby the development of the tax over time is characterised by the equation of motion $\dot{\tau}_i(t) = r\tau_i(t)$. Actually, the subsequently derived results are not limited to a unilateral unit tax on resource consumption. They can be interpreted in a wider sense if one lets $\tau_i(t)$ denote the absolute vertical downward shift of the incomplete coalition's inverse demand curve in period t compared to the position of the laissez-faire demand curve. As any unilateral policy, or a policy mix, that reduces demand for the fossil resource within the coalition can induce these downward shifts, including subsidies on renewable energy or bio fuels, the results are not limited to the specific example of a unit tax. The results derived below hinge on the growth rate of the induced absolute vertical downward shifts of the incomplete coalition's inverse demand curve compared to the position that this curve would have in the absence of any policy and not on the shifts being induced by a unilateral unit tax on resource consumption. However, it is convenient to keep the interpretation that the absolute vertical downward shifts of the coalition's demand curve over time are triggered by a unilateral unit tax on resource consumption.

To evaluate the effect of a unilateral unit tax that is constant in present value terms on the speed of global extraction, the respective equilibrium extraction path needs to be derived. Substitution of the arbitrage condition $\dot{\underline{P}}(t) = r\left[\underline{P}(t) - g\big(S(t)\big)\right]$ (3.11) and the differential equation $\dot{\tau}_i(t) = r\tau_i(t)$ into the above equation (3.27) gives the equation describing the change of the global equilibrium resource flow $R(t)$ over time under the considered unilateral unit tax. It is given by

$$\dot{R}(t) = \frac{\partial R_i}{\partial P^C} \cdot r\left[P^c(t) - g\big(S(t)\big)\right] + \frac{\partial R_{-i}}{\partial \underline{P}} \cdot r\left[\underline{P}(t) - g\big(S(t)\big)\right] \quad (3.28)$$

whereby the direction of movement for a point in R_i, R_{-i}, S space is defined by

$$\frac{dR}{dS} = r\left[\beta\varepsilon_i\left(1 - \frac{g(S)}{P_i(R_i)}\right) + (1-\beta)\varepsilon_{-i}\left(1 - \frac{g(S)}{P_{-i}(R_{-i})}\right)\right] \quad (3.29)$$

where β in (3.29) is now the coalition's share in global resource consumption along the new equilibrium extraction path under the considered unilateral unit tax. Independent of calendar time, equation (3.29) determines the direction of movement for a point in R_i, R_{-i}, S space that is compatible with the equilibrium conditions relevant under the unilateral tax. Comparing equation (3.18), which characterises the laissez-faire equilibrium path in the case in which $\varepsilon_i \neq \varepsilon_{-i}$, with equation (3.29) reveals that both equations define the same direction of movement for a point in R_i, R_{-i}, S space. However, this alone is not sufficient to infer the effect that a unilateral unit tax that is constant in present value terms has on the speed of global extraction, as will become apparent subsequently.

Presume that both the coalition and the fringe countries exhibit the same constant price elasticity of demand ε. In this case, equation (3.29) defines the same direction of movement for a point in R_i, R_{-i}, S space as equation (3.19), which characterises the laissez-faire extraction for the case where $\varepsilon = \varepsilon_i = \varepsilon_{-i}$. Importantly, that equation (3.29) and equation (3.19) define the same direction of movement for a point in R_i, R_{-i}, S space in the case where $\varepsilon = \varepsilon_i = \varepsilon_{-i}$ reveals that in this case, a unilateral unit tax that is constant in present value terms is neutral for the speed of global resource extraction. The global resource flow extracted for a given level of the stock in situ is the same under such a unilateral unit tax on resource consumption and in the laissez-faire case. The reason is that in the case in which $\varepsilon = \varepsilon_i = \varepsilon_{-i}$, the global laissez-faire resource flow that prevails for a given stock level in situ is independent of the coalition's share in global laissez-faire consumption, as follows from equation (3.20). This condition fails if both groups exhibit a different price elasticity of demand. If the coalition and the fringe countries exhibit a different price elasticity of demand, the speed of extraction in the laissez-faire case hinges on the weighted average of the two price elasticities, weighted by the groups' shares in global laissez-faire resource consumption, as is apparent from equation (3.18). Therefore, any change in the groups' consumption shares brought about by the introduction of the unilateral unit tax can also change the extraction speed compared to the laissez-faire case, although the tax itself is constant in present value terms.

However, if the price elasticity of demand is identical for both groups, the global resource flow that meets the laissez-faire equations (3.19) and (3.20), given the requirement that the path must lead to the terminal point $S = 0$, must be the same, irrespective of the coalition's share in global consumption. Therefore, and because equation (3.19) defines the same direction of movement for a point in R_i, R_{-i}, S space as equation (3.29) for the case where $\varepsilon = \varepsilon_i = \varepsilon_{-i}$, the global resource flow prevailing for a given level of the stock in situ must be the same in both cases. However, this does not imply that the extraction path that results in R_i, R_{-i}, S space under the considered tax is the same as the laissez-faire path. Despite the fact that both paths must lead to the terminal point $S = 0$ and that the global resource flow is the same for a given level of the stock in situ, the paths are different due to carbon leakage.

Compared to the laissez-faire starting point A depicted in figure 3.4, the starting point of the path resulting under the unilateral unit tax, which is constant in present value terms, is shifted downwards and to the right in R_i, R_{-i} space. The world market price for the resource along the new equilibrium extraction path under the unilateral tax must lie everywhere below the laissez-faire world market price so that the supplier arbitrage condition (3.11) is again met in the presence of the tax while the resource stock is exhausted as time proceeds to infinity. The fringe countries increase their aggregate resource consumption in response to the lower world market price whereby their consumed equilibrium resource flow $R_{-i}(t)$ satisfies the equilibrium condition $P_{-i}\big(R_{-i}(t)\big) = \underline{P}(t)$ along the new path. This increase shifts the starting point of the new equilibrium path to the right in R_i, R_{-i} space compared to the laissez-faire starting point A. However, importantly, because the direction of movement for a point in R_i, R_{-i}, S space under the considered tax is, just as in the laissez-faire case, defined by equation (3.19), the global resource flow for a given level of the stock in situ must be the same along the new equilibrium extraction path, despite the unilateral tax. Therefore, the shift of the starting point in R_i, R_{-i} space to the right must exactly be compensated by a respective downward shift in R_i, R_{-i} space. The starting point A' depicted in figure 3.4 satisfies this requirement.

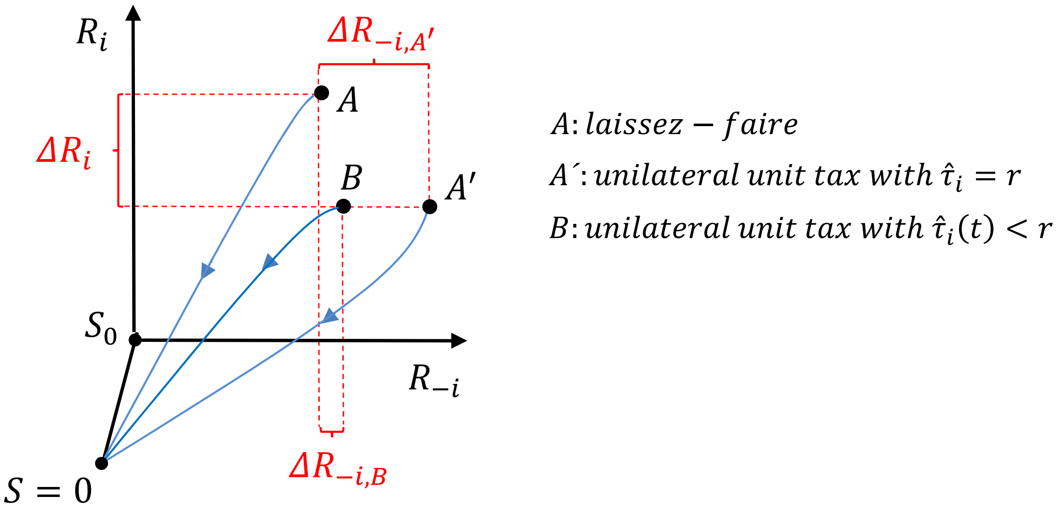

Figure 3.4: Resource extraction paths: laissez-faire and unilateral unit tax scenarios.

Let the initial absolute reduction in the incomplete coalition's resource consumption along the new equilibrium path, i.e. given that the supply side has reacted to the tax, be denoted by ΔR_i, as depicted in figure 3.4. Furthermore, let the initial increase in the fringe consumption along the new equilibrium path be depicted by $\Delta R_{-i,A'}$. Because the global resource flow for a given stock level in situ under the unilateral unit tax that increases at the market rate of interest must be the same as in the laissez-faire case, it must hold that $\Delta R_i = \Delta R_{-i,A'}$. The rate of carbon leakage, which in the case considered is given by $\Delta R_{-i,A'}/\Delta R_i$, is 100 per cent. The lower equilibrium resource flow $R_i(t)$ consumed by the incomplete coalition under the unilateral tax satisfies the equilibrium condition $P_i\big(R_i(t)\big) = P^C(t)$ along the new extraction path. The consumer price that prevails within the coalition exceeds the respective laissez-faire resource price in every period because the global extraction path is unaltered while the fringe countries increase their consumption compared to the laissez-faire case along the new equilibrium path in response to the lower world market price. The advantage of such a policy is that both the incomplete coalition and the fringe countries can purchase the resource at a lower world market price along the entire new equilibrium extraction path.

Figure 3.4 depicts the equilibrium extraction path resulting under the unilateral unit tax that is constant in present value terms for the case where both groups exhibit the same constant price elasticity of demand, given the assumption that demand is independent of calendar time. It is important to note that ΔR_i and $\Delta R_{-i,A'}$ denote the absolute changes in the resource flows consumed along the new equilibrium extraction path for a given stock level, i.e. given that the supply side has had the chance to react to the tax. That the global resource flow for a given resource stock in situ would be the same under the unilateral tax and in the laissez-faire case implies that a unilateral unit tax that grows at the market rate of interest is neutral for the global speed of resource extraction under the assumptions made. But the international distribution of the global equilibrium resource flow along the new equilibrium extraction path is different from the laissez-faire distribution because along the new equilibrium path, the fringe countries consume every resource unit that the coalition refrains from. This result shows that, for the case of time-independent demand functions, it is the growth rate of a unilateral unit tax on resource consumption that drives the intertemporal supply reaction if the coalition's share in global resource consumption was constant over time in the absence of any policy. Whether the coalition's share in global resource consumption would increase, decrease or remain constant over time in the absence of any policy is thus crucial in terms of the evaluation of how a unilateral unit tax affects the speed of global resource extraction.

Suppose next that the incomplete coalition implements a unilateral unit tax that changes over time according to the equation of motion $\dot{\tau}_i(t) = r\tau_i(t) - X$ where X is a constant, positive and finite number. This implies that the tax decreases in present value terms. The assumptions that the coalition and the fringe countries exhibit the same constant price elasticity of demand and that demand is independent of calendar time are kept. As before, the equation that characterises the equilibrium extraction path under this tax is derived by substituting the supplier arbitrage condition $\dot{\underline{P}}(t) = r\left[\underline{P}(t) - g\big(S(t)\big)\right]$ (3.11) and the differential equation $\dot{\tau}_i(t) = r\tau_i(t) - X$ into equation (3.27). The equation that defines the direction of movement for a point in R_i, R_{-i}, S space under the considered unilateral tax is

$$\frac{dR}{dS} = \varepsilon r\left[\beta\left(1 - \frac{g(S)}{P_i(R_i)}\right) + (1-\beta)\left(1 - \frac{g(S)}{P_{-i}(R_{-i})}\right)\right] - \varepsilon\beta\frac{X}{P_i(R_i)} \quad (3.30)$$

where $\beta = \frac{R_i}{R_i + R_{-i}}$ in (3.30) is now the coalition's share in global resource consumption that prevails along the new equilibrium extraction path under the considered tax. Comparing equation (3.30) with equation (3.19), which characterises the laissez-faire path for the case $\varepsilon = \varepsilon_i = \varepsilon_{-i}$, shows that the former defines a flatter direction of movement for each point in

R_i, R_{-i}, S space as long as the coalition's share in global consumption, β, is positive. This will be the case along the entire new extraction path. The reason is that only if either $R_{-i} \to \infty$ or $R_i \to 0$ would $\beta \to 0$, although neither possibility is feasible. It is not possible that $R_{-i} \to \infty$ because the resource stock in situ is finite. Moreover, because its price elasticity of demand is bounded by assumption, the coalition consumes a positive resource flow along the entire equilibrium extraction path. The resource flow consumed by the coalition converges to zero only as time proceeds to infinity, in which case the direction of movement for a point in R_i, R_{-i}, S space, as defined by equation (3.30), converges to the respective laissez-faire direction of movement defined by equation (3.19).

The equilibrium extraction path under the unilateral unit tax that decreases in present value terms must still lead to the terminal point $S = 0$ to meet the transversality condition (3.10). Moreover, that equation (3.30) defines a flatter direction of movement for each point in R_i, R_{-i}, S space compared to the respective laissez-faire equation (3.19) is again sufficient to infer that the global resource flow extracted for a given level of the stock in situ under the tax falls short of the respective laissez-faire flow. Recall that the global laissez-faire resource flow that satisfies equations (3.19) and (3.20) is the same irrespective of the coalition's share in global laissez-faire consumption. Hence, because equation (3.30) defines a flatter direction of movement for each point in R_i, R_{-i}, S space than equation (3.19), the global resource flow that is extracted for a given stock in situ in the presence of the considered tax must fall short of the respective laissez-faire flow to be compatible with equation (3.30) and the requirement that the path must lead to the terminal point $S = 0$.

Presume that the coalition's initial consumption reduction under the tax considered, which decreases in absolute terms, is the same as under the former tax, which was constant in present value terms. Although this is by no means a necessity, this assumption allows making the argument within the established figure 4.3. The reduction in the coalition's initial resource consumption in absolute terms along the new equilibrium extraction path is thus depicted by ΔR_i in figure 3.4, which shifts downwards the starting point of the new path compared to the laissez-faire starting point A in R_i, R_{-i} space. Again, the fringe countries increase their resource consumption in response to the reduction in the world market price for the resource that the unilateral tax induces. The resource flow consumed by the fringe countries along the new equilibrium path satisfies the equilibrium condition $P_{-i}\big(R_{-i}(t)\big) = \underline{P}(t)$. Thus, the starting point of the new path is again shifted to the right in R_i, R_{-i} space compared to the laissez-faire starting point A. However, importantly, this shift to the right, as depicted by the absolute change in the initial fringe consumption $\Delta R_{-i,B}$ in figure 3.4, must fall short of the downward shift induced by coalition's initial consumption reduction. In the present case, it must hold that $\Delta R_{-i,B} < \Delta R_i$ because equation (3.30) and the condition that all equilibrium paths must lead to the terminal point $S = 0$ require that the global flow extracted for a given level of the stock in situ under the considered unilateral unit tax must fall short of the respective laissez-faire flow.

The rate of carbon leakage, which is now given by $\Delta R_{-i,B}/\Delta R_i$, must be less than 100 per cent. A starting point that meets this criterion is depicted by point B in figure 3.4. The new equilibrium resource flow consumed by the coalition satisfies the equilibrium condition $P_i\big(R_i(t)\big) = P^C(t)$, which, as the coalition's initial resource consumption must be reduced compared to the laissez-faire case, implies that the initial consumer price in the coalition countries exceeds the initial laissez-faire resource price. Thus, given the assumptions that demand is independent of calendar time and that the coalition and the fringe countries exhibit the same constant price elasticity of demand, a unilateral unit tax that decreases in present value terms unambiguously slows down the speed at which the global resource stock is depleted over time compared to the laissez-faire case. In terms of calendar time, the global resource flow supplied and consumed in the presence of the unilateral unit tax, which declines in present value terms, falls short of the laissez-faire flow in the present and correspondingly must exceed the laissez-faire flow from some future point in time onwards.

As previously mentioned, one can also interpret $\tau_i(t)$ as the absolute vertical downward shift of the incomplete coalition's inverse demand curve that a certain mix of unilateral policies, including the subsidisation of renewable energy sources, induces in period t compared to the laissez-faire position of this curve. In this sense, the derived results are not limited to the interpretation of a unilateral unit tax on resource consumption but apply equivalently to an entire mix of unilateral policies that reduce the incomplete coalition's demand over time. Under the assumptions made, the intertemporal reaction of the resource supply side hinges on the growth rate of the absolute vertical downward shifts $\tau_i(t)$ over time, rather than the presumption made here that these downward shifts are induced by a unit tax. Ultimately, it is the growth rate of the wedge that the incomplete coalition's unilateral demand reductions drive between the laissez-faire resource price and the hypothetical world market price that would prevail if the supply side stuck to the laissez-faire extraction path that drives the intertemporal supply reaction, as follows from the Long-Sinn invariance theorem. Whether the incomplete coalition's demand for the resource is reduced via carbon taxes or via subsidies on renewable energy is of minor relevance for the supply side.

3.4.2 TIME-DEPENDENT RESOURCE DEMAND

This section studies the case in which the incomplete coalition and the fringe countries exhibit time-dependent demand functions for the resource. The assumption that both groups exhibit the same constant price elasticity of demand is kept and it is assumed that extraction costs are negligible. With zero extraction costs, i.e. with $g = 0$, it follows from the supplier's stationary condition (3.8) that $\underline{P}(t) = \lambda(t)$ in each period t. In the absence of extraction costs, the world market price $\underline{P}(t)$ equals the resource rent $\lambda(t)$ in each period. Furthermore, the equation of motion that characterises the development of the resource rent $\lambda(t)$ over time for the case of zero extraction costs follows from the differential equation (3.9) by letting $g = 0$. It is given by

$$\dot{\lambda}(t) = r\lambda(t). \quad (3.31)$$

Hence, with zero extraction costs, the intertemporal arbitrage condition of the representative resource supplier that characterises the intertemporal equilibrium on the global resource market is given by

$$\dot{\underline{P}}(t) = r\underline{P}(t). \quad (3.32)$$

Suppose again that the coalition levies a unilateral unit tax $\tau_i(t)$ on resource consumption that might change over time. Furthermore, presume that the demand for the resource of the coalition and the fringe countries in the presence of the tax in period t is respectively given by $R_i\big(\underline{P}(t) + \tau_i(t), t\big)$ and $R_{-i}\big(\underline{P}(t), t\big)$, whereby the downward sloping inverse demand functions of the incomplete coalition and the fringe countries are respectively given by $P_i(R_i(t), t)$ and $P_{-i}(R_{-i}(t), t)$. The exogenous arrival of a perfect substitute technology for the fossil resource is excluded by assumption.

As usual, along any equilibrium extraction path it must hold that $R(t) = R_i(\,t) + R_{-i}(\,t)$ (3.13) where $R_i(\,t)$ and $R_{-i}(\,t)$ are the equilibrium flows consumed by the coalition and the fringe countries and where $R(t)$ is the global equilibrium flow. Hence, it must also hold that $\dot{R}(t) = \dot{R}_i(\,t) + \dot{R}_{-i}(\,t)$ (3.14) along an equilibrium extraction path. Differentiating the demand function of the coalition and the fringe countries with respect to time respectively gives

$$\frac{dR_i(\underline{P}(t)+\tau_i(t),t)}{dt} = \dot{R}_i(\underline{P}(t)+\tau_i(t),t) = \frac{\partial R_i}{\partial P^C} \cdot \left[\dot{\underline{P}}(t) + \dot{\tau}_i(t)\right] + \frac{\partial R_i}{\partial t} \quad (3.33)$$

and

$$\frac{dR_{-i}(\underline{P}(t),t)}{dt} = \dot{R}_{-i}(\underline{P}(t),t) = \frac{\partial R_{-i}}{\partial \underline{P}} \cdot \dot{\underline{P}}(t) + \frac{\partial R_{-i}}{\partial t} \quad (3.34)$$

where the partial time derivatives $\partial R_i/\partial t$ and $\partial R_{-i}/\partial t$ reflect exogenous changes in the coalition's and the fringe countries' demand for the resource. Substitution of (3.33) and (3.34) into $\dot{R}(t) = \dot{R}_i(t) + \dot{R}_{-i}(t)$ (3.14) then gives

$$\dot{R}(t) = \frac{\partial R_i}{\partial P^C} \cdot \left[\dot{\underline{P}}(t) + \dot{\tau}_i(t)\right] + \frac{\partial R_i}{\partial t} + \frac{\partial R_{-i}}{\partial \underline{P}} \cdot \dot{\underline{P}}(t) + \frac{\partial R_{-i}}{\partial t}. \quad (3.35)$$

Now consider again first the case in which the incomplete coalition levies a unilateral unit tax that grows at the market rate of interest whereby $\dot{\tau}_i(t) = r\tau_i(t)$. From (3.35) it subsequently follows by substitution of $\dot{\underline{P}}(t) = r\underline{P}(t)$ (3.32) and $\dot{\tau}_i(t) = r\tau_i(t)$ that

$$\dot{R}(t) = \frac{\partial R_i}{\partial P^C} \cdot rP^C(t) + \frac{\partial R_i}{\partial t} + \frac{\partial R_{-i}}{\partial \underline{P}} \cdot r\underline{P}(t) + \frac{\partial R_{-i}}{\partial t}. \quad (3.36)$$

Given the assumption that the incomplete coalition and the fringe countries exhibit the same constant price elasticity of demand, the growth rate of the global equilibrium resource flow in the presence of the unilateral unit tax, which is constant in present value terms, then follows from (3.36) as

$$\hat{R}(t) = -r\varepsilon + \beta(t) \cdot \frac{\partial R_i/\partial t}{R_i(t)} + \left(1-\beta(t)\right) \cdot \frac{\partial R_{-i}/\partial t}{R_{-i}(t)} \quad (3.37)$$

where $\beta(t) = \frac{R_i}{R_i + R_{-i}}$ is the coalition's share in global resource consumption along the equilibrium extraction path under the tax considered.

Presume first that it holds that $\frac{\partial R_i/\partial t}{R_i(t)} = \frac{\partial R_{-i}/\partial t}{R_{-i}(t)}$, that is, the demand of the coalition and the fringe countries grows or shrinks in an arbitrary period at the same rate for exogenous reasons. Equation (3.37) can then be reduced to

$$\hat{R}(t) = -r\varepsilon + \frac{\partial R_i/\partial t}{R_i(t)}. \quad (3.38)$$

To evaluate the effect of the considered unilateral unit tax on the speed of global resource extraction, the growth rate of the global laissez-faire resource flow in the considered example also needs to be derived. It follows by respectively taking the time derivatives of the laissez-faire demand functions $R_i(P(t),t)$ and $R_{-i}(P(t),t)$ of the two groups, whereby $P(t)$ is the laissez-faire resource price. By substituting the respective time derivatives into the equilibrium condition $\dot{R}(t) = \dot{R}_i(\,t) + \dot{R}_{-i}(\,t)$ (3.14) and by using the laissez-faire arbitrage condition $\dot{P}(t) = rP(t)$, which follows from equation (3.12) by letting $g = 0$, the growth rate of the global resource flow in the laissez-faire case can be derived as

$$\hat{R}(t) = -r\varepsilon + \beta(t) \cdot \frac{\partial R_i/\partial t}{R_i(t)} + \big(1 - \beta(t)\big) \cdot \frac{\partial R_{-i}/\partial t}{R_{-i}(t)} \quad (3.39)$$

where $\beta(t)$ in (3.39) is now the coalition’s share in global laissez-faire resource consumption.

Notably, if it holds that $\frac{\partial R_i/\partial t}{R_i(t)} = \frac{\partial R_{-i}/\partial t}{R_{-i}(t)}$, equation (3.39) reduces to equation (3.38). Hence, given that both groups exhibit the same constant price elasticity of demand and that extraction costs are zero, a unilateral unit tax that is constant in present value terms does not alter the speed of global resource extraction compared to the laissez-faire case if the demand of the coalition and the fringe countries grows or shrinks at the same rate over time for exogenous reasons.[13] If these conditions hold, the growth rate of the global resource flow under the unilateral tax is the same as in the laissez-faire case. This implies that the extraction path must be the same because all equilibrium extraction paths must guarantee full exhaustion of the global resource stock as time proceeds to infinity due to the assumption that the price elasticity of global demand is bounded, as shown in Appendix A3.1. If both groups exhibit the same constant price elasticity of demand, if extraction costs are negligible and if the demand of the coalition and the fringe countries grows or shrinks at the same rate over time for exogenous reasons, the wedge that a unilateral unit tax that is constant in present value terms drives between the laissez-faire resource price and the hypothetical world market price that would prevail in the presence of the tax did the supply side not react to the tax must also be constant in present value terms. This follows logically from the Long-Sinn invariance theorem. The tax is in this case neutral for the speed of global extraction and the rate of carbon leakage is 100 per cent.

The arising question is now whether the incomplete coalition’s share in global resource consumption in the absence of any policy is again constant under the assumptions made. This is indeed the case. Given the assumption that the coalition and the fringe countries exhibit the

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[13] Note that this implies that the exogenous rate at which the demand of the coalition and the fringe countries grows or shrinks over time is the same in any scenario, i.e., irrespective of whether a policy is conducted. However, there is no reason why this should not be the case, since the rate is exogenous.

same constant price elasticity of demand ε, it follows by differentiating the coalition's demand function $R_i(P(t), t)$ with respect to time that the growth rate of the flow that the coalition consumes in the laissez-faire case is given by

$$\hat{R}_i(t) = -\varepsilon r + \frac{\partial R_i/\partial t}{R_i(t)}. \quad (3.40)$$

Substituting (3.40) and the growth rate of the global laissez-faire resource flow (3.39) into equation $\hat{\beta}(t) = \hat{R}_i(t) - \hat{R}(t)$ (3.21) subsequently gives the growth rate of the coalition's share in global consumption in the laissez-faire case as

$$\hat{\beta}(t) = \big(1 - \beta(t)\big)\left(\frac{\partial R_i/\partial t}{R_i(t)} - \frac{\partial R_{-i}/\partial t}{R_{-i}(t)}\right) \quad (3.41)$$

where $\beta(t)$ in (3.41) is the coalition's share in global consumption in the absence of any policy. Equation (3.41) shows that if the coalition and the fringe countries exhibit the same constant price elasticity of demand and if it holds that $\frac{\partial R_i/\partial t}{R_i(t)} = \frac{\partial R_{-i}/\partial t}{R_{-i}(t)}$, the coalition's share in global consumption in the absence of any policy is constant over time. In this case, it is the growth rate of a unilateral unit tax that is levied on resource consumption that drives the intertemporal supply decision.

What can accordingly be demonstrated is that if the demand of the coalition and the fringe countries grows or shrinks over time at the same rate for exogenous reasons, a unilateral unit tax that decreases in present value terms unambiguously slows down the speed of global resource extraction if both groups have the same constant price elasticity of demand and if extraction costs are negligible. To derive this result, consider again the unilateral unit tax that develops over time according to the equation of motion $\dot{\tau}_i(t) = r\tau_i(t) - X$ where X is a constant, positive and finite number. By substituting this differential equation and the supplier arbitrage condition $\dot{\underline{P}}(t) = r\underline{P}(t)$ (3.32) into equation (3.35), the growth rate of the global resource flow in the presence of this unilateral tax can be derived as

$$\hat{R}(t) = -r\varepsilon + \beta(t) \cdot \frac{\partial R_i/\partial t}{R_i(t)} + \big(1 - \beta(t)\big) \cdot \frac{\partial R_{-i}/\partial t}{R_{-i}(t)} + \beta(t)\varepsilon \frac{X}{P_i(R_i(t), t)} \quad (3.42)$$

where $P_i(R_i(t), t)$ is the inverse demand function of the coalition and where $\beta(t)$ is the coalition's share in global consumption under the considered tax. With $\frac{\partial R_i/\partial t}{R_i(t)} = \frac{\partial R_{-i}/\partial t}{R_{-i}(t)}$, equation (3.42) reduces to

$$\hat{R}(t) = -r\varepsilon + \frac{\partial R_i/\partial t}{R_i(t)} + \beta(t)\varepsilon \frac{X}{P_i(R_i(t), t)}. \quad (3.43)$$

If it holds that $\frac{\partial R_i/\partial t}{R_i(t)} = \frac{\partial R_{-i}/\partial t}{R_{-i}(t)}$, a unilateral unit tax that decreases in present value terms unambiguously slows down the speed of global resource extraction compared to the laissez-faire case. This becomes apparent by comparing equation (3.43) with equation (3.39) for the case $\frac{\partial R_i/\partial t}{R_i(t)} = \frac{\partial R_{-i}/\partial t}{R_{-i}(t)}$ and recalling that the resource stock must be exhausted in both cases due to the assumption that the price elasticity of global demand is bounded. For each point in time t, equation (3.43) defines a greater growth rate for the global equilibrium resource flow compared to the growth rate of the laissez-faire flow (3.39) for the case $\frac{\partial R_i/\partial t}{R_i(t)} = \frac{\partial R_{-i}/\partial t}{R_{-i}(t)}$ as long as the coalition consumes the resource, i.e. as long as $\beta(t) > 0$. The latter condition is again satisfied because the price elasticity of the coalition's demand is bounded, which implies that it consumes a positive resource flow along the entire path. Moreover, although $R_{-i} \rightarrow \infty$ would imply that $\beta \rightarrow 0$, this is not a feasible solution as the global stock is finite.

Because the growth rate of the global equilibrium resource flow under the unilateral unit tax that decreases in present value terms is greater than the growth rate of the laissez-faire resource flow in every period under the assumptions made, the resource stock in situ that prevails in an arbitrary period in the laissez-faire case must fall short of the in situ stock that prevails in the respective period under the tax. The reason is that if the extraction path under the unilateral tax would start out with the same or a larger initial resource flow than the laissez-faire extraction path, the flow would have to lie above the laissez-faire flow in every period to satisfy equation (3.43). This is not possible as the global stock is finite. Therefore, the initial flow extracted under the tax must fall short of the laissez-faire flow. The extraction path under the unilateral tax that declines in present value terms starts with a lower initial level of resource extraction and it cuts the laissez-faire path from below only once in time, as, once this happens, the greater growth rate implies that the path must remain above the laissez-faire path ever after. Those resource quantities extracted less under the tax compared to the laissez-faire case in the early periods are only extracted in the later periods, namely from the period onwards when the extraction path that prevails under the tax cuts the laissez-faire path from below. The remaining stock in situ is larger in every period under the unilateral unit tax than it would be in the laissez-faire case in the same period, while in both cases the stock level in situ converges to zero as time proceeds to infinity due to the boundedness assumption regarding the price elasticities of demand, as shown in Appendix A3.1. Thus, the unilateral unit tax unambiguously slows down the speed of global resource extraction because, under the assumptions made, the intertemporal supply reaction is again determined by the growth rate of the tax.

However, unfortunately it follows that for the cases in which the demand of the incomplete coalition and the fringe countries grows or shrinks over time for exogenous reasons at a different rate, the effect of a unilateral unit tax on the speed of global resource extraction not only depends on the growth rate of the tax itself, even if both groups have the same constant price elasticity of demand, if extraction costs are neglected and if the unilateral unit tax is constant in present value terms. Similar to the case of differing price elasticities of demand, a policy-induced shift in the groups' shares in global resource consumption compared to the laissez-faire consumption shares can now affect the speed of resource extraction if the demand of the coalition and the fringe countries grows or shrinks over time at a different rate for exogenous reasons. This becomes apparent by comparing equations (3.37) and (3.39), where the extent to which the growth rates $\frac{\partial R_i/\partial t}{R_i(t)}$ and $\frac{\partial R_{i-}/\partial t}{R_{-i}(t)}$ determine the growth rate of the global resource flow in the different scenarios hinges on the groups' shares in global resource consumption along the respective equilibrium path. Also, if the demand of the coalition and the fringe countries grows or shrinks over time for exogenous reasons at a different rate, it follows from equation (3.41) that the incomplete coalition's share in global consumption in the absence of any policy is no longer constant. The consequence is again that not only the growth rate of a unilateral unit tax determines how the tax affects the global speed of extraction compared to the laissez-faire case.

One interpretation of the partial derivatives $\partial R_i/\partial t$ and $\partial R_{-i}/\partial t$ is that they reflect exogenous technological progress, which reduces the demand for the resource over time within both groups. Thus, to justify the assumption that the demand of both groups grows or shrinks at the same rate over time for exogenous reasons in each period, one would have to assume that exogenous technological progress spreads globally in each period over time. This might be justifiable to presume. However, another reason behind the exogenous shifts in the resource demand of the two groups could be population growth. If the population within the coalition grows or shrinks at a different rate than the population outside the coalition, and if this implies that the coalition's demand grows or shrinks at a different rate over time than the demand of the fringe countries, then one cannot infer the intertemporal supply reaction from the growth rate of a unilateral unit tax levied on resource consumption alone.

3.5 INCOMPLETE CLIMATE COALITION AS A STACKELBERG LEADER

This section analyses the decision problem of an incomplete climate coalition that incurs output losses from global warming and exhibits some degree of market power on the global fossil resource market. The incomplete coalition's decision problem is analysed by extending the Stackelberg differential game approach introduced in Chapter 2 for a passive fringe of resource consuming countries outside the coalition. It is assumed that the coalition leads the game and that it anticipates the reactions of the representative resource supplier and the fringe countries to a change in the world market price for the resource when deciding upon its optimal resource consumption path.

The literature in which a dominant resource importer faces a passive fringe of other resource importers as well as a competitive resource supply side, a setting also considered in Karp (1984), Maskin and Newbery (1978, 1990) and Karp and Newbery (1993), focuses on the dominant importer’s motive to lower the world market price for the resource. The papers mentioned abstract from the global warming problem. Maskin and Newbery (1978) and Kemp and Long (1980) demonstrate that the open-loop tariff chosen by a dominant importer is dynamically inconsistent in the presence of a choke price for the resource. Once the sum of the import tariff and the producer price reaches the dominant importer’s choke price, it is beneficial for the dominant importer to reduce the import tariff to continue consumption. As Kemp and Long (1980) point out, the existence of fringe importers is not necessary to obtain this result.

Maskin and Newbery (1990) consider a dominant importer that faces competitive suppliers and a passive fringe of other resource importers in the absence of a choke price. They show that the open-loop unit tariff chosen by the dominant importer grows at the market rate of interest. Moreover, abstracting from extraction costs, the authors demonstrate that the open-loop solution is only time-consistent if both the dominant importer and the fringe countries exhibit the same constant price elasticity of demand and if the demand of the dominant importer and the demand of the fringe countries grows or shrinks at the same rate over time for exogenous reasons. As has been demonstrated in the two foregoing sections, these assumptions imply that the dominant importer’s open-loop unit tariff, which grows at the market rate of interest, does not alter the speed of global resource extraction. The aim of the present analysis of an incomplete climate coalition is to investigate how the introduction of the global warming problem affects the incomplete coalition’s open-loop policy choice. It is thus assumed that the coalition can commit itself to the announced open-loop policy path. The presented model presumes that the incomplete climate coalition considers the relation between the development of the global fossil resource stock in situ and the severity of the global warming problem because it has market power on the global resource market and because its member countries suffer output losses from the accumulation of CO_2 in the atmosphere, as explained in the following.

3.5.1 OUTPUT LOSSES AND COALITION SIZE

The global climate coalition analysed in the foregoing chapter considers the global output losses associated with the process of global warming when deciding on its optimal resource consumption path over time. It is natural to conjecture that this is different with respect to a climate coalition that comprises only a subgroup of the world's countries.

A sensible assumption to make is that the incomplete climate coalition acts rational in the sense that it only considers those output losses from global warming that occur to its member countries. In the literature concerning the formation of international climate coalitions, it is usually assumed that the coalition members also maximise their joint welfare.[14] The present analysis again follows Sinn (2008a) by introducing the global warming problem. As before, let the function $\omega\big(S(t)\big)$ with $\omega_S > 0$ and $\omega_{SS} < 0$ denote the part of global output that is not destroyed by global warming in period t. The larger the resource stock in situ, $S(t)$, in period t remains, the less output is lost via the process of global warming. As previously mentioned, it is assumed that the incomplete climate coalition is of an everlasting stable size in terms of its members whereby no country joins or leaves the coalition over time. The coalition considers the part of the global output losses in each period that occur to its members. Let the parameter α, which is constant and for which it holds that $0 < \alpha < 1$, capture the share in global output losses from global warming that occur to the member countries of the coalition altogether. Because the coalition is of a stable size, α is independent of calendar time. In an arbitrary period t, the part of global output not destroyed by the process of global warming that is relevant for the decision problem of the incomplete climate coalition is thus given by

$$\alpha \cdot \omega\big(S(t)\big). \quad (3.44)$$

Note that this formulation implies that it is assumed that at least one country outside the incomplete coalition also suffers output losses from global warming. Moreover, it also implies that the share in global output losses that occurs to the member countries of the coalition is constant as the global resource stock in situ declines.

3.5.2 OPEN-LOOP SOLUTION

This section derives the open-loop solution to the decision problem of an incomplete climate coalition of a stable size in terms of its member countries that suffer output losses from global warming. As in Maskin and Newbery (1990) and Karp and Newbery (1993), the coalition's decision problem is expressed as an optimal control problem that is solved by applying

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[14] Cf. Carraro and Siniscalco (1993) and Barrett (1994), among others.

Pontryagin's maximum principle. When deciding on its optimal resource consumption path in the initial period, the incomplete coalition takes into account the reaction of the representative resource supplier and the reaction of the passive fringe countries outside the coalition to a change in the world market price for the resource. All parties have perfect foresight.

The incomplete coalition produces output in period t by using the resource flow $R_i(t)$ as an input in the production function $\phi_i\big(R_i(t)\big)$, which exhibits positive and decreasing marginal productivity. The analysis abstracts from exogenous technological progress whereby the production function is independent of calendar time. Moreover, it is assumed that $\lim_{R_i \to 0} \phi_i'\big(R_i(t)\big) = \infty$, which again captures the assumption that no perfect substitute for all purposes of fossil resource usage is available. The part of global output that is not destroyed by global warming and is relevant for the incomplete coalition is depicted by the term $\alpha \cdot \omega\big(S(t)\big)$ (3.44), as introduced above. Because the fringe countries also consume the resource, the equation of motion for the global resource stock as the incomplete coalition considers it when deciding on its optimal resource consumption path is now given by

$$\dot{S}(t) = -R_i(t) - R_{-i}\left(\underline{P}(t)\right) \quad (3.45)$$

where, as before, the aggregate resource demand of the fringe countries is given by the demand function $R_{-i}\left(\underline{P}(t)\right)$ with $\partial R_{-i}\big(\underline{P}\big)/\partial\, \underline{P} < 0$, whereby $\underline{P}(t)$ is the world market price for the resource. The passive fringe countries take the development of the world market price for the resource and the development of the global resource stock in situ over time as given. The above formulation of introducing a passive fringe of resource consuming countries into the incomplete coalition's decision problem is in line with Maskin and Newbery (1978, 1990) and Karp and Newbery (1993). Because the incomplete climate coalition exhibits some degree of market power on the global resource market, it is aware of the fact that it can influence the development of the global resource stock in situ via its consumed resource flow $R_i(t)$.

Recall that in the absence of extraction costs, the equation of motion that characterises the development of the resource rent $\lambda(t)$ that the representative supplier obtains over time follows from the differential equation (3.9) by letting $g = 0$. It is given by $\dot{\lambda}(t) = r\lambda(t)$ (3.31). This also implies that the world market price develops over time according to $\dot{\underline{P}}(t) = r\underline{P}(t)$ (3.32). The solution to the differential equation (3.31) is

$$\lambda(t) = \lambda_0 e^{rt} \quad (3.46)$$

where $\lambda_0 = \lim_{t\to\infty} e^{-rt}\lambda(t)$. Equation (3.46) gives the resource rent that the representative supplier obtains in period t. The rent is constant in present value terms. Just as the global coalition, the incomplete coalition has market power and it is aware of the fact that it can affect the resource rent that it has to pay to the supply side over time. However, in contrast to the global coalition, the incomplete coalition can never drive the resource rent to zero, not even on the terminal resource unit. This is due to the assumption that the price elasticity of demand of the fringe countries is bounded, which implies that the coalition will never be the sole resource consumer in the world.

The incomplete climate coalition chooses its resource flow $R_i(t)$ over time to maximise its discounted net output in the presence of the global warming problem, net of the payments to the supply side. The market rate of interest r is exogenously given and constant. The coalition's problem is to

$$max \int_0^\infty e^{-rt}\left[\phi_i\big(R_i(t)\big) + \alpha\omega\big(S(t)\big) - \underline{P}(t)R_i(t)\right]dt \quad (3.47)$$

subject to the equation of motion for the global resource stock

$$\dot{S}(t) = -R_i(t) - R_{-i}\left(\underline{P}(t)\right) \quad (3.45)$$

and subject to the arbitrage condition $\dot{\lambda}(t) = r\lambda(t)$ (3.31), as well as the conditions $S(0) = S_0$ and $R_i(t) \geq 0$. Because it holds that $\underline{P}(t) = \lambda(t)$ in each period, the constraint (3.31) can be eliminated by substituting the resource rent $\lambda(t) = \lambda_0 e^{rt}$ (3.46) into the coalition's objective (3.47), as well as the equation of motion for the global stock (3.45). This gives the coalition's objective as

$$max \int_0^\infty e^{-rt}\left[\phi_i\big(R_i(t)\big) + \alpha\omega\big(S(t)\big) - \lambda_0 e^{rt}\cdot R_i(t)\right]dt \quad (3.48)$$

and, respectively, the equation of motion for the global stock as

$$\dot{S}(t) = -R_i(t) - R_{-i}(\lambda_0 e^{rt}). \quad (3.49)$$

Let $\mu_i(t)$ denote the incomplete coalition's co-state variable for the global resource stock in situ in period t. The coalition's problem is to maximise the objective (3.48) subject to (3.49) and the conditions $S(0) = S_0$ and $R_i(t) \geq 0$. The current value Hamiltonian for this problem reads

$$H_i = \phi_i\big(R_i(t)\big) + \alpha\omega\big(S(t)\big) - \lambda_0 e^{rt}\cdot R_i(t) - \mu_i(t)[R_i(t) + R_{-i}(\lambda_0 e^{rt})]. \quad (3.50)$$

The conditions for optimality are the stationary condition

$$H_{R_i} = \phi_i'\big(R_i(t)\big) - \lambda_0 e^{rt} - \mu_i(t) = 0 \quad (3.51)$$

and the canonical equation for the resource stock in situ

$$-H_S = \dot{\mu}_i(t) - r\mu_i(t) = -\alpha\omega_S\big(S(t)\big) \quad (3.52)$$

while the transversality condition is

$$\lim_{t\to\infty}\Big\{\phi_i\big(R_i(t)\big) + \alpha\omega\big(S(t)\big) - \lambda(t)\cdot R_i(t) - \mu_i(t)\big[R_i(t) + R_{-i}\big(\lambda(t)\big)\big]\Big\}\, e^{-rt} = 0. \quad (3.53)$$

The stationary condition (3.51) implies that an optimal consumption plan requires that the incomplete coalition purchases a resource flow $R_i(t)$ over time whereby in each period t, the marginal product of a resource unit employed in production, $\phi_i'\big(R_i(t)\big)$, equals the sum of the resource rent $\lambda_0 e^{rt}$ and its opportunity cost of consuming the resource unit in this period, as reflected by the shadow value for the resource stock in situ, $\mu_i(t)$. If the incomplete coalition had a negligible share in global resource consumption, the development of the global resource stock over time would be exogenous from its perspective whereby $\mu_i(t)$ would be zero, i.e. in each period the coalition would consume a flow $R_i(t)$ whereby the marginal product of a resource unit employed in production would equal the resource rent, which is the world market price for the resource.

Now abstract for a moment from the global warming problem whereby $\omega_S = 0$ in the canonical equation (3.52). Let $P_i\big(R_i(t)\big) = \phi_i'\big(R_i(t)\big)$ denote the downward sloping inverse demand function of the coalition. Furthermore, suppose that the coalition levies a unilateral unit tax on its resource consumption and let this tax be denoted by $\tau_i(t)$. Moreover, let the consumer price within the coalition be $P^C(t)$. With $\underline{P}(t) = \lambda(t)$, it subsequently follows from the coalition's stationary condition (3.51) that the unilateral unit tax $\tau_i(t)$ that the coalition levies in period t equals the shadow value $\mu_i(t)$, because along an equilibrium extraction path in the presence of a unilateral unit tax, the coalition consumes a resource flow $R_i(t)$ that satisfies $P_i\big(R_i(t)\big) = \phi_i'\big(R_i(t)\big) = P^C(t)$. With $\tau_i(t) = \mu_i(t)$ and with $\omega_S = 0$ it thus follows from the canonical equation (3.52) that in the absence of the global warming problem, the unilateral unit tax develops over time according to the differential equation

$$\dot{\tau}_i(t) = r\tau_i(t). \quad (3.54)$$

The tax is constant in present value terms.[15] If the global warming problem was absent and if extraction costs are negligible, the incomplete coalition levies a unit tax with the pure aim to push down the resource rent trajectory. Furthermore, this unilateral unit tax is neutral for the speed of global resource extraction if the incomplete coalition and the fringe countries exhibit the same constant price elasticity of demand and if the demand of both groups grows or shrinks at the same rate over time for exogenous reasons. Because it is assumed here that the incomplete coalition's production function is independent of calendar time, satisfying the latter condition would require that the demand of the fringe countries is also stationary, as follows from the arguments provided in section 3.4.2. However, the unilateral unit tax shifts down the entire world market price path compared to the laissez-faire price path in any case whereby both groups benefit from lower payments to the supply side along the new extraction path.

Now consider the case in which the member countries of the coalition suffer output losses from global warming, i.e. consider the original case where $\omega_S > 0$. Differentiating the coalition's stationary condition (3.51) with respect to time and using the canonical equation (3.52) shows that the coalition's optimal resource consumption path in the open-loop case is now characterised by the differential equation

$$\frac{\partial \phi_i'\big(R_i(t)\big)}{\partial t} = r\phi_i'\big(R_i(t)\big) - \alpha\omega_S\big(S(t)\big). \quad (3.55)$$

The right-hand side of equation (3.55) depicts the interest that the coalition earns on the marginal product of the resource when purchasing another resource unit in period t, less the output losses incurred by its member countries which the purchase of this unit brings about via a higher CO_2 concentration in the atmosphere and the process of global warming. The left-hand side reflects the increase in the marginal product of the resource from which the coalition can benefit if it purchases the resource unit only one period later due to the increased scarcity of the resource that prevails by then. Optimality requires that the incomplete coalition purchases a resource flow over time whereby these benefits are equal along its resource consumption path.

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[15] Karp and Newbery (1990) already show that the open-loop tariff chosen by a dominant resource importer increases at the market rate of interest in the absence of the global warming problem. Kemp and Long (1980) demonstrate this result in the presence of a choke price regarding an ad valorem import tariff, which is constant over time. The latter also show that the presence of the choke price renders the open-loop solution dynamically inconsistent.

Suppose again that the incomplete coalition implements its optimal resource consumption path by levying a unit tax $\tau_i(t)$ on resource consumption. The differential equation that characterises the development of the unilateral unit tax $\tau_i(t)$ that forces the individual consumer within the coalition to internalise the coalition's opportunity costs of resource consumption, as reflected by its shadow value $\mu_i(t)$, over time, follows with $\tau_i(t) = \mu_i(t)$ from the canonical equation (3.52) as

$$\dot{\tau}_i(t) = r\tau_i(t) - \alpha\omega_S\big(S(t)\big) \quad (3.56)$$

which implies that the tax grows at the rate

$$\hat{\tau}_i(t) = r - \frac{\alpha\omega_S\big(S(t)\big)}{\tau_i(t)}. \quad (3.57)$$

The tax decreases in present value terms. In contrast to the case in which the global warming problem was assumed to be absent and where the unilateral unit tax grows at the market rate of interest, introducing the global warming problem implies that the incomplete coalition adjusts the growth rate of the unilateral unit tax downwards, below the market rate of interest. As the incomplete coalition's production function is independent of calendar time by assumption, the open-loop tax would thus unambiguously slow down the speed of global resource extraction if the demand of the fringe countries was also stationary and if both groups had the same constant price elasticity of demand. To which extent the unilateral open-loop unit tax would increase the efficiency of the intertemporal resource allocation in this case is discussed in the following section 3.6.

Under the unilateral open-loop tax, the world market price develops over time according to $\underline{\dot{P}}(t) = r\underline{P}(t)$ (3.32) whereby the world market price grows at the market rate of interest. The development of the consumer price over time, which is relevant for the member countries of the incomplete coalition, can be derived by differentiating the consumer price, which is given by $P^C(t) = \underline{P}(t) + \tau_i(t)$, with respect to time. This gives $\dot{P}^C(t) = \underline{\dot{P}}(t) + \dot{\tau}_i(t)$. Substitution of the equation of motion for the tax (3.56) and the supplier arbitrage condition (3.32) subsequently reveals that in the presence of the global warming problem, the consumer price within the incomplete coalition develops over time according to the equation of motion

$$\dot{P}^C(t) = rP^C(t) - \alpha\omega_S\big(S(t)\big). \quad (3.58)$$

Under the unilateral unit tax, the supply side loses some of its resource rent compared to the laissez-faire case because the world market price along the new equilibrium extraction path lies everywhere below the laissez-faire resource price whereby the intertemporal arbitrage condition $\dot{\underline{P}}(t) = r\underline{P}(t)$ (3.32) is again satisfied while the resource stock is exhausted as time proceeds to infinity. Both the coalition and the fringe countries pay a lower world market price under the unilateral policy. Because the incomplete coalition can never drive the resource rent which the representative supplier obtains to zero, not even on the terminal resource unit, it follows from the supplier's stationary condition (3.8) with $g = 0$ and $P^C(t) - \tau_i(t) = \underline{P}(t)$ that

$$\lim_{t\to\infty} \underline{P}(t) = \lim_{t\to\infty} \lambda_0 e^{rt} = \infty. \quad (3.59)$$

The world market price for the resource, which is equal to the resource rent in each period, converges to infinity as time proceeds to infinity. Moreover, it follows from $\dot{\lambda}(t) = r\lambda(t)$ (3.31) that the resource rent grows at the market rate of interest. That implies that the present value of the resource rent, $\lambda(t)e^{-rt}$, does not converge to zero as time proceeds to infinity. From the supplier's transversality condition $\lim_{t\to\infty} \lambda(t)S(t)e^{-rt} = 0$ (3.10) it thus follows that the global resource stock must converge to zero as time proceeds to infinity. Hence, as the global resource flow and the global resource stock converge to zero as time proceeds to infinity, the coalition's transversality condition (3.53) is met. Moreover, due to the assumption that $\lim_{R_i\to 0} \phi_i'(R_i(t)) = \infty$, it also follows that $\lim_{t\to\infty} \phi_i'(R_i(t)) = \infty$ as the flow $R_i(t)$ converges to zero as time proceeds to infinity. The boundary condition for the unilateral open-loop unit tax follows by taking the limit of the coalition's stationary condition (3.51) as time proceeds to infinity while letting $\mu_i(t) = \tau_i(t)$. It is given by

$$\lim_{t\to\infty} \tau_i(t) = \lim_{t\to\infty}\left[\phi_i'(R_i(t)) - \lambda_0 e^{rt}\right]. \quad (3.60)$$

As has been derived before, both the marginal product of the resource and the resource rent individually go to infinity as time proceeds to infinity, which leaves the boundary condition of the unilateral open-loop unit tax undetermined. However, because the global resource stock must converge to zero as time proceeds to infinity to meet the representative supplier's transversality condition (3.10), the coalition's transversality condition (3.53) is met anyway.

Levying the unilateral open-loop unit tax affects the development of the incomplete coalition's share in global resource consumption along the new extraction path. With $g = 0$, the growth rate of the coalition's consumed flow under the unilateral unit tax is found by substituting the arbitrage condition $\dot{\underline{P}}(t) = r\underline{P}(t)$ (3.32) and the equation of motion for the unilateral open-loop unit tax $\dot{\tau}_i(t) = r\tau_i(t) - \alpha\omega_S(S(t))$ (3.56) into equation (3.25). Under the tax, the coalition's share grows at the rate

$$\hat{R}_i(t) = \frac{\dot{R}_i(t)}{R_i(t)} = -\varepsilon_i \left[r - \frac{\alpha\omega_S(S(t))}{P_i(R_i)}\right]. \quad (3.61)$$

Moreover, the respective growth rate of the global resource flow follows by substituting the arbitrage condition (3.32) and the canonical equation for the unilateral open-loop tax (3.56) into equation (3.27) while letting $g = 0$. It is given by

$$\hat{R}(t) = \frac{\dot{R}(t)}{R(t)} = -r\left[\beta(t) \cdot \varepsilon_i + \left(1 - \beta(t)\right) \cdot \ \varepsilon_{-i}\right] + \beta(t)\varepsilon_i \frac{\alpha\omega_S(S(t))}{P_i(R_i)}. \quad (3.62)$$

Finally, substituting (3.61) and (3.62) into $\hat{\beta}(t) = \hat{R}_i(t) - \hat{R}(t)$ (3.21) then gives

$$\hat{\beta}(t) = -r\left(1 - \beta(t)\right)(\varepsilon_i \ - \varepsilon_{-i}) + \left(1 - \beta(t)\right)\varepsilon_i \frac{\alpha\omega_S(S(t))}{P_i(R_i)} \quad (3.63)$$

while in the case in which both groups exhibit the same constant price elasticity of demand ε, it follows that

$$\hat{\beta}(t) = \left(1 - \beta(t)\right)\varepsilon \frac{\alpha\omega_S(S(t))}{P_i(R_i)} > 0. \quad (3.64)$$

In the presence of the unilateral open-loop unit tax, the coalition's share in global resource consumption increases along the new equilibrium extraction path if the coalition and the fringe countries exhibit the same constant price elasticity of demand, if demand is independent of calendar time and if extraction costs are negligible. For the case of an identical price elasticity of demand ε regarding both groups, the growth rate of the equilibrium flow consumed by the fringe countries follows by substituting the arbitrage condition $\dot{\underline{P}}(t) = r\underline{P}(t)$ (3.32) into (3.26). It is given by

$$\hat{R}_{-i}(t) = -r\varepsilon. \quad (3.65)$$

Now, comparing the growth rate of the coalition's equilibrium flow (3.61) with the growth rate (3.65) for the case in which $\varepsilon_i = \varepsilon$ reveals why the coalition's consumption share increases over time in the presence of the open-loop unit tax under the assumptions made, namely, because its consumed resource flow shrinks at a lower rate over time than that of the fringe countries due to its unilateral open-loop unit tax. The subsequent section evaluates the potential of the coalition's open-loop policy to increase the efficiency of the intertemporal resource allocation.

3.6 INCOMPLETE COALITION AND EFFICIENCY OF INTERTEMPORAL RESOURCE ALLOCATION

This section examines the effect of the derived unilateral open-loop policy on the global speed of resource extraction, assuming that demand is independent of calendar time and that extraction costs are negligible. Sticking to the convenient graphical representation of the extraction paths in R_i, R_{-i}, S space, which has been introduced in section 3.4.1 before, this section also evaluates the potential of the incomplete coalition's unilateral open-loop policy to increase the efficiency of the global intertemporal resource allocation.

Notably, as shown in section 3.4.2, allowing for time-dependent demand functions would not alter the results derived in this section regarding the effect of the unilateral open-loop unit tax on the speed of global extraction as long as the demand of the coalition and the fringe countries shrinks or grows at the same rate over time for exogenous reasons. Also, a generalisation of the subsequent results to other policy measures that reduce the incomplete coalition's demand for the resource over time, such as subsidies on renewable energy or subsidies on bio fuel, is easily possible. If one interprets the unilateral open-loop unit tax $\tau_i(t)$ as the absolute vertical downward shift of the incomplete coalition's inverse demand curve in an arbitrary period t compared to the position that this curve would have had in this period in the absence of any policy, the coalition would have to make sure that these downward shifts grow at the same rate as the unilateral open-loop unit tax, while the respective growth rate is defined by equation (3.57) in section 3.5. Any unilateral policy mix that reduces the demand of the incomplete coalition over time to the same extent as the unilateral open-loop tax can thus in principle implement the same intertemporal resource allocation.

The equation that characterises the normative extraction path in R_i, R_{-i}, S space is derived first. For this purpose, suppose that the Pigou tax, which internalises the global warming externality that the combustion of a resource unit induces, is levied on global resource consumption.[16] In the present framework, the Pigou tax is given by

$$\tau_{Pigou}(t) = \int_t^{\infty} e^{-r(x-t)}\, \omega_S\big(S(x)\big)dx. \quad (3.66)$$

In each period, the Pigou tax reflects the present value of the output losses that the combustion of a resource unit induces from the period of combustion until infinity. Note that the Pigou tax is bounded due to the assumption that the marginal output losses from global warming are bounded. Differentiating the Pigou tax (3.66) with respect to time reveals that the tax changes over time according to the differential equation

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[16] Cf. Pigou (1920).

$$\dot{\tau}_{Pigou}(t) = r\tau_{Pigou}(t) - \omega_S\big(S(t)\big). \quad (3.67)$$

The resource demand of the coalition and the fringe countries under the Pigou tax is given by $R_i\left(\underline{P}(t) + \tau_{Pigou}(t)\right)$ and $R_{-i}\left(\underline{P}(t) + \tau_{Pigou}(t)\right)$, respectively, where $\underline{P}(t)$ is the producer, or, world market price along the new equilibrium extraction path under the tax. With $P^C(t)$ denoting the respective consumer price, it holds that $P^C(t) = \underline{P}(t) + \tau_{Pigou}(t)$ in every period. Differentiation of both demand functions with respect to time respectively gives

$$\frac{d\Big(R_i\big(\underline{P}(t)+\tau_{Pigou}(t)\big)\Big)}{dt} = \dot{R}_i\left(\underline{P}(t) + \tau_{Pigou}(t)\right) = \frac{\partial R_i}{\partial P^C} \cdot \left[\underline{\dot{P}}(t) + \dot{\tau}_{Pigou}(t)\right] \quad (3.68)$$

and

$$\frac{d\Big(R_{-i}\big(\underline{P}(t)+\tau_{Pigou}(t)\big)\Big)}{dt} = \dot{R}_{-i}\left(\underline{P}(t) + \tau_{Pigou}(t)\right) = \frac{\partial R_{-i}}{\partial P^C} \cdot \left[\underline{\dot{P}}(t) + \dot{\tau}_{Pigou}(t)\right]. \quad (3.69)$$

Substitution of (3.68) and (3.69) into $\dot{R}(t) = \dot{R}_i(t) + \dot{R}_{-i}(t)$ (3.14) then gives

$$\dot{R}(t) = \left[\frac{\partial R_i}{\partial P^C} + \frac{\partial R_{-i}}{\partial P^C}\right]\left[rP^C(t) - \omega_S\big(S(t)\big)\right]$$

which, owing to $dR/dS = \dot{R}/\dot{S} = -\left(\dot{R}_i + \dot{R}_{-i}\right)/R$ and because it holds that $P_i(R_i) = P_{-i}(R_{-i}) = P^C$ along the equilibrium extraction path under the global Pigou tax, can be written as

$$\frac{dR}{dS} = r[\varepsilon_i \cdot \beta + \varepsilon_{-i} \cdot (1-\beta)] - \varepsilon_i \cdot \beta \frac{\omega_S(S)}{P_i(R_i)} - \varepsilon_{-i} \cdot (1-\beta)\frac{\omega_S(S)}{P_{-i}(R_{-i})}. \quad (3.70)$$

In equation (3.70), the coalition’s share in global resource consumption along the normative equilibrium extraction path is β. Equation (3.70) defines a direction of movement for each point in R_i, R_{-i}, S space under the globally levied Pigou tax, independent of calendar time. In fact, because the Pigou tax is levied on every resource unit that is combusted in the world and because the extraction path must lead to the terminal point $S = 0$ as the price elasticity of demand of both groups and the Pigou tax are bounded, equation (3.70) characterises the Pareto efficient equilibrium extraction path.[17] Importantly, because along the equilibrium path

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[17] That the extraction path in the presence of the global Pigou tax and zero extraction costs must lead to the terminal point $S = 0$ follows from the asymptotic properties provided in Appendix A2.2 to Chapter 2 by letting $g = 0$ and if it is noted that along the equilibrium extraction path under the globally applied Pigou tax it holds that $P_i(R_i) = P_{-i}(R_{-i}) = P(R) = P^C$.

under the global Pigou tax the resource flows R_i, R_{-i} and R respectively satisfy $P_i(R_i) = P_{-i}(R_{-i}) = P(R) = P^C$, equation (3.70) can be reduced to

$$\frac{dR}{dS} = [\varepsilon_i \cdot \beta + \varepsilon_{-i} \cdot (1-\beta)]\left[r - \frac{\omega_S(S)}{P(R)}\right] \quad (3.71)$$

Moreover, if it is assumed that the incomplete coalition and the fringe countries exhibit the same constant price elasticity of demand ε, equation (3.71) reduces further to

$$\frac{dR}{dS} = \varepsilon\left[r - \frac{\omega_S(S)}{P(R)}\right]. \quad (3.72)$$

The notion that equation (3.71) can be reduced to equation (3.72) if the coalition and the fringe countries exhibit the same constant price elasticity of demand implies that the global normative resource flow extracted for a given stock in situ is always the same in this case, irrespective of the groups' shares in global resource consumption.

Next, consider the case in which the incomplete climate coalition implements the unilateral open-loop unit tax derived in the previous section. In the presence of an arbitrary unilateral unit tax, the resource flow demanded by the coalition over time is characterised by equation (3.25)

$$\frac{d\left(R_i\left(\underline{P}(t)+\tau_i(t)\right)\right)}{dt} = \dot{R}_i\left(\underline{P}(t) + \tau_i(t)\right) = \frac{\partial R_i}{\partial P^C} \cdot \left[\,\dot{\underline{P}}(t) + \dot{\tau}_i(t)\right]$$

whereby substituting the arbitrage condition $\dot{\underline{P}}(t) = r\underline{P}(t)$ (3.32) and the equation of motion that characterises the coalition's unilateral open-loop unit tax $\dot{\tau}_i(t) = r\tau_i(t) - \alpha\omega_S\left(S(t)\right)$ (3.56) into the above equation gives

$$\frac{d\left(R_i\left(\underline{P}(t)+\tau_i(t)\right)\right)}{dt} = \dot{R}_i\left(\underline{P}(t) + \tau_i(t)\right) = \frac{\partial R_i}{\partial P^C} \cdot \left[\,r\underline{P}(t) + r\tau_i(t) - \alpha\omega_S\left(S(t)\right)\,\right] \quad (3.73)$$

which is the change of the resource flow demanded by the coalition over time in the open-loop solution. It depends on the development of the unilateral unit tax and the development of the world market price over time. In order to force the individual consumer within the incomplete coalition to internalise the coalition's opportunity cost of resource consumption over time, the coalition levies the unilateral open-loop unit tax on resource consumption. Recall furthermore that the change of the resource flow demanded by the fringe countries over time in the presence of the coalition's unilateral tax is given by

$$\frac{d\left(R_{-i}\left(\underline{P}(t)\right)\right)}{dt} = \dot{R}_{-i}\left(\underline{P}(t)\right) = \frac{\partial R_{-i}}{\partial \underline{P}} \cdot \dot{\underline{P}}(t) \quad (3.26)$$

as derived in section 3.4.1. Again, substituting (3.73) and (3.26) into the equilibrium condition $\dot{R}(t) = \dot{R}_i(t) + \dot{R}_{-i}(t)$ (3.14) gives the development of the global equilibrium resource flow over time under the unilateral open-loop unit tax as

$$\dot{R}(t) = \frac{\partial R_i}{\partial P^C} \cdot \left[\, r\underline{P}(t) + r\tau_i(t) - \alpha\omega_S\left(S(t)\right) \right] + \frac{\partial R_{-i}}{\partial \underline{P}} \cdot r\underline{P}(t)$$

from which, because it holds that $P_i(R_i) = P^C$ along the equilibrium extraction path, it follows that

$$\frac{dR}{dS} = r[\varepsilon_i \cdot \beta + \varepsilon_{-i} \cdot (1-\beta)] - \varepsilon_i \cdot \beta \frac{\alpha\omega_S(S)}{P_i(R_i)} \quad (3.74)$$

while β in (3.74) is now the coalition's share in global resource consumption that prevails along the equilibrium extraction path under the unilateral open-loop unit tax. Equation (3.74) determines the direction of movement for a point in R_i, R_{-i}, S space that is compatible with the equilibrium conditions that are relevant in the presence of the unilateral open-loop unit tax. The equilibrium extraction path that prevails under the unilateral open-loop tax must satisfy equation (3.74) and it must lead to the terminal point $S = 0$ to meet the representative supplier's transversality condition (3.10), as discussed in the foregoing section 3.5. If the price elasticity of demand is identically ε for both groups, equation (3.74) can be reduced to

$$\frac{dR}{dS} = \varepsilon\left[r - \beta\frac{\alpha\omega_S(S)}{P_i(R_i)}\right]. \quad (3.75)$$

To evaluate the effect of the unilateral open-loop unit tax on the speed of global resource extraction, the laissez-faire path for the considered case of time-independent demand and zero extraction costs needs to be derived as well. In this case, the direction of movement for a point in R_i, R_{-i}, S space in the laissez-faire case follows from (3.18) while letting $g = 0$. It is given by

$$\frac{dR}{dS} = r[\varepsilon_i \cdot \beta + \varepsilon_{-i} \cdot (1-\beta)] \quad (3.76)$$

where β in (3.76) is the coalition's share in global consumption along the laissez-faire extraction path. If the coalition and the fringe countries exhibit a different price elasticity of demand, the global laissez-faire extraction speed hinges on the weighted average of the two price elasticities, weighted by the groups' consumption shares. In contrast, if one assumes that both groups exhibit the same price elasticity of demand ε, equation (3.76) reduces to

$$\frac{dR}{dS} = \varepsilon r. \quad (3.77)$$

In this case, the global laissez-faire flow extracted for a given level of the resource stock in situ is independent of the groups' shares in global consumption. The laissez-faire extraction path must lead to the terminal point $S = 0$ because the price elasticity of global demand is bounded.[18]

The laissez-faire path that satisfies equation (3.77) and the requirement that the stock must be exhausted in equilibrium is depicted in figure 3.5 and its starting point is denoted by A^*.[19] Besides the laissez-faire path, figure 3.5 also depicts the equilibrium resource extraction path that results under the unilateral open-loop unit tax and the extraction path that prevails under the globally applied Pigou tax. In both cases, it is assumed that the coalition and the fringe countries exhibit the same constant price elasticity of demand. This assumption makes it possible to unambiguously evaluate the potential of the incomplete coalition's unilateral open-loop unit tax to increase the efficiency of the intertemporal resource allocation.

Equation (3.72), which characterises the Pareto efficient extraction path for the case in which both groups have the same constant price elasticity of demand, defines a flatter direction of movement for each point in R, S and thus also for each point in R_i, R_{-i}, S space compared to the laissez-faire equation (3.77). In order to ensure that the equilibrium extraction path leads to the terminal point $S = 0$ and satisfies equation (3.72) along the way, the global resource flow extracted under the globally applied Pigou tax must fall short of the respective global laissez-faire flow for a given level of the resource stock in situ. In order to reduce the initial global resource flow extracted under the global Pigou tax below the laissez-faire level, at least either the initial resource flow consumed within the coalition or the initial flow consumed by the fringe countries must be reduced compared to the laissez-faire case.

That in fact both groups reduce their initial resource consumption compared to the laissez-faire case follows from the fact that the equilibrium resource flows consumed by the coalition and the fringe countries must satisfy the equilibrium condition $P_i(R_i) = P_{-i}(R_{-i}) = P^C$ along

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[18] That the laissez-faire extraction path must lead to the terminal point $S = 0$ in the present case of zero extraction costs and a bounded price elasticity of global demand follows from the asymptotic properties provided in Appendix A2.2 in Chapter 2 by considering the laissez-fare case and by letting $g = 0$.

[19] Note that this starting point A^* is different from the starting point A depicted in figure 3.4, where stock-dependent unit extraction costs are assumed.

the new path, while the initial consumer price must lie above the initial laissez-faire resource price whereby the global initial resource consumption is actually reduced compared to the laissez-faire case. Hence, the new starting point under the global Pigou tax must lie below and to the left of the laissez-faire starting point A^* in R_i, R_{-i} space, as depicted by the starting point D in figure 3.5.[20] Under the globally levied Pigou tax, the global resource stock is depleted at the Pareto efficient speed because the global warming externality induced by every resource unit that is burned over time is internalised. Supply in the future is increased at the expense of present supply and the consumer price that all consumers in the world pay lies first above the laissez-faire price in early periods, while from some point in time onwards it falls short of the laissez-faire price.

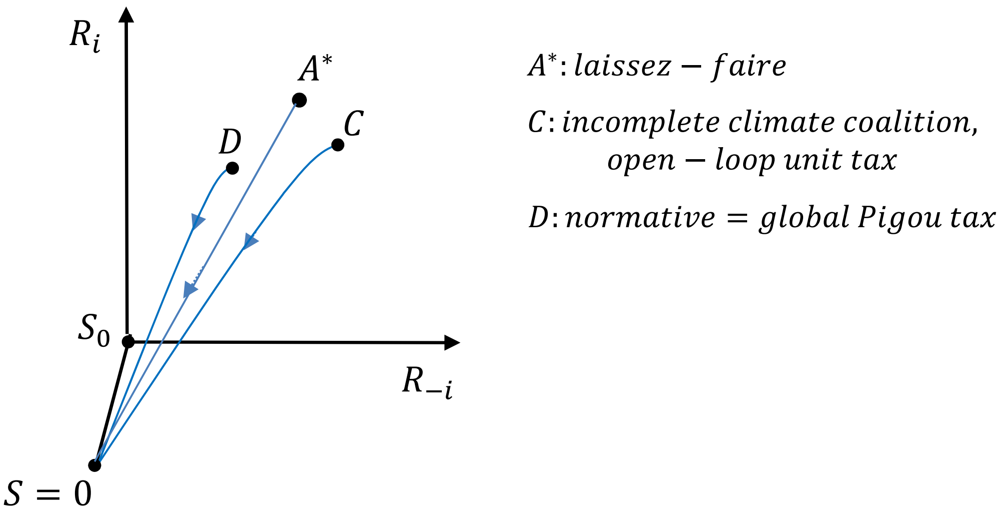

Figure 3.5: Resource extraction paths: laissez-faire, unilateral open-loop and normative scenario.

Consider now the extraction path that results under the unilateral open-loop unit tax if both groups exhibit the same price elasticity of demand. Equation (3.75), which characterises the respective open-loop extraction path under the unilateral tax, defines a flatter direction of movement for each point in R_i, R_{-i}, S space than the laissez-faire equation (3.77) as long as the coalition consumes the resource. As previously mentioned, the latter condition is met along the entire extraction path as the coalition's price elasticity of demand is bounded by assumption.[21] The equilibrium path under the open-loop tax must lead to the terminal point $S = 0$ and it needs to satisfy equation (3.75) along the way. Hence, because equation (3.75)

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[20] Note that a starting point D' that would lie between point A^* and point C but to the left of point A^* in R_i, R_{-i} space would also meet these criteria.

[21] Recall also that although equation (3.75) would equal equation (3.77) for $R_{-i} \to \infty$, this is not a feasible solution because the resource stock in situ is finite.

defines a flatter direction of movement for every point in R_i, R_{-i}, S space compared to equation (3.77), the global equilibrium resource flow extracted under the unilateral open-loop unit tax for a given level of the resource stock in situ must fall short of the respective laissez-faire level under the assumptions made. The world market price along the open-loop equilibrium extraction path lies everywhere below the laissez-faire resource price whereby the intertemporal arbitrage condition of the representative resource supplier is met while the resource stock is exhausted. Both the incomplete coalition and the fringe countries benefit from a lower world market price along the open-loop extraction path compared to the laissez-faire case.

Because the unilateral open-loop unit tax slows down the speed of global resource extraction compared to the laissez-faire case under the assumptions made, the coalition must reduce its initial consumption below the respective laissez-faire level, which implies that the initial consumer price must exceed the initial laissez-faire resource price. The coalition's reduction in its initial resource consumption shifts the starting point of the open-loop equilibrium extraction path downwards in R_i, R_{-i} space compared to the laissez-faire starting point A^*. However, because the global resource flow extracted for a given stock level in situ must be lower under the unilateral tax than in the laissez-faire case, the coalition's initial consumption reduction cannot be entirely offset by the increase in resource consumption that the fringe countries undertake in response to the lower world market price. A carbon leakage rate of 100 per cent for a given stock level would imply that the global resource flow for a given stock level would be the same as in the laissez-faire case, whereby the flow would be too large to be compatible with the equilibrium conditions that are relevant under the open-loop tax; given the made assumptions. The starting point of the equilibrium path that results under the unilateral open-loop tax lies below and to the right of the laissez-faire starting point A^*, as depicted by the starting point C in figure 3.5. The carbon leakage rate must be less than 100 per cent.

Abstracting from extraction costs and assuming that the incomplete coalition and the fringe countries exhibit the same constant price elasticity of demand and that demand is independent of calendar time, or, if demand depends on calendar time, assuming that the demand of the coalition and the fringe countries grows or shrinks at the same rate over time for exogenous reasons, it follows that the unilateral open-loop unit tax chosen by the incomplete climate coalition unambiguously slows down the speed of global resource extraction compared to the laissez-faire case. The fringe countries increase their resource consumption in response to the policy-induced decline in the world market price, but under the assumptions made, the unilateral policy nevertheless shifts some resource supply from the present to the future compared to the laissez-faire extraction path. However, the delay of some extraction from the present to the future is not a prerequisite for the incomplete coalition's discounted net output, as measured by its objective (3.48), to be maximised. Irrespective of how the coalition's unilateral open-loop policy affects the speed of global extraction compared to the laissez-faire case, the incomplete coalition's discounted net output in the open-loop solution exceeds the discounted net output that it would receive in the absence of any policy. Intuitively, given the possibility to credibly commit itself to a certain resource consumption path, the coalition could always implement the laissez-faire extraction path if that would imply a larger discounted net output.[22]

If the coalition and the fringe countries exhibit the same constant price elasticity of demand, if the demand of the coalition and the fringe countries grows or shrinks at the same rate over time for exogenous reasons and if extraction costs are negligible, then the unilateral open-loop policy not only maximises the coalition's discounted net output, but it also increases the efficiency of the intertemporal resource allocation. However, the resulting extraction path does not suffice the criterion of intertemporal Pareto efficiency. The normative equation (3.72) defines a flatter direction of movement for each point in R, S and thus in R_i, R_{-i}, S space compared to equation (3.75), which characterises the open-loop solution. Because the global normative flow extracted for a given stock level in situ is independent of the groups' consumption shares under the assumptions made and because all equilibrium paths must lead to the terminal point $S = 0$, this implies that under the coalition's unilateral open-loop policy, a larger global resource flow is extracted for a given stock level in situ than what would be efficient.

Importantly, the derived open-loop solution presumes that the coalition can commit itself to the announced open-loop tax path. The question whether the open-loop solution is dynamically consistent in the sense that the coalition would not want to renege its original plan once extraction has started and some time has gone by is thus not investigated. The open-loop solution would be dynamically inconsistent if the coalition would deviate from the announced open-loop tax path at some future point in time once extraction has begun. In order to briefly discuss the implication of an upward or downward deviation from the announced

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[22] Cf. also Maskin and Newbery (1990), p. 150, who state that a dominant importer cannot be worse off in the commitment solution compared to the time-consistent solution because, given the possibility to commit, the dominant importer can always mimic the time-consistent solution.

open-loop tax path for the speed of global resource extraction, presume again that both groups exhibit the same constant price elasticity of demand, that demand is independent of calendar time and that extraction costs are negligible. The boundedness assumption regarding the price elasticity of demand implies that the resource stock is exhausted in any case. Furthermore, suppose for simplicity that there are only two periods in time, namely the present and the future. Presume first that the coalition would want to lower the future tax level below the announced open-loop level. The representative supplier would anticipate this deviation when initially deciding on her entire extraction path and she would react accordingly. However, given the assumptions made, the unilateral unit tax would still trigger a shift in resource supply from the present to the future because the tax would still decrease in present value terms, which under the made assumptions is sufficient to fight global warming. Presume next that the coalition would want to increase the future tax level above the originally announced open-loop level. If this increase would be sufficiently large to imply that the unilateral unit tax would increase in present value terms, the representative resource supplier would, given the assumptions made, react by shifting some supply from the future to the present, i.e. the Green Paradox would result. In the light of the global warming problem, this latter case would be the problematic one.

In the presented framework, it is the global warming problem that triggers the incomplete climate coalition’s decision to levy a unilateral open-loop unit tax that grows at a rate lower than the market rate of interest. Whether a unilateral unit tax that declines in present value terms actually constitutes a feasible policy that can be implemented given the societal, democratic and political constraints, which undoubtedly exist in reality, is an important question. As emphasised in Sinn (2008a,b, 2012), in terms of real world climate policies, it might be reasonable to presume that while the global warming problem becomes increasingly severe, the public will call for stronger actions to reduce global carbon consumption as time proceeds. The next chapter discusses the implications of the results derived thus far for the design of real world climate policies.

APPENDIX 3

A3.1 SUPPLIER REACTION TO A UNILATERAL UNIT TAX

Given are the asymptotic properties of the system (3.8)-(3.10) for the case in which the coalition levies a unilateral unit tax on its resource consumption while the time-independent and downward sloping inverse demand functions of the incomplete coalition and the fringe countries are respectively given by $P_i\big(R_i(t)\big)$ and $P_{-i}\big(R_{-i}(t)\big)$, as considered in section 3.4.1. The asymptotic properties of the system (3.8)-(3.10) for the case of time-dependent demand functions and zero extraction costs, as considered in section 3.4.2, follow accordingly by letting $g = 0$ and by considering $P_i(R_i(t), t)$ and $P_{-i}(R_{-i}(t), t)$ as the time-dependent and downward sloping inverse demand functions of the incomplete coalition and the fringe countries, respectively, while excluding the exogenous arrival of a perfect substitute technology for the resource by assumption.

Because the resource stock in situ is finite, feasibility of the solution requires that $R(t) \to 0$ as $t \to \infty$. Note that in the presence of the incomplete coalition's unilateral unit tax on resource consumption it holds that $P_i\big(R_i(t)\big) = P^C(t)$ and $P_{-i}\big(R_{-i}(t)\big) = \underline{P}(t)$ along an equilibrium extraction path. Given the boundedness assumptions regarding the price elasticities of demand of both groups, which imply that $\lim_{R_i \to 0} P_i\big(R_i(t)\big) = \infty$ and $\lim_{R_{-i} \to 0} P_{-i}\big(R_{-i}(t)\big) = \infty$, it thus follows that both $P^C(t) \to \infty$ and $\underline{P}(t) \to \infty$ as $t \to \infty$ as it must hold that $R(t) = [R_i(t) + R_{-i}(t)] \to 0$ as $t \to \infty$. Moreover, it follows from the supplier's stationary condition

$$P^C(t) - \tau_i(t) = g\big(S(t)\big) + \lambda(t) \quad (3.8),$$

whereby $P^C(t) - \tau_i(t) = \underline{P}(t)$, that $\lambda(t) \to \infty$ as $t \to \infty$ because $\underline{P}(t) \to \infty$ for $t \to \infty$ and because the unit extraction costs are bounded by assumption. Furthermore, it again follows from the supplier's canonical equation (3.9) that

$$\hat{\lambda}(t) = r + \frac{g_S\big(S(t)\big)R(t)}{\lambda(t)}. \quad (3.9a)$$

As it holds that $\lambda(t) \to \infty$ for $t \to \infty$, equation (3.9a) reveals that $\hat{\lambda}(t) \to r$ as $t \to \infty$ because it must hold that $R(t) \to 0$ as $t \to \infty$ and because the derivative g_S is assumed to be bounded. Hence, as $\lambda(t)e^{-rt} > 0$ as time proceeds to infinity, the supplier's transversality condition $\lim_{t\to\infty} \lambda(t)S(t)e^{-rt} = 0$ (3.10) is only met if $S(t) \to 0$ as $t \to \infty$. The global resource stock must converge to zero as time proceeds to infinity whereby the present value of the supplier's Hamiltonian (3.7) converges to zero as time proceeds to infinity.

4 IMPLICATIONS FOR THE DESIGN OF AN EFFECTIVE CLIMATE POLICY

Thus far, the analysis has demonstrated that the global climate coalition comprising all countries slows down the speed at which the global fossil resource stock is depleted over time to the Pareto efficient level if the coalition is constrained to a time-consistent policy. The global warming externality induced by the combustion of each fossil resource unit is in this case internalised. Moreover, abstracting from extraction costs, the analysis showed that under the assumptions that the incomplete coalition and the fringe countries exhibit the same constant value of price elasticity of demand and that the demand of both groups grows or shrinks at the same rate over time for exogenous reasons, the incomplete climate coalition that comprises a stable subset of the world's countries also slows down the speed at which the global resource stock is exhausted over time, presuming that it can commit itself to the announced unilateral open-loop policy path.

The aim of this chapter is to discuss the implications of these findings for the design of practical real world climate policies. In a first step, the incomplete coalition's open-loop policy is analysed in a simplified two-period world. Presuming that the coalition implements its preferred resource consumption path by levying a unit tax, the two-period framework allows for studying the effect of the unilateral unit tax on the intertemporal and the international resource distribution in more detail. Because the European Union has a cap-and-trade system rather than a tax on carbon consumption in place, it is subsequently shown how the incomplete coalition can achieve the same intertemporal resource allocation that would result under the unilateral open-loop unit tax by directly dictating the resource flow that its member countries are allowed to consume over time. Subsequently, the case in which the incomplete coalition pursues an altruistic policy in the sense that it seeks to reduce the global speed of resource extraction compared to that speed that would result under its unilateral open-loop policy is investigated. Because several assumptions have to be satisfied to guarantee that the open-loop policy path chosen by the incomplete coalition actually slows down the speed of global resource extraction compared to the laissez-faire case, this chapter also shows how the incomplete coalition can certainly slow down the speed of global extraction compared to the laissez-faire case, if that was the target. Furthermore, it is discussed whether a unilateral climate policy can be made more effective in fighting global warming by implementing supplementing policy measures addressing the problem of carbon leakage. Moreover, the assumption that demand-reducing policies that lose their strictness over time can easily be implemented in reality will be challenged in the light of the actual policy developments that take place. Finally, it will be explained how a time-path of caps on global emissions can implement the Pareto efficient intertemporal resource allocation.

4.1 UNILATERAL UNIT TAX IN A TWO-PERIOD WORLD

This section condenses the foregoing analysis of the unilateral open-loop unit tax chosen by the incomplete coalition to its main implication in a simplified two-period world. The thought experiment keeps the assumption of an identical price elasticity of demand regarding the coalition and the fringe countries while abstracting from time-dependent demand and extraction costs. Under these assumptions, the unilateral open-loop unit tax levied by the incomplete coalition slows down the speed of global resource extraction to some extent. Allowing for time-dependent demand functions would not alter the results as long as the demand of the incomplete coalition and the fringe countries grows or shrinks over time at the same rate for exogenous reasons. Two periods are considered, the present (and near future), denoted by period 1 and identified by subscript 1, and the far away future, denoted by period 2 and respectively identified by subscript 2.

In figure 4.1, the available global stock of the resource in situ is given by S and its size is reflected by the combined width of the two depicted boxes. The entire stock is distributed across the two considered periods, whereby the width of the left box reflects the global resource flow supplied in period 1 and the width of the right box reflects the global resource flow supplied in period 2. The distribution of the global resource stock across period 1 and 2 is the result of the intertemporal maximisation problem of the representative resource supplier as discussed in the foregoing chapter in section 3.3. Along the laissez-faire equilibrium extraction path, the global resource flows supplied in period 1 and 2 are denoted by R_{0_1} and R_{0_2}, respectively. In each box, the resource flow consumed by the coalition in the respective period is depicted from the left to the right and the residual resource flow consumed by the fringe countries is correspondingly depicted from the right to the left. The inverse demand curves of the incomplete climate coalition and the fringe countries in the laissez-faire case are depicted by $P_i(R_i)$ and $P_{-i}(R_{-i})$ in both periods, respectively.

In the laissez-faire case, the international equilibrium on the global resource market is in both periods characterised by the intersection of the inverse demand curve of the coalition and the fringe countries. The resulting equilibrium allocations on the international resource market in period 1 and 2 are respectively denoted by 0_1 and 0_2. They determine the international distribution of the global resource flow within a given period. The laissez-faire resource flows consumed by the incomplete coalition in period 1 and 2 are denoted by $R_{i,0_1}$ and $R_{i,0_2}$, respectively. The resource flows consumed by the fringe countries in period 1 and 2 are, respectively, given by the residual flows in each period, i.e. by $R_{0_1} - R_{i,0_1}$ and $R_{0_2} - R_{i,0_2}$. The laissez-faire world market price for the resource in period 1 is P_1 and it changes over time according to the intertemporal arbitrage condition that characterises the supply side in the laissez-faire case. The latter follows from (3.12) with $g = 0$ and it is given by $\dot{P}(t) = rP(t)$. In discrete time, this translates into the arbitrage condition $P_1(1 + r) = P_2$, where P_1 and P_2 are the laissez-faire prices in period 1 and 2, respectively. Along the laissez-faire equilibrium extraction path, the price increases at the market rate of interest r. As the global demand for the resource is independent of calendar time by assumption, global resource supply in period 1 exceeds global supply in period 2, i.e. in the laissez-faire case, the left box in figure 4.1 is wider than the right.

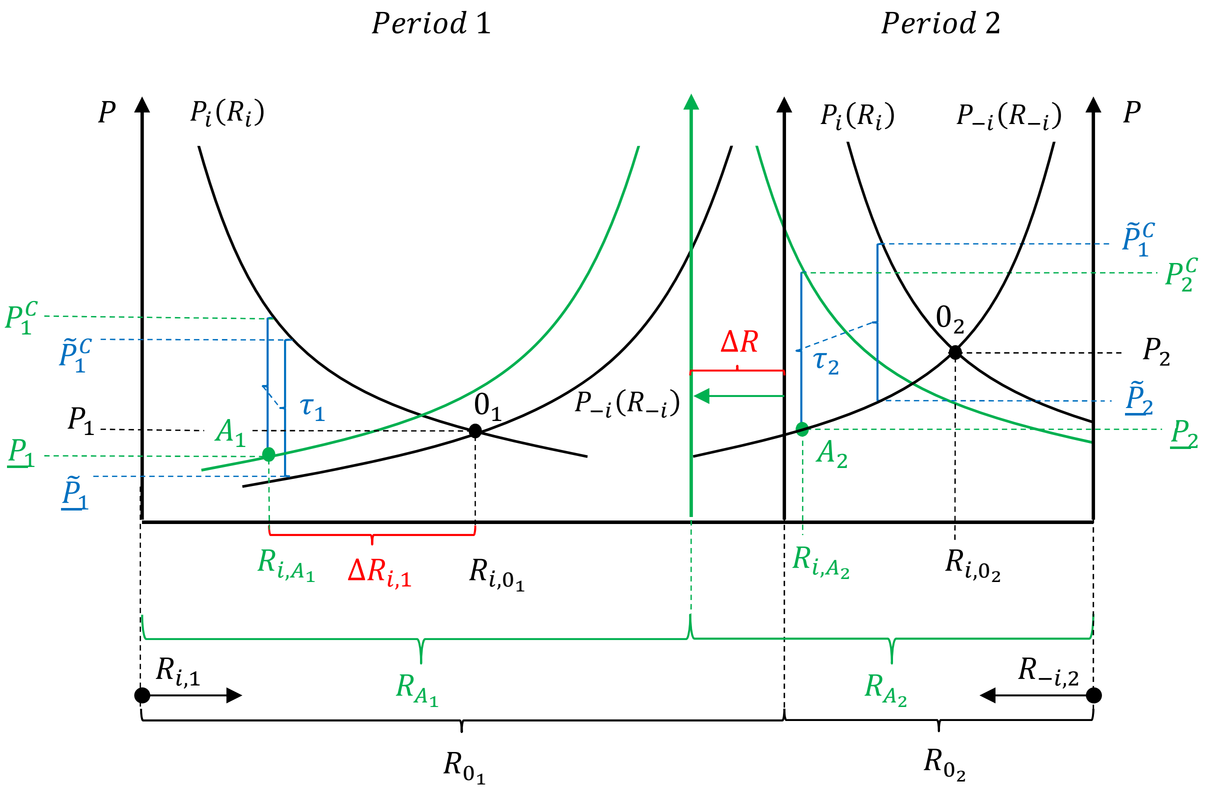

Figure 4.1: Unilateral unit tax, intertemporal supply reaction and international distribution of the global resource flow.

Now, consider the case in which the incomplete climate coalition levies the unilateral open-loop unit tax that decreases in present value terms. Denote the unilateral open-loop unit tax levied by the incomplete coalition in period 1 and 2 by τ_1 and τ_2, respectively. As has been explained before, if one interprets τ_1 and τ_2 as the absolute vertical downward shifts of the incomplete coalition's inverse demand curve in period 1 and 2 compared to the laissez-faire position of this curve, the wedges τ_1 and τ_2 can be given a broader interpretation in the sense that they are induced by a demand-reducing policy-mix pursued by the incomplete coalition, including subsidies on renewable energy or bio fuels. Provided that the absolute vertical downwards shifts over time mimic the unilateral unit tax path, they trigger the same intertemporal supply reaction as the considered unilateral unit tax. Here, the interpretation sticks to the case of a unilateral unit tax.

In order to investigate how the unilateral tax affects the intertemporal resource allocation and the international distribution of the global resource flow among the coalition and the fringe countries in both periods, consider in a first step again the hypothetical case in which the supply side would not react to the tax by shifting supply in time. Given the laissez-faire extraction path, the unilateral tax τ_1 induces a wedge in period 1 between the hypothetical consumer price that would prevail in the coalition countries, depicted by $\tilde{P}_1^C$, and the hypothetical world market price, depicted by $\underline{\tilde{P}_1}$. Accordingly, the tax τ_2 drives a wedge between the hypothetical consumer price $\tilde{P}_2^C$ and the hypothetical producer price $\underline{\tilde{P}_2}$ in period 2. As has been discussed before, in the hypothetical situation in which the representative supplier would not react to the tax, i.e. in the case of a fixed intertemporal resource supply schedule, the resource quantity that the coalition members refrain from in one period would be entirely consumed in the fringe countries instead. The rate of carbon leakage would be 100 per cent and the unilateral unit tax would have no effect on the intertemporal resource extraction path.

However, the representative supplier naturally reacts to the unilateral tax and, as follows from the Long-Sinn invariance theorem, this reaction depends on the pressure that the tax exerts on the world market price for the resource over time, as measured at the laissez-faire extraction path. In the figure, this pressure is measured by the wedge $P_1 - \underline{\tilde{P}_1}$ in period 1 and the wedge $P_2 - \underline{\tilde{P}_2}$ in period 2. When deciding whether to react in response to the unilateral tax by shifting supply in time, the supplier anticipates whether the present value of the tax burden that she has to bear regarding each sold resource unit increases, decreases or remains constant over time. If the wedge between the laissez-faire price and the hypothetical world market price increases in present value terms then extraction speeds up, whereas if it decreases in present value terms then extraction slows down. Accordingly, the global extraction path remains unchanged, despite the tax, if the wedge between the laissez-faire price and the hypothetical world market price is constant in present value terms.

As has been demonstrated in the foregoing chapter, in the case in which the coalition and the fringe countries exhibit the same constant price elasticity of demand and in which the demand of both groups grows or shrinks at the same rate over time for exogenous reasons, a unilateral unit tax on resource consumption that grows at the market rate of interest implies that the wedge that this tax induces between the laissez-faire price and the hypothetical world market price must also grow at the market rate of interest. This followed logically from the Long-Sinn invariance theorem. Moreover, under the assumptions made, it has been demonstrated that the wedge that a unilateral unit tax on resource consumption induces between the laissez-faire price and the hypothetical world market price increases in present value terms if the tax increases in present value terms and, vice versa, that the wedge decreases in present value terms if the tax does.

Figure 4.1 depicts the case of the unilateral open-loop unit tax chosen by the incomplete coalition that decreases in present value terms. Hence, under the assumptions made, the present value of the tax burden that the supplier has to bear regarding each resource unit over time if she would stick to the laissez-faire extraction path decreases in present value terms. Therefore, she shifts some supply from period 1 to 2 compared to the laissez-faire case. The intertemporal shift in the supplied resource flow from the present to the future leads to the left shift of the middle ordinate to the new middle ordinate as depicted in figure 4.1. The intertemporal supply shift is reflected by the amount ΔR, which is now only extracted in period 2 rather than period 1. Supply in period 2 increases at the expense of supply in period 1. Thus, in the considered case, the incomplete coalition's unilateral policy fights climate change. Due to the left shift of the middle ordinate, the inverse demand curve of the fringe countries is shifted leftwards in period 1. For the same reason, the coalition's inverse demand curve is shifted to the left in period 2. The global equilibrium resource flows supplied under the unilateral unit tax in period 1 and 2 are depicted by R_{A_1} and R_{A_2}, respectively. The representative resource supplier increases supply in period 2 at the expense of supply in period 1 until the world market price $\underline{P}_2$ is sufficiently reduced and the world market price $\underline{P}_1$ is sufficiently increased that an intertemporal equilibrium on the resource market is again restored. Along the new equilibrium extraction path, the international resource allocation in period 1 is reached in point A_1. Accordingly, the new equilibrium allocation in period 2 is reached in point A_2. The resource flows consumed in the coalition under the unilateral tax in period 1 and 2 are denoted by R_{i,A_1} and R_{i,A_2}, respectively. In both periods, the fringe countries consume the residual flows which are given by $R_{A_1} - R_{i,A_1}$ and $R_{A_2} - R_{i,A_2}$ in period 1 and 2, respectively.

By shifting some resource quantities from period 1 to 2 compared to the original extraction path, the representative supplier induces a decrease in the producer price in period 2 compared to the hypothetical producer price $\tilde{\underline{P}}_2$. The new world market price in period 2, given that the supplier has reacted to the tax, is depicted by $\underline{P}_2$. Correspondingly, as global supply decreases in period 1, the world market price in period 1 along the new equilibrium extraction path is given by $\underline{P}_1$ and it exceeds the hypothetical producer price $\tilde{\underline{P}}_1$ that would have prevailed had the supplier not reacted to the tax. Along the new intertemporal equilibrium extraction path, the world market price for the resource again increases from $\underline{P}_1$ to $\underline{P}_2$ according to the intertemporal arbitrage condition of the representative supplier, i.e. according to $\dot{\underline{P}}(t) = r\underline{P}(t)$ (3.32), which translates into $\underline{P}_1(1+r) = \underline{P}_2$ in discrete time. Along the new equilibrium extraction path, consumers within the coalition now pay the consumer prices P_1^C and P_2^C in period 1 and 2, respectively.[1] However, both the coalition and the fringe countries can now purchase the resource at the lower world market price for the resource in both periods, as respectively depicted by $\underline{P}_1$ and $\underline{P}_2$. Note that the latter holds irrespective of whether the unilateral open-loop unit tax actually slows down the speed of global extraction compared to the laissez-faire case. Moreover, by levying the unilateral unit tax, the incomplete coalition in any case collects tax revenues, which can be redistributed among its member countries.

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[1] Note that the consumer price P_1^C that the coalition members pay in period 1 must exceed the respective laissez-faire resource price P_1 because under the assumptions made, the unilateral open-loop unit tax slows down extraction compared to the laissez-faire case. This implies that the global resource flow supplied in period 2 is increased at the expense of the supply in period 1. For the globally consumed resource flow to be lower in period 1 compared to the laissez-faire case, the consumer price P_1^C must exceed the laissez-faire price P_1. However, it is not apparent whether the consumer price P_2^C that the coalition members pay in period 2 lies above or below the respective laissez-faire price P_2. Suppose that the coalition would levy a unilateral unit tax that grows at the market rate of interest. The resource supply side would not adjust the extraction path in response to the tax under the assumptions made. Hence, the consumer price that the coalition members would have to pay would lie above the laissez-faire price in both periods due to the tax. By contrast, if the coalition would tax its resource consumption in period 1 only, the consumer price P_2^C that the coalition members pay in period 2 would lie below the laissez-faire price P_2 because in this case supply in period 2 is increased at the expense of supply in period 1, while no tax is imposed in period 2. In the case considered here, in which the coalition commits itself to levy a unilateral unit tax that decreases in present value terms, the supply side shifts some supply from period 1 to 2. Figure 4.1 depicts a situation in which the induced increase in future supply depresses the world market price in period 2, although the decrease is too small to imply a consumer price P_2^C that falls short of the laissez-faire price P_2.

What matters for the climate is the extent of the shift of the middle ordinate as depicted by ΔR in the figure. Under the unilateral tax, the coalition reduces its consumption in period 1 by the amount $\Delta R_{i,1}$ along the new equilibrium extraction path, as depicted in figure 4.1. In contrast, the fringe countries increase their consumption in period 1 while the rate of carbon leakage is less than 100 per cent. The amount ΔR depicts the part of the resource flow that the incomplete coalition refrains from in period 1 that is not consumed by the fringe countries within the same period but is rather delayed to period 2. Abstracting from extraction costs, the good news for the climate is thus that in the case in which the coalition and the fringe countries exhibit the same constant price elasticity of demand and in which the demand of both groups grows or shrinks at the same rate over time for exogenous reasons, the incomplete coalition's open-loop policy fights climate change to some extent.

4.2 FROM PRICE TO QUANTITY REGULATION

This section investigates how the intertemporal extraction path that results under the incomplete coalition's unilateral open-loop unit tax can be implemented via a quantity regulation instead of the price regulation discussed thus far. Since the paper by Weitzman (1974), it has been known that, given perfect information, a certain desired reduction in resource consumption can be reached equivalently either via a price instrument like a unit tax or by directly constraining the resource quantity itself to the desired level. One instrument that directly controls the consumed resource flow over time is a quantity constraint on the emissions from the combustion of fossil fuels, which could be realised via a cap-and-trade system, such as the one that the European Union has in place. A cap-and-trade system that is implemented by an incomplete climate coalition puts an upper bound on the emissions that can be released by the coalition's member countries within a given period whereby the time-path of the caps effectively dictates the resource flow that the coalition consumes over time. Furthermore, to achieve an efficient allocation of carbon inputs among the member countries within a given period, emission permits can be traded between the participating entities.

In order to analyse the case in which the incomplete coalition sets unilateral emission caps, consider again the simplified two-period world that was introduced in the previous section. Suppose that the incomplete climate coalition seeks to implement the same intertemporal resource allocation as the one that results under the unilateral open-loop unit tax. As before, the fringe countries implement no policy whatsoever in either period. Figure 4.2 again depicts the situation on the global resource market similarly to figure 4.1, with the difference that the incomplete coalition now imposes unilateral emission caps in period 1 and 2, respectively, which constrain the resource flow consumed by its member countries in both periods. Constraining the consumed resource flow within a given period to a certain level is equivalent to imposing a respective cap on emissions.

Like before, the original widths of the two boxes reflect the global laissez-faire resource flows supplied along the laissez-faire equilibrium extraction path in period 1 and 2, denoted by R_{0_1} and R_{0_2}. In each period, the resource flow consumed by the coalition is depicted on the abscissa from the left to the right and the resource flow consumed by the fringe countries is respectively depicted from the right to the left. The international laissez-faire equilibrium, as depicted by the points 0_1 and 0_2, is in each period determined by the intersection of the inverse demand curve of the coalition, $P_i(R_i)$, and the fringe countries, $P_{-i}(R_{-i})$. The laissez-faire resource price increases at the market rate of interest from P_1 in period 1 to P_2 in period 2. In the absence of any policy, the coalition respectively consumes the flows $R_{i,0_1}$ and $R_{i,0_2}$ in period 1 and 2 while the fringe countries consume the residual flows $R_{0_1} - R_{i,0_1}$ and $R_{0_2} - R_{i,0_2}$. Along the equilibrium extraction path it must hold that $R_{0_1} + R_{0_2} = S$ where S is the global resource stock. The stock is exhausted as is required along any equilibrium path due to the assumption that the price elasticity of demand of the coalition and the fringe countries is bounded.

What can be shown is that to mimic the intertemporal resource allocation that would result under the unilateral open-loop unit tax considered in figure 4.1 via a respective time-path of unilateral emission caps, the incomplete coalition would have to constrain its consumption in period 1 and 2 to the flows that would prevail under the unilateral open-loop unit tax along the new equilibrium extraction path, i.e. after the supply side has reacted to the tax. In figure 4.2, these caps are depicted by the vertical branches that cut the inverse demand curves of the coalition in period 1 and 2. Under these caps, the maximum resource flow which the coalition can consume in period 1 and 2 is given by R_{i,A_1} and R_{i,A_2}, respectively. The reason why announcing these emission caps for period 1 and 2 triggers the same intertemporal supply reaction as the unilateral open-loop unit tax considered in figure 4.1 is explained in what follows.

In the two-period case, the intertemporal equilibrium under the unilateral open-loop unit tax is characterised by the pair of world market prices $\left(\underline{P}_1, \underline{P}_2\right)$ and the pair of the globally supplied resource flows $\left(R_{A_1}, R_{A_2}\right)$. Under the unilateral tax, the incomplete coalition consumes the pair of flows $\left(R_{i,A_1}, R_{i,A_2}\right)$ and the fringe countries consume the pair of residual flows

$\left(R_{A_1} - R_{i,A_1}, R_{A_2} - R_{i,A_2}\right)$. Let $R_i\left(P^C(t)\right)$ with $\partial R_i/\partial P^C < 0$ and $R_{-i}\left(\underline{P}(t)\right)$ with $\partial R_{-i}/\partial \underline{P} < 0$ denote the demand functions of the coalition and the fringe countries, respectively, in the presence of the unilateral unit tax, whereby $\underline{P}(t)$ is the world market price and where $P^C(t)$ is the consumer price within the coalition in period t.

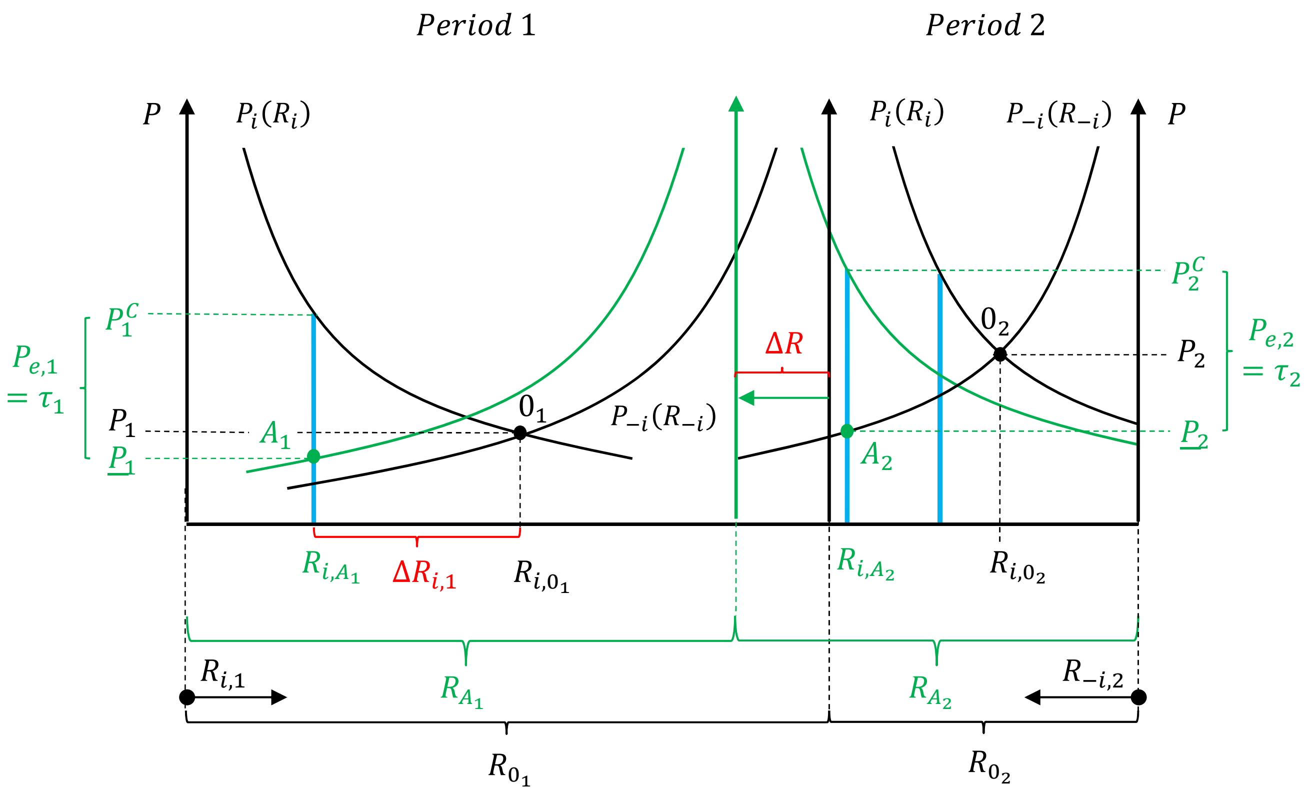

Figure 4.2: Unilateral emission caps, intertemporal supply reaction and international distribution of the global resource flow.

Along the equilibrium extraction path under the unilateral open-loop unit tax it thus holds that $R_i(P_1^C) = R_{i,A_1}$ and that $R_{-i}\left(\underline{P}_1\right) = R_{A_1} - R_{i,A_1}$ in period 1. Equivalently, in period 2 it holds that $R_i(P_2^C) = R_{i,A_2}$ and that $R_{-i}\left(\underline{P}_2\right) = R_{A_2} - R_{i,A_2}$. Also, along the equilibrium extraction path under the unilateral tax it must hold that $R_{i,A_1} + R_{i,A_2} + R_{A_1} - R_{i,A_1} + R_{A_2} - R_{i,A_2} = R_{A_1} + R_{A_2} = S$. That the resource stock is exhausted in any case is an equilibrium condition because the two groups exhibit a bounded price elasticity of demand.

Now consider the case in which the incomplete coalition constrains its consumed resource flow over time to the levels R_{i,A_1} and R_{i,A_2} in period 1 and 2, respectively, which fall short of its respective laissez-faire consumption flows. Given these caps, the laissez-faire price pair

(P_1, P_2) cannot constitute and intertemporal equilibrium on the global resource market. The reason is that given the caps and the laissez-faire prices, global demand would be reduced in period 1 and 2 compared to the laissez-faire case whereby the global stock would not be exhausted. In order to show that the supply reaction that restores an intertemporal equilibrium on the resource market is the same under the considered caps as under the unilateral open-loop unit tax, it is necessary to show that given that the coalition constrains its resource consumption to the levels R_{i,A_1} and R_{i,A_2} in period 1 and 2, respectively, the only pair of world market prices that restores an intertemporal equilibrium on the resource market is the open-loop world market price pair $(\underline{P}_1, \underline{P}_2)$.

Suppose, by contrast, that along the new equilibrium extraction path the prevailing world market price in period 1 was $\underline{P}_1{}^*$ and presume that $\underline{P}_1{}^* > \underline{P}_1$. Hence, it would follow from the supplier arbitrage condition $\underline{P}_1{}^*(1+r) = \underline{P}_2{}^*$ that also the new word market price in period 2, $\underline{P}_2{}^*$, must exceed the open-loop price $\underline{P}_2$, i.e. it would also hold that $\underline{P}_2{}^* > \underline{P}_2$. Because the world market price would be higher in both periods compared to the equilibrium that results under the unilateral open-loop unit tax, the fringe countries would consume a lower resource flow in both periods while the coalition would still consume its open-loop resource flows R_{i,A_1} and R_{i,A_2} in period 1 and 2, respectively.[2] Thus, a world market price path that lies everywhere above the open-loop world market price path cannot restore an intertemporal equilibrium on the resource market as the global stock would not be exhausted. Accordingly, a world market price path that lies everywhere below the open-loop world market price path cannot constitute an intertemporal equilibrium. In this case, the fringe countries would want to consume a larger resource flow in both periods compared to the open-loop equilibrium, while the coalition would still consume its open-loop flows R_{i,A_1} and R_{i,A_2}. This would imply that global demand in period 1 and 2 would exceed the available global stock overall, which cannot constitute an intertemporal equilibrium.

Given that the incomplete coalition constrains its resource flows to the open-loop levels R_{i,A_1} and R_{i,A_2} in period 1 and 2, respectively, the only pair of world market prices that satisfies the arbitrage condition of the representative resource supplier and ensures that the global resource stock is exhausted along the equilibrium extraction path is the open-loop price pair $(\underline{P}_1, \underline{P}_2)$.

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[2] Note that the coalition's caps R_{i,A_1} and R_{i,A_2} will always be binding in the sense that the coalition will actually consume these flows along the equilibrium extraction path that results under these caps. The reason is that the world market price path in the presence of the caps must lie below the laissez-faire price path to guarantee that the stock is exhausted. Moreover, the consumer price path that is relevant for the consumers within the coalition must exceed the laissez-faire price path, because the coalition constrains its resource consumption below its respective laissez-faire consumption in both periods.

Therefore, the incomplete coalition can equivalently implement the equilibrium extraction path that would result under the unilateral open-loop unit tax by directly constraining its resource flows to the equilibrium levels that it would consume along the equilibrium extraction path under its unilateral open-loop unit tax. The resulting intertemporal and international allocation of resources is the same in both cases. The intertemporal supply reaction is again depicted by the shift of the right ordinate to the left new ordinate in figure 4.2, whereby ΔR depicts the resource amount that is shifted in time from period 1 to 2 as before. The intertemporal supply reaction shifts the inverse demand curve of the fringe countries in period 1 to the left, while in period 2 the inverse demand function of the incomplete coalition is shifted to the left. The global resource flow supplied in period 1 along the open-loop equilibrium path under the unilateral emission caps is given by R_{A_1} and the global flow in period 2 is correspondingly given by R_{A_2}. The equilibrium on the international resource market in the presence of the considered unilateral emission caps is still depicted by the points A_1 and A_2, which determine the international distribution of the global flows in period 1 and 2. Just like under the unilateral open-loop unit tax, the coalition consumes the flows R_{i,A_1} and R_{i,A_2} while the fringe countries consume the residual flows $R_{A_1} - R_{i,A_1}$ and $R_{A_2} - R_{i,A_2}$ in period 1 and 2, respectively.

Because the unilateral caps that the coalition sets reduce the global resource demand compared to the laissez-faire case, the world market price path that prevails along the open-loop equilibrium path under the caps must lie everywhere below the laissez-faire price path. The consumer prices that prevail within the coalition under the caps in period 1 and 2, as depicted by P_1^C and P_2^C in figure 4.2, exceed the respective world market prices along the open-loop extraction path, while the difference between the two prices in each period reflects the price for an emission certificate that prevails in the respective period. Let the price for an emission certificate in period 1 and 2 be respectively given by $P_{e,1}$ and $P_{e,2}$, as depicted in figure 4.2. The certificate price measures the scarcity of the certificates in each period. Because the incomplete coalition announces a time-path of unilateral emissions caps that triggers the same intertemporal supply reaction as the unilateral open-loop unit tax, the price for an emission certificate in each period equals the respective level of the unilateral unit tax for this period. This must be the case because the coalition consumes the same resource flows in both periods under the caps and the tax, which implies that the consumer price path is the same in both scenarios. As also the world market price path is the same in both cases, it must also hold that $P_{e,1} = \tau_1$ and that $P_{e,2} = \tau_2$ if the coalition implements the open-loop equilibrium extraction path via a time-path of respective unilateral emission caps. The certificate price in period 1 thus also indicates whether the intertemporal resource allocation that results under the caps and the unilateral tax coincide, as explained in more detail below.

Suppose that the coalition would constrain its resource consumption in period 1 to the open-loop level R_{i,A_1} as before, but rather that it would constrain its consumption to the level $\overline{R_{i,2}}$ in period 2 that falls short of its open-loop consumption level R_{i,A_2}. In this case, the world market price in period 1 and 2 would be lower, the certificate price in period 1 would be higher and global supply in period 1 would increase compared to the open-loop solution. The reason is the following. Under the tightened period-2-cap, the open-loop world market price pair $\left(\underline{P}_1,\underline{P}_2\right)$ no longer constitutes an intertemporal equilibrium on the resource market because given this price pair, global demand in period 1 would remain unchanged, as the period-1-cap is the same as before, but global demand in period 2 would be reduced due to the stricter period-2-cap. Hence, given the price pair $\left(\underline{P}_1,\underline{P}_2\right)$ and the stricter period-2-cap, the global stock would not be exhausted. In order to restore an intertemporal equilibrium, the new world market price path under the tightened period-2-cap must lie everywhere below the open-loop world market price path. This in turn implies that, compared to the open-loop solution, the fringe countries increase their resource consumption in period 1 and in period 2, while the coalition still consumes its open-loop resource flow R_{i,A_1} in period 1 due to the unchanged period-1-cap. Thus, global supply in period 1 must be larger and global supply in period 2 must accordingly be lower than in the open-loop solution. The speed of global resource extraction increases compared to the open-loop equilibrium under the tightened period-2-cap.

Under the tightened period-2-cap, the price for an emission certificate in period 1 exceeds the level of the respective unilateral open-loop unit tax; given that the period-1-cap is fixed at the open-loop level. Because global supply in period 1 is larger than in the open-loop equilibrium, the demand for emission certificates in period 1 increases, thereby driving up their price given the fixed total number of certificates determined by the period-1-cap. Recall that the coalition still consumes its open-loop resource flow in period 1 because the period-1-cap is unchanged, which implies that the consumer price in period 1 is also the same as in the open-loop equilibrium. However, the world market price in period 1 is now lower under the tightened period-2-cap and thus the certificate price in period 1, which is given by the difference between the consumer price and the world market price, must exceed the unilateral open-loop unit tax for period 1. Therefore, given that the open-loop period-1-cap is set, one can state that if the certificate price in period 1 exceeds the level of the unilateral open-loop unit tax for this period, the unilateral emission cap is tightened too much from period 1 to 2 to mimic the intertemporal resource allocation that would result under the unilateral open-loop unit tax. Accordingly, the global resource stock is depleted quicker than under the tax. In this case, the coalition would have to loosen the cap in period 2 to slow down the extraction speed. Precisely, in order to mimic the intertemporal allocation that results under the unilateral open-loop unit tax, it would have to loosen the cap in period 2 to the level R_{i,A_2}.

By contrast, if the certificate price in period 1 falls short of the tax level in the presence of the open-loop period-1-cap, the cap is tightened too little over time and the resource stock is depleted at a lower speed than under the unilateral open-loop unit tax. In order to mimic the intertemporal resource allocation that would result under the tax, the coalition would correspondingly have to tighten the cap to the level R_{i,A_2} in period 2. Hence, given that the open-loop period-1-cap is set, the price for an emission certificate that prevails in period 1 indicates whether the intertemporal resource allocation under the unilateral caps is the same or whether it is more or less conservative compared to the intertemporal allocation that results under the unilateral open-loop unit tax. If the price for an emission certificate that prevails in the presence of the open-loop period-1-cap in period 1 equals the level of the unilateral open-loop unit tax for this period, the intertemporal resource allocation under the emission caps and the tax coincide, as depicted in figure 4.2. Note that the derived equivalence of the price regulation in the form of a unilateral unit tax and the quantity regulation does not hinge on the presumption made here that the incomplete coalition levies its unilateral open-loop unit tax. The coalition can mimic the intertemporal allocation that would result under any unilateral unit tax on resource consumption by directly constraining its resource consumption to those consumption levels over time that it would consume along the equilibrium extraction path under the tax.

4.3 ALTRUISTIC UNILATERAL CLIMATE POLICY

An interesting question is whether the incomplete coalition could possibly slow down the speed of global resource extraction compared to the speed that would result under its unilateral open-loop policy, which actually maximises its discounted net output, if the coalition for some reason wanted to achieve this goal.[3] For instance, one could think of the case in which the European Union wants to encourage the fringe countries outside the coalition to also accept emission reduction targets for their economies by pursuing an

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[3] Cf. Sinn (2012), pp. 213-6, on a related discussion.

altruistic instead of a purely selfish unilateral policy. Such an objective could also include moral benefits from assuming responsibility for the development of the past global CO_2 emissions path that the industrialised countries have largely determined. Whether such an altruistic strategy will also actually motivate the fringe countries to cap their emissions or whether in fact the opposite is true is not the question to be answered here; rather, the question is solely whether the coalition can achieve more for the climate compared to its open-loop policy, if it wanted to.

It is obvious that the incomplete climate coalition can only constrain the resource flow consumed by its member countries. Thus, there is a natural boundary regarding the extent to which it can decrease the global demand for the resource over time. Nevertheless, it can be shown that the incomplete coalition is able to slow down the speed of global resource extraction compared to the speed that would prevail under its unilateral open-loop policy. This result requires neither an assumption regarding the price elasticities of demand nor the assumption that the demand of the two groups grows or shrinks over time at the same rate for exogenous reasons.

To make the point, let the consumer price pair that prevails in period 1 and 2 in the coalition in the presence of the unilateral open-loop policy be given by (P_1^C, P_2^C). Suppose that the coalition's demand function is given by $R_i(P_1^C, t_1)$ in period 1 and $R_i(P_2^C, t_2)$ in period 2 while it holds that $\partial R_i / \partial P^C < 0$ and where t_1 and t_2 capture the dependence of the demand functions on calendar time. Furthermore, let the world market price pair that constitutes an intertemporal equilibrium on the resource market under the coalition's unilateral open-loop policy again be denoted by $\left(\underline{P}_1, \underline{P}_2\right)$, while this price pair will be the same as in figures 4.1 and 4.2 by mere coincidence only. The demand function of the fringe countries in the presence of the coalition's unilateral open-loop policy is given by $R_{-i}\left(\underline{P}_1, t_1\right)$ in period 1 and $R_{-i}\left(\underline{P}_2, t_2\right)$ in period 2, while it holds that $\partial R_{-i} / \partial \underline{P} < 0$ and where t_1 and t_2 again capture that demand depends on calendar time.

In figure 4.1, the coalition‘s open-loop policy unambiguously slowed down the global speed of resource extraction compared to the laissez-faire case due to the assumptions made. Here, no assumptions regarding the price elasticities of demand or the time-dependence of the demand functions of the two groups are made. Therefore, no statement is made whether the incomplete coalition's unilateral open-loop policy actually slows down the speed of global resource extraction compared to the laissez-faire case. The question to be answered is solely whether the coalition can in principle slow down the speed of global extraction compared to the speed that would result under its unilateral open-loop policy.

First, consider the case in which the coalition loosens its period-2-cap compared to the time-path of the unilateral caps that would implement the open-loop solution while the cap still constrains the coalition's consumption below its respective laissez-faire level. Suppose hypothetically that the open-loop world market price pair $(\underline{P}_1, \underline{P}_2)$ would still prevail, i.e. the supply side would not react. Under the loosened period-2-cap, the open-loop price pair $(\underline{P}_1, \underline{P}_2)$ no longer constitutes an intertemporal equilibrium because under this price pair, global resource demand in period 1 would be unchanged, as the period-1-cap remains unchanged, while global demand in period 2 would be larger than before due to the loosened period-2-cap. Hence, total demand for the resource would exceed the global stock. Therefore, the new world market price path that restores the equilibrium on the global resource market must lie everywhere above the open-loop world market price path to satisfy the arbitrage condition of the representative resource supplier while simultaneously guaranteeing that the stock is exhausted.[4] Because the new world market price in period 1 exceeds the open-loop equilibrium price $\underline{P}_1$, the fringe countries reduce their resource consumption in period 1. Moreover, because the period-1-cap remains unchanged, the coalition consumes its open-loop resource flow in period 1. Thus, as the fringe countries reduce their consumption in period 1 while the coalition consumes its open-loop flow, global supply must be shifted from period 1 to 2 to some extent under the loosened period-2-cap compared to the intertemporal resource allocation resulting in the benchmark equilibrium under the unilateral open-loop policy.

By loosening the cap in period 2 compared to the unilateral caps that would implement the same extraction speed as the unilateral open-loop unit tax, the coalition can reduce the speed of global resource extraction compared to the open-loop benchmark equilibrium. Such an altruistic policy benefits the climate compared to the case in which the coalition acts purely selfishly. However, under the loosened period-2-cap, both the coalition and the fringe countries have to pay a higher world market price for the resource along the new extraction path compared to the open-loop equilibrium. The fringe countries consume a lower resource flow than in the open-loop solution in both periods due to the higher world market price path. The coalition consumes its open-loop flow in period 1, as the period-1-cap is unchanged. In period 2, the coalition consumes a larger flow under the loosened period-2-cap compared to

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[4] Note, however, that the new world market price path that prevails under the loosened period-2-cap still lies below the laissez-faire price path.

the open-loop equilibrium which is possible as supply in period 2 has increased while the fringe countries consume less than before in period 2 due to the higher world market price in this period.

The above logic can accordingly be used to explain that tightening the period-2-cap speeds up extraction compared to the equilibrium extraction path that would result under the unilateral open-loop policy.[5] Given the open-loop world market price pair $\left(\underline{P}_1, \underline{P}_2\right)$, the global resource stock would not be exhausted in the presence of the tightened period-2-cap because global demand in period 2 would decrease compared to the open-loop case while global demand in period 1 would be unchanged, as the period-1-cap remains unchanged. Hence, the new world market price path that restores an intertemporal equilibrium must lie everywhere below the open-loop world market price path. The lower world market price in period 1 unambiguously increases global demand in period 1 because the coalition's period-1-cap remains unchanged, which implies that the coalition still consumes its open-loop flow, while the fringe countries increase their consumption in response to the lower world market price. Thus, the speed of resource extraction must increase under the stricter period-2-cap compared to the extraction speed that results under the coalition's unilateral open-loop policy. The fringe countries consume more of the resource in both periods because the world market price is lower than in the open-loop equilibrium. The coalition consumes the same flow as in the open-loop solution in period 1 because this cap is unchanged while in period 2, the coalition consumes less than before because the period-2-cap is now stricter.

If the incomplete coalition would for some reason prefer to change the period-1-cap (instead of the period-2 cap) compared to the open-loop benchmark equilibrium, it can also slow down the speed of resource extraction compared to the speed that would result under the unilateral open-loop policy if it tightens the period-1-cap. Under the tightened period-1-cap, the open-loop world market price pair $\left(\underline{P}_1, \underline{P}_2\right)$ no longer constitutes an intertemporal equilibrium. Given this price pair and the stricter period-1-cap, global demand for the resource in period 1 would fall short of the global demand that would prevail in this period in the open-loop equilibrium. As global demand in period 2 would remain the same as in the open-loop

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[5] Eichner and Pethig (2011) as well as Ritter and Schopf (2013) study the question of how tightening the period-2-cap affects the global extraction path compared to a benchmark equilibrium path that would result under a given time-path of exogenously given emission caps in a two-period general equilibrium framework. In their analyses, tightening the period-2-cap does not necessarily shift supply from the future to the present compared to the benchmark equilibrium. Here, the partial equilibrium analysis allows for deriving the conclusion that tightening the period-2-cap unambiguously speeds up extraction compared to the benchmark situation, irrespective of whether the benchmark caps themselves would slow down or speed up extraction compared to the laissez-faire case.

equilibrium, the global stock would thus not be exhausted. Therefore, the new world market price path that restores the intertemporal equilibrium must lie below the open-loop world market price path to guarantee exhaustion of the resource while satisfying the intertemporal arbitrage condition of the representative resource supplier. Given the unchanged period-2-cap, the coalition consumes the same resource flow in period 2 as in the open-loop solution, although the world market price is now lower. In period 1, the coalition consumes a smaller resource flow than previously, due to the stricter cap. The fringe countries increase their consumption in response to the lower world market price in period 2. Hence, global supply in period 2 must increase compared to the extraction path that would result under the unilateral open-loop policy. The coalition slows down the speed of global extraction compared to the open-loop equilibrium by tightening its period-1-cap. The fringe countries also increase their resource consumption in period 1 in response to the lower world market price that prevails under the tightened period-1-cap. However, the leakage rate must be below 100 per cent because the world market price in period 2 is lower than in the open-loop benchmark equilibrium while the period-2-cap is unchanged, implying larger global consumption in period 2.

In contrast, by loosening the period-1-cap the incomplete coalition would increase the speed of resource extraction compared to the speed that would result under its unilateral open-loop policy. Again, given the open-loop world market price pair $\left(\underline{P}_1, \underline{P}_2\right)$, total global demand would exceed the global resource stock because global demand in period 1 would increase compared to the open-loop solution due to the loosened period-1-cap while global demand in period 2 would remain unchanged. Therefore, the new world market price path must lie above the open-loop world market price path to restore an intertemporal equilibrium on the global resource market. Given the higher world market price in period 2, the fringe countries reduce their consumption in period 2 while the coalition still consumes its open-loop flow because its period-2-cap remains unchanged. This implies that global supply in period 2 must be reduced and thus that supply in period 1 must increase compared to the open-loop equilibrium. Hence, by loosening the period-1-cap, the incomplete coalition speeds up global extraction compared to the extraction path that would result under its unilateral open-loop policy.

Finally, an important question is also whether the incomplete coalition would certainly be able to slow down the speed of global resource extraction compared to the laissez-faire case, if that was the target, even if no assumptions regarding the groups' price elasticities of demand or the rate at which the demand of the coalition and the fringe countries grows or shrinks over time for exogenous reasons are made. The answer is that the coalition can always achieve an intertemporal supply shift from the present to the future compared to the laissez-faire case by constraining its resource consumption in period 1 while not constraining it in period 2. The reason is the following. Consider a laissez-faire equilibrium extraction path where the price pair (P_1, P_2) characterises the laissez-faire prices in period 1 and 2, respectively, which satisfy the intertemporal arbitrage condition of the representative resource supplier, i.e. $P_1(1+r) = P_2$. Given this benchmark equilibrium, suppose that the incomplete coalition constrains its consumed resource flow below its laissez-faire consumption in period 1 by setting a cap on its emissions in this period. The coalition's consumption in period 2 remains unconstrained. Given the coalition's period-1-cap, the laissez-faire resource price pair (P_1, P_2) no longer constitutes an intertemporal equilibrium on the global resource market because under this price pair, global demand in period 2 would remain unchanged, while global demand in period 1 would be lower than before due to the coalition's cap. Hence, the global stock would not be exhausted.

In order to restore an intertemporal equilibrium, the new world market price path must lie below the laissez-faire price path. As the new world market price in period 2 thus lies below the respective laissez-faire price, global demand in period 2 unambiguously increases as no cap is implemented in this period. This implies that the coalition's policy triggers an intertemporal supply shift from period 1 to 2 compared to the laissez-faire case, thereby fighting climate change. The fringe countries increase their resource consumption in response to the lower world market price in period 1 and in period 2 whereby carbon leakage undermines the effectiveness of the coalition's unilateral policy in shifting some resource supply from the present to the future, but the leakage rate is below 100 per cent. The coalition can also purchase the resource at a lower world market price along the entire new extraction path, whereby its consumption in period 2 increases compared to the laissez-faire case. However, due to its period-1-cap, the coalition's resource consumption in period 1 falls short of its laissez-faire consumption in this period. If the incomplete coalition certainly seeks to slow down the speed of global resource extraction, the strategy of imposing a unilateral cap on emissions today that constrains the resource flow consumed by its members below the respective laissez-faire flow in the present while not constraining resource consumption in the future can achieve this goal.

Accordingly, following the same logic, the coalition would unambiguously speed up global extraction compared to the laissez-faire case, i.e. it would trigger the Green Paradox, if it would constrain its resource flow below its laissez-faire flow in period 2 while not constraining its consumption in period 1. In this case, the new world market price path that restores an intertemporal equilibrium also lies everywhere below the laissez-faire price path because, given the period-2-cap and the laissez-faire price path, the global stock would not be exhausted. Thus, given that the world market price in period 1 falls short of the respective laissez-faire price, global resource consumption in period 1 increases as no cap is imposed in this period. Compared to the laissez-faire equilibrium extraction path, some supply is shifted from period 2 to period 1. The fringe countries consume a larger resource flow in both periods and the coalition consumes a larger flow in period 1 compared to the laissez-faire case, while it consumes less in period 2 due to its cap. In the light of this result, the Green Paradox hypothesis will be discussed in more detail in the section after the next.

4.4 FIGHTING CARBON LEAKAGE?

As was shown in the preceding section, the incomplete climate coalition generally can unilaterally fight global warming by constraining its resource consumption today below the laissez-faire level while not constraining its consumption in the future. However, in any case, the effectiveness of the unilateral climate policy in slowing down the speed of global extraction is to some extent undermined by the fringe countries because they increase their consumption in response to the lower world market price for the resource. Policy measures seeking to support the unilateral climate policy would have to weaken the incentive of the fringe countries to absorb those resource quantities that the coalition refrains from in an arbitrary period whereby less carbon leaks into the fringe countries. This section discusses whether supplementing policies can actually achieve this goal.

Supplementing policies aiming to reduce the extent to which carbon leaks into the fringe countries in response to the unilateral climate policy would have to make sure that those resource quantities that the coalition refrains from in one period are not consumed by the fringe countries instead within the same period. Regarding carbon leakage that occurs via the channel of international trade in carbon intensive goods, import tariffs set by the incomplete coalition on carbon intensive goods that seek to reduce the coalition’s demand for carbon intensive imports produced in the fringe countries can in principle be an effective measure to reduce carbon leakage. However, such tariffs might easily conflict with WTO law and principles.[6] Generally, implementing import tariffs to protect certain, in this case, the carbon intensive industries from international competition would interfere with WTO law as such

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[6] Tariffs on carbon intensive goods to level the playing field are also discussed in the literature, cf. Lockwood and Whalley (2010), Boehringer et al. (2010) and Fischer and Fox (2012), among others.

tariffs discriminate foreign goods compared to those produced within the climate coalition. Article XX of the General Agreement on Tariffs and Trade (GATT) could provide a legitimation for the implementation of an import tariff if such a tariff satisfies the characteristics of an environmental exception stated there.[7] Exceptions (b) and (g) in Article XX respectively refer to the protection of “human, animal or plant life or health” and “to the conservation of exhaustible natural resources”. If these articles were applicable, they could allow for the implementation of import tariffs besides their discriminating nature. Nonetheless, whether one of the exceptions is applicable is subject to debate from a legal perspective.[8]

Unfortunately, regarding carbon leakage that occurs via the global resource market, as considered throughout the present analysis, the problem is that implementing an import tariff on carbon intensive goods that enter the coalition from outside does not stop the carbon from leaking into the fringe countries via the global resource market itself.[9] Although the import tariff set by the incomplete coalition might reduce the demand for the fossil resource in the fringe countries below the level that would prevail had the import tariff not been set, because the fringe countries potentially export less carbon intensive goods to the coalition under the tariff, such a tariff cannot stop the carbon from leaking into the fringe countries due to the lower world market price for the resource. The fringe countries increase their resource consumption in response to the unilateral policy as the policy pushes down the world market price below the resource price that would prevail in the absence of any policy, given the natural case of a downward sloping demand curve.

The European Union is aware of the fact that unilateral climate policy advances are limited regarding their ability to tackle the global warming problem due to the mechanism of carbon leakage.[10] Given the difficulties in quantifying carbon leakage, the European Commission states that: “Evidence gained so far from the emissions patterns of energy-intensive industries is inconclusive, in particular as to the extent EU climate policy has triggered the relocation of economic activity outside Europe.”[11] The European Commission also takes account of the disadvantages that its unilaterally pursued climate policy brings about for the energy-intensive industries that are exposed to international competition and it essentially sees three reasonable

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[7] General Agreement on Tariffs and Trade (GATT), 1986, pp. 37-8, Article XX, General Exceptions.

[8] Cf. de Cendra (2006) and Zane (2011) for two opposing views.

[9] Cf. Sinn (2012), p. 147, on this argument.

[10] European Commission, Analysis of options to move beyond 20% carbon emission reductions and assessing the risk of carbon leakage, Brussels, 2010.

[11] European Commission, Analysis of options to move beyond 20% carbon emission reductions and assessing the risk of carbon leakage, p. 11, Brussels, 2010.

measures to keep energy-intensive industries within the European Union competitive against the rest of the world, namely: the continuation of free emission allowances for energy-intensive industries; levelling the playing field via import tariffs on carbon intensive goods; and increasing the abatement effort of the non-EU countries. Unfortunately, the only effective way to reduce the extent to which carbon leaks into the fringe countries via the global resource market is seemingly by enlarging the coalition itself. Although the history of the international climate negotiations thus far has dampened expectations that a global climate coalition will be established soon, it remains the target. The prospects to achieve this goal are evaluated after the next section. Beforehand, the following section explains the Green Paradox hypothesis and its implications for the speed at which the global climate coalition needs to be established.

4.5 THE GREEN PARADOX HYPOTHESIS

Admittedly, one does not know whether and to what extent the unilateral policy advances of the European Union have influenced the almost increasingly rising global CO_2 emissions path depicted in figure 3.1, because the counterfactual laissez-faire emissions path is unknown. But this section discusses a possible explanation for the unbroken increasing trend in global CO_2 emissions: the Green Paradox hypothesis. The hypothesis has been introduced in Sinn (2008a,b, 2012) and it states that demand-reducing climate policies might actually achieve the opposite of what they intend, namely, that they might speed up extraction instead of slowing it down if they reduce the global demand for the resource over time too rapidly.

The relevance of the Green Paradox can be underlined by looking at the past. Figure 4.3 depicts the development of the price for crude oil, measured in 2013 US dollars, on the right abscissa and the development of the oil consumption of the four largest CO_2 emitters in 2012 plus the European Union, measured in million barrels daily, on the left abscissa. The graph reveals that after the oil crisis and the energy crisis in the mid- to late-1970s had lost their impacts, the development of the real oil price was more or less flat for the two decades from the mid-1980s until the beginning of the new millennium. Oil consumption has increased steeply over the past decades in China and India; for instance, China consumed 10.8 million barrels oil per day in 2013, which is 50 times its daily consumption back in 1965; while India’s daily oil consumption has increased by almost a factor of 15, from approximately 0.25 million barrels per day in 1965 to 3.7 million barrels per day in 2013.[12] For comparison, during the same time span, the US increased its daily consumption by approximately a factor

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[12] BP Statistical Review of World Energy, June 2014.

of 1.6, from about 11.5 million barrels to 18.9 million barrels. Overall, daily global crude oil consumption increased between 1965 and 2013 from 30.8 million barrels to 91.3 million barrels. Note that one reason behind the decrease in the EU's oil consumption from 14.8 million barrels per day in 2007 to 12.8 million barrels per day in 2013 could indeed be the first commitment period of the Kyoto protocol, which commenced in 2008.

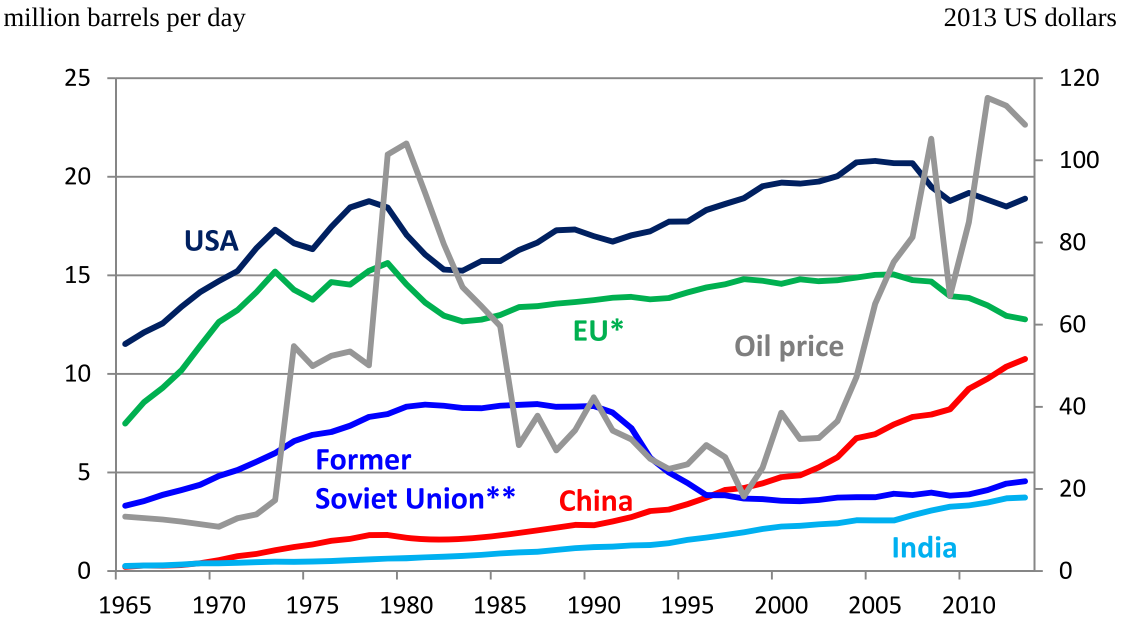

Figure 4.3: Development of crude oil consumption in million barrels per day of the four largest CO_2 emitters in 2012 and the EU and development of the crude oil price in 2013 US dollars.

Source: BP Statistical Review of World Energy, June 2014. *European members of the OECD plus Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Former Yugoslav Republic of Macedonia, Gibraltar, Malta, Romania, Serbia, Montenegro and Slovenia. Excludes Estonia, Latvia and Lithuania prior to 1985 and Slovenia prior to 1991. **Comprises Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russian Federation, Tajikistan, Turkmenistan and the Ukraine.

The Green Paradox hypothesis highlights that it is the intertemporal reaction of the resource supply side that, in addition to other factors, explains why the unbroken increasing trend in oil consumption was accompanied by a flat development of the real oil price, at least over the two decades from 1985 to 2005. Although an increase in global oil demand makes it rational for suppliers to increase supply as long as the resource price increases according to their intertemporal arbitrage condition that characterises the equilibrium on the global resource market, the Green Paradox hypothesis states that a deeper reason has incentivised resource owners to supply a larger global resource flow than what the increase in the global demand would have called for, thereby keeping the real world market price for oil below the level that would have otherwise prevailed.

The hypothesis is that if resource suppliers expect a climate policy in the future that sufficiently depresses the future world market price path for the resource, it is optimal for the representative supplier to respond to the policy by increasing supply in the present above the level that would have prevailed in the absence of any expected future climate policy. As discussed before, the representative competitive resource supplier can thereby reduce the present value of the total losses that she has to bear due to the policy compared to the laissez-faire case. Therefore, the gradual advances during the past international climate negotiations and, more importantly, the plans made to reduce global fossil resource demand in the future might have triggered an increase in present resource supply above what the increase in global demand would have called for, given that the resource owners around the world fear that an increasingly stricter future climate policy will severely reduce their future world market prices received for their resources.

The fear of future demand-reducing climate policies might have even triggered an intertemporal supply reaction sufficiently large in magnitude to keep the real oil price at a relatively low level, at least over the two decades from 1985 to 2005. If the forces of the Green Paradox are at work, the increase in present supply drives down the present world market price for the resource compared to the laissez-faire world market price whereby present global resource consumption increases above the laissez-faire level at the expense of future consumption. The implication for the environment is clear. A climate policy that provokes the Green Paradox accelerates the speed of global resource extraction and renders the global warming problem increasingly severe. The essential difference between a climate policy that provokes the Green Paradox and one that fights global warming is that the former implies higher global resource consumption in the present, while the latter policy implies higher global resource consumption in the future, although in both cases the world market price path that prevails under the policy lies everywhere below the laissez-faire resource price path. The following thought experiment shall clarify the mechanism underlying the Green Paradox hypothesis within the framework derived in Chapter 3.

Figure 4.4 again depicts the laissez-faire extraction path, the normative path and the path resulting under the unilateral open-loop unit tax in R_i, R_{-i}, S space under the assumptions that the coalition and the fringe countries exhibit the same constant price elasticity of demand and that demand is independent of calendar time. As before, it is furthermore assumed that extraction costs are negligible. Despite the Green Paradox path, all depicted paths have been derived in section 3.6 of the foregoing chapter. The different starting points reflect the initial resource flow consumed within the incomplete coalition, R_i, and the resource flow consumed in the fringe countries, R_{-i}, which are compatible with the respective equilibrium conditions in the different scenarios and the requirement that all paths must lead to the terminal point $S = 0$. As time goes by, the global resource stock in situ is depleted and the global resource flow converges to zero in all cases given the assumptions made.

In order to derive the Green Paradox extraction path depicted in figure 4.4, suppose that the incomplete climate coalition implements a unilateral unit tax $\tau_i(t)$ on resource consumption that changes over time according to the equation of motion $\dot{\tau}_i(t) = r\tau_i(t) + Y$ where Y is a positive, constant and finite number. The unilateral unit tax thus increases in present value terms and thereby reflects the idea behind the Green Paradox, namely, that the increasing occurrence of heat waves, storms and droughts is likely to increase the public pressure on politicians to fight global warming by severely tightening the climate policy measures over time. Essentially, if the unit tax $\tau_i(t)$ is interpreted as the absolute vertical downward shift of the coalition's inverse demand curve in period t compared to the case that this curve would have in the absence of any policy, any mix of policy measures, including subsidies on renewable energy or bio fuels, which induces the same time-path of vertical downward shifts of the coalition's demand curve over time as the considered tax would trigger the same intertemporal supply reaction. The argument is thus again not limited to a unilateral unit tax on resource consumption.

The direction of movement for a point in R_i, R_{-i}, S space that characterises the equilibrium extraction path under the considered unilateral unit tax can be derived analogously to the path that results under the unilateral open-loop unit tax, which has been derived in section 3.6 in the foregoing chapter. The same equilibrium conditions as for the unilateral unit tax scenario considered there also apply here, aside from the fact that the unilateral tax now develops over time according to the equation of motion $\dot{\tau}_i(t) = r\tau_i(t) + Y$. Given the assumption that the incomplete coalition and the fringe countries exhibit the same constant price elasticity of demand and that demand is independent of calendar time, the direction of movement for a point in R_i, R_{-i}, S space under the unilateral unit tax that increases in present value terms is defined by

$$\frac{dR}{dS} = \varepsilon\left[r + \beta\frac{Y}{P_i(R_i)}\right] \quad (4.1)$$

where ε is the absolute value of the price elasticity of global demand and where $\beta = \frac{R_i}{R_i+R_{-i}}$ is the incomplete coalition's share in global resource consumption along the equilibrium extraction path under the considered tax. Furthermore, $P_i(R_i)$ is the downward sloping inverse demand function of the incomplete coalition. As shown in Appendix A3.1 to Chapter 3, the Green Paradox equilibrium path that satisfies equation (4.1) must lead to the terminal point $S = 0$ because the price elasticity of demand of both groups is bounded by assumption.

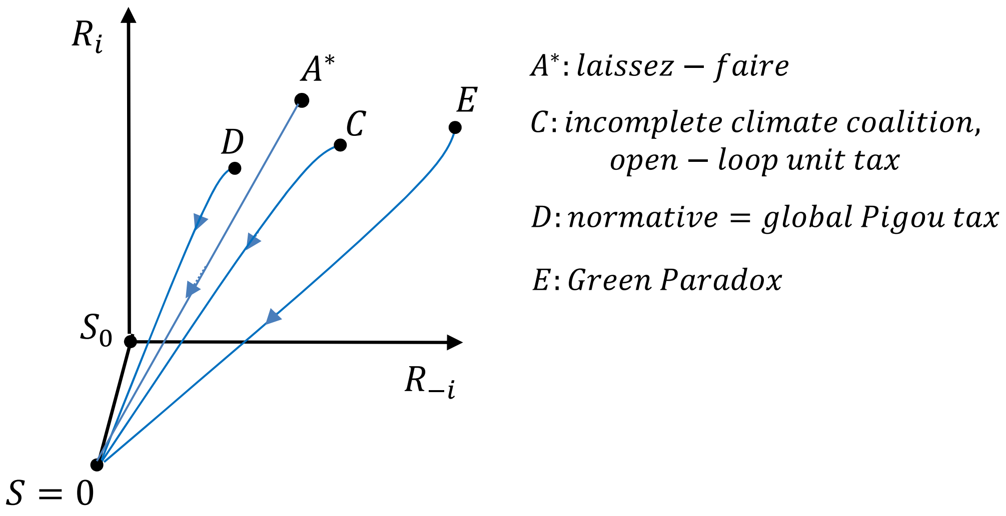

Figure 4.4: Resource extraction paths: laissez-faire, unilateral open-loop, normative and Green Paradox scenario.

In contrast to the case in which the unilateral unit tax declines in present value terms, equation (4.1) defines a steeper direction of movement for each point in R_i, R_{-i}, S space compared to the laissez-faire case, which in the case of zero extraction costs is defined by equation

$$\frac{dR}{dS} = \varepsilon r \quad (3.77)$$

as derived in section 3.6 in the foregoing chapter. In fact, any unilateral unit tax on resource consumption that grows at a rate that exceeds the market rate of interest implies an extraction path that lies everywhere above the laissez-faire path in figure 4.4, given the assumptions that the coalition and the fringe countries exhibit the same constant value of price elasticity of demand and that demand is independent of calendar time. Under such a tax, the global resource flow extracted for a given stock level in situ must exceed the respective laissez-faire flow as long as the incomplete coalition consumes a positive flow, which is the case along the entire equilibrium extraction path because the coalition's price elasticity of demand is bounded by assumption. Note that though this section abstracts from extraction costs, this result also holds in the presence of stock-dependent unit extraction costs, as follows from the analysis in section 3.4.1 of the foregoing chapter.

Because the world market price under the tax must lie everywhere below the laissez-faire resource price to guarantee exhaustion of the stock, the fringe countries increase their resource consumption in response to the tax. This implies that the starting point of the Green Paradox path is shifted to the right compared to the laissez-faire starting point A^*. Moreover, the Green Paradox path depicted in figure 4.4 presumes that the initial resource flow consumed by the coalition falls short of its initial laissez-faire consumption. This is only one possibility. It is also possible that the coalition increases its initial resource consumption above the laissez-faire level. This would be the case if the unilateral tax would trigger an intertemporal supply shift from the future to the present that is sufficiently large to reduce the consumer price within the coalition below the laissez-faire price. In any case, the initial global resource flow supplied under the tax must exceed the initial global laissez-faire flow to make the equilibrium path compatible with equation (4.1) and the requirement that the path must lead to the terminal point $S = 0$. The Green Paradox path, which starts in point E in figure 4.4, meets these criteria. In terms of calendar time, present resource supply is increased above the laissez-faire level at the expense of future supply, thereby speeding up the process of global warming compared to the laissez-faire case. Under the tax, both the incomplete coalition and the fringe countries purchase the resource at a lower world market price along the entire equilibrium extraction path, although the unilateral unit tax that increases in present value terms is detrimental for the environment because it accelerates the speed of global resource extraction instead of slowing it down.

In general, the Green Paradox can result if climate policy measures reduce global demand for the resource too rapidly over time. Such policy paths are, unfortunately, likely to occur in reality where the set of feasible policy paths is often constrained by societal and democratic constraints. In Sinn (2008a,b, 2012) it is stressed that it is probably difficult to implement demand-reducing policies that only slowly reduce demand over time when the process of global warming leads to heavier storms, floods and more severe droughts as time proceeds. What is important to note is that the Green Paradox is not limited to a specific set of instruments or measures.[13] In principle, any demand-reducing policy can incentivise the

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[13] Cf. Sinn (2008a, b, 2012) and especially Sinn (2008a), p. 381-2.

resource suppliers to anticipate extraction from the future to the present compared to their original extraction plan if these policies reduce the global demand for the fossil resource sufficiently quickly over time. Precisely, as follows from the Long-Sinn invariance theorem, if they decrease global demand sufficiently quickly over time to induce a wedge between the laissez-faire resource price and the hypothetical world market price that would prevail under the policy if the supply side would stick to the laissez-faire extraction path that increases in present value terms.

A significant literature body investigating the conditions under which the Green Paradox can occur has been established over recent years. Di Maria and van der Werf (2012b) structure this literature and provide an overview. The papers distinguish different channels via which the Green Paradox can be triggered: due to suboptimal carbon taxes, cf. Hoel (2012) and Edenhofer and Kalkuhl (2013), due to the subsidisation of a substitute for the resource or the introduction of carbon capture and storage, cf. Hoel (2008), Grafton et al. (2010), Hoel and Jensen (2010), Hoel (2011a,b), Gerlagh (2011), van der Ploeg and Withagen (2012b) and Nachtigall and Rübbelke (2013), as well as due to climate policy announcement effects and the anticipation of backstops, cf. Strand (2007), Smulders et al. (2012) and Di Maria et al. (2012a). The literature also finds that the abundance of coal might weaken the forces of the Green Paradox, cf. van der Ploeg and Withagen (2012a) and Michielsen (2014). However, literature discussing carbon leakage and the intertemporal supply decision of the fossil resource supply side simultaneously is rather rare, including, to the author’s knowledge, Sinn (2008a,b, 2012), Eichner and Pethig (2011, 2013), Hoel (2011b) and Ritter and Schopf (2013).

Abstracting from extraction costs and assuming that a perfect backstop technology for the resource is available at a constant cost, Hoel (2011b) finds that if a country that initially exhibits a lower carbon tax than another country increases the level of its tax, a Green Paradox occurs if the price elasticity of demand for the resource plus substitute, which is identical for both countries, is sufficiently low. In a two-period general equilibrium model, Eichner and Pethig (2011) consider an incomplete climate coalition that constrains its consumption in period 1 and 2 and faces competitive suppliers and passive fringe countries. The authors investigate how tightening the coalition’s unilateral cap in either period 1 or 2 affects the extraction speed compared to the benchmark equilibrium. Ritter and Schopf (2013) extend this model for stock-dependent unit extraction costs whereby the global resource stock is not necessarily exhausted in any case. The basic conclusion is that in these general equilibrium frameworks, the speed of global resource extraction can increase compared to the benchmark equilibrium irrespective of whether the unilateral cap is tightened in period 1 or in period 2. As demonstrated in section 4.3, the two-period partial equilibrium nature of the present analysis allows for unambiguous results in the sense that tightening (loosening) the period-2-cap unambiguously speeds up (slows down) extraction compared to the equilibrium path that would result under a given time-path of caps, irrespective of whether the benchmark caps itself would speed up or slow down the speed of extraction compared to the laissez-faire case. In contrast, it was also shown that tightening (loosening) the period-1-cap slows down (speeds up) extraction compared to the benchmark equilibrium. Eichner and Pethig (2013) furthermore show in a two-period general equilibrium model that the cost-effective policy in the case of global cooperation is characterised by a uniform emission tax levied in the first period only. Moreover, in the case of an incomplete climate coalition where the countries inside and outside the coalition are symmetric, aside from the size of the resource stock they own, the authors find that the cost-effective unilateral policy carried out by the incomplete coalition requires that emissions are regulated in both periods.

Aside from Sinn (2008a), the papers mentioned that analyse how demand reductions undertaken by a subgroup of the world's countries affect the speed of global resource extraction abstract from the possibility that the demand for the resource may also depend on calendar time. The present analysis shows that the principle time-dependence of demand is important to consider, in particular, if the demand of the incomplete coalition and the fringe countries grows or shrinks at a different rate over time for exogenous reasons. Also, it appears that the price elasticity of resource demand plays a prominent role for the success of a unilateral climate policy in fighting climate change if the incomplete coalition and the countries outside the coalition exhibit different price elasticities of demand. As follows from section 3.4 in the foregoing chapter, it is the growth rate of the absolute vertical downward shifts of the coalition's inverse demand curve over time compared to the laissez-faire position of this curve, for instance induced by a unilateral unit tax on resource consumption, which determines the intertemporal reaction of the resource supply side if both groups have the same constant price elasticity of demand, if the demand of both groups grows or shrinks at the same rate over time for exogenous reasons and if extraction costs are negligible. Unfortunately, if these assumptions fail to be valid, an incomplete climate coalition that seeks to slow down the speed of global extraction certainly needs to be all the more careful in reducing its demand unilaterally over time. If the coalition and the fringe countries exhibit different price elasticities of demand, the effect of the unilateral demand reductions undertaken by the incomplete coalition on the speed of global resource extraction also hinges on the change in the weighted average of the groups' price elasticities of demand (weighted by their shares in global resource consumption) that the coalition's demand reductions bring about. This was shown in section 3.4.1 in the former chapter. In addition, section 3.4.2 revealed that similar difficulties in evaluating the effect of unilateral demand reductions on the global speed of extraction arise if the resource demand within the fringe countries grows or shrinks more quickly over time for exogenous reasons than that of the incomplete coalition.

As was explained within the two-period framework in section 4.3, a fool-proof rule for the incomplete climate coalition to shift some resource supply from period 1 to 2 by unilaterally reducing its consumption is to constrain its consumption in period 1 while not constraining it in period 2. Unfortunately, following the same logic, the incomplete coalition would in turn trigger the Green Paradox by not constraining its emissions in period 1 while constraining them in period 2. Under the new, lower world market price path that would restore an intertemporal equilibrium, both the coalition and the fringe countries would increase their resource consumption above their respective laissez-faire levels in period 1, thereby worsening the global warming problem. Furthermore, the incomplete coalition would speed up extraction compared the speed that would result under a given time-path of binding unilateral emission caps if it would either tighten the period-2-cap or loosen the period-1-cap compared to the original benchmark caps. To the disfavour of the climate, both cases are probably more likely to occur in reality than the case in which the coalition would only constrain its consumption today and not in the future. Regarding an effective real world climate policy, it has become apparent that a major challenge for any demand-reducing policy is not to make present resource extraction relatively more attractive for the supply side than future extraction. In this light, the next section discusses one exception in which the Green Paradox can no longer occur.

4.6 TOWARDS A CAP ON GLOBAL CARBON EMISSIONS

Chapter 2 has demonstrated that the target from an intertemporal efficiency perspective shall be to reach a global climate coalition that comprises all countries. In the time-consistent solution, the global climate coalition internalises the global warming externality that the combustion of each resource unit over time induces. This section demonstrates how the global coalition can implement the Pareto efficient intertemporal resource allocation by directly constraining the global resource flow over time to the efficient level. This is equivalent to presuming that the coalition imposes binding caps on global CO_2 emissions over time, thereby constraining the globally consumed resource flow to the efficient level.

Figure 4.5 depicts the situation for the simplified two-period world considered in this chapter. The width of the box corresponds to the global resource stock in situ S. The global resource flow supplied and consumed in period 1 is denoted by R_1 and it is depicted on the abscissa from the left to the right. Respectively, the resource flow supplied and consumed in period 2, denoted by R_2, is depicted from the right to the left. The global demand for the resource in period 1 is depicted by the inverse demand curve $P(R_1)$ and the global demand in period 2 is depicted by the inverse demand curve $P(R_2)$. The laissez-faire equilibrium is characterised by point 0_1 in period 1 and point 0_2 in period 2. The global laissez-faire resource flow in period 1 is $R_{0,1}$ and the laissez-faire resource flow in period 2 is $R_{0,2} = S - R_{0,1}$. The laissez-faire resource price in period 1 is P_1 and the price in period 2 is P_2. The representative resource supplier supplies a resource flow over time whereby the laissez-faire equilibrium price increases according to her intertemporal arbitrage condition $P_1(1 + r) = P_2$. Because demand is assumed to be independent of calendar time, the supplied resource flow in period 1 exceeds the flow supplied in period 2.

It is subsequently explained that the global climate coalition can dictate the Pareto efficient intertemporal resource allocation by simply constraining the global resource flow in period 1 to the Pareto efficient level. Let the efficient resource flow in period 1 be depicted by $R_{A,1}$ while the respective cap that constrains the global resource flow is indicated by the branch that cuts the global inverse demand curve $P(R_1)$. Because the price elasticity of global demand is bounded, the global stock must be exhausted in equilibrium. Hence, the global cap that constrains resource consumption in period 1 also determines global consumption in period 2. The resource flow consumed in period 2 is thus given by $S - R_{A,1}$. Given the global cap in period 1, the consumer price P_1^C that all consumers in the world pay in period 1 is determined by point A_1, while the consumer price P_2^C that prevails in period 2 is determined by point A_2. Compared to the laissez-faire case, the extraction of the quantity $R_{0,1} - R_{A,1}$ is delayed in time from period 1 to 2. This is the intertemporal consumption shift necessary to restore intertemporal efficiency.

Because future supply is increased at the expense of present supply under the cap, the consumer price P_1^C must exceed the respective laissez-faire price P_1 in period 1 while in period 2, the consumer price P_2^C falls short of the laissez-faire price P_2. As the cap reduces global demand compared to the laissez-faire case, the world market price path along the Pareto efficient extraction path must fall short of the laissez-faire price path to guarantee exhaustion of the global stock.

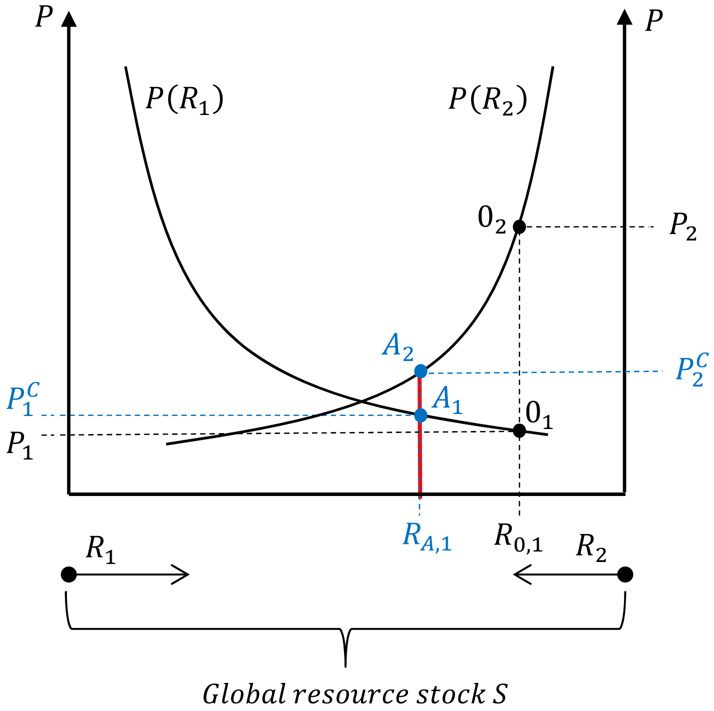

Figure 4.5: Global cap on emissions that implements the normative intertemporal resource allocation.

Recall that if extraction costs are zero or constant, the resource rent that the representative supplier receives in the laissez-faire case in period t is given by $\lambda(t) = \lambda_0 e^{rt}$ (3.46) where $\lambda_0 = \lim_{t\to\infty} e^{-rt}\lambda(t)$. Hence, by announcing that it will not pay more than the unit extraction costs for the terminal resource unit, the global climate coalition can drive the rent on the terminal resource unit and thereby the entire rent trajectory to zero in this case.[14] The price received by the suppliers would thus equal the constant unit extraction costs in every period. However, if the unit extraction costs increase as the resource stock in situ is depleted, the supply side obtains some resource rent. This has been discussed in Chapter 2 where it was demonstrated that in the presence of stock-dependent unit extraction costs, and given the assumption that the coalition cannot discriminate the price of the single resource unit, the coalition has to pay the differential rent to the supply side while the representative supplier supplies a resource flow over time such that she is indifferent between selling another resource unit today or tomorrow along the equilibrium extraction path.

Although both a unit tax on global resource consumption and a time-path of caps on global emissions can similarly implement the Pareto efficient intertemporal resource allocation, directly controlling the global resource flow by capping global emissions over time has a

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[14] Cf. also Dasgupta and Heal (1979), 334-6 and Karp (1984), p. 74-5, on this argument.

major advantage against a unit tax in the light of the Green Paradox hypothesis. As emphasised in Sinn (2008a,b, 2012), the advantage of directly controlling the consumed resource flow over time by setting global emission caps is that the Green Paradox is certainly avoided, irrespective of how quickly increasingly tighter emission caps actually reduce the global demand for the resource over time.[15] Directly controlling the consumed resource flow over time via a cap on global emissions implies that the cap constitutes a binding global consumption constraint in each period. Regardless of how rapidly the cap on global emissions is tightened over time, suppliers are unable to sell a larger resource flow than what the cap allows for in each period. The suppliers can no longer sell off their resource stocks today in the fear of increasingly tighter caps in the future once the global emissions path is dictated by a global cap. Therefore, a Green Paradox outcome is no longer possible if the climate coalition comprises all countries. As soon as the coalition is incomplete, this advantage obviously vanishes.

As the global climate coalition can implement the Pareto efficient resource extraction path by directly dictating the global resource flow over time, reaching a global climate coalition remains the target from an intertemporal efficiency perspective. As in the present situation the existing climate coalition is incomplete, the coalition obviously must grow over time in terms of its member countries to reach this target. What has been spared in the discussion is the necessary transition process from an incomplete to a global climate coalition. The status of the current Kyoto process confirms that reaching a global climate coalition comprising all countries will take time. For the time being, the reality is that among the world's 20 largest CO_2 emitters only the EU member countries and Australia are committed to reduce their emissions.

Recommending a climate policy for the transition phase from an incomplete to a global climate coalition is a difficult task and it is beyond the scope of this analysis. However, what has become apparent is that irrespective of the reason for which the global fossil resource demand is reduced over time, whether due to carbon taxes or subsidies on renewable energy or emission caps, it is the speed at which the global demand is reduced over time, which matters for the intertemporal reaction of the supply side. Unfortunately, as Sinn (2008a,b, 2012) stresses, an incomplete climate coalition that gradually grows in terms of its member

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[15] The advantage that the Green Paradox can be avoided by directly regulating the global resource flow over time is arguably one of many aspects that one has to consider when comparing price and quantity instruments, but it is seemingly an important one. Edenhofer and Kalkuhl (2014) formally compare price and quantity instruments to regulate carbon consumption and the authors also discuss the informational requirements of different instruments.

countries has exactly the potential to reduce the global demand for the resource sufficiently quickly over time to trigger the Green Paradox. If one reasonably presumes that the joining countries will have to reduce their resource consumption below their laissez-faire levels when joining the coalition, global demand will be reduced over time as the coalition grows. Thus, in order to avoid a long phase in which the resource suppliers sell off their resource stocks in the present because they fear increasingly larger reductions in global resource demand in the future due to a growing climate coalition, the global community needs to impose a cap on global CO_2 emissions as quickly as possible. If this is not possible, the global community would, according to the Long-Sinn invariance theorem, at least have to convince the supply side that the global fossil resource demand will be reduced over time very slowly compared to the global laissez-faire demand whereby the wedge that the demand reductions drive between the laissez-faire resource price and the hypothetical world market price that would prevail did the supply side not react to these demand reductions always decreases in present value terms. However, it is probably difficult to convince the supply side that the global demand for the resource will be reduced only very slowly over time if the global warming problem becomes increasingly severe.

Currently, various initiatives of countries and regions to progressively constrain their CO_2 emissions by implementing unilateral caps can be observed all over the world. The most prominent example of a regional emission trading system is probably the European Union Emission Trading System (EU ETS). The system became operative in 2005 and started with an experimental testing phase. In 2008, the Kyoto reduction targets became binding and the system currently covers approximately 45 per cent of all greenhouse gas emissions emitted by the European Union.[16] It includes energy-intensive industries and power plants. Since 2012, also flight operators have to submit an emission permit per tonne of CO_2 emitted during any flight from, to and within the European Union.[17] The target for the first commitment period, which ended in 2012, has been to reduce greenhouse gas emissions within the EU by 8 per cent compared to 1990 levels. The target for the second commitment period is to reduce greenhouse gas emissions within the EU by 20 per cent by 2020 compared to 1990 levels. Achieving this target requires tightening the total emission allowance over time. Therefore, the cap will be tightened during the second commitment period by 1.74 per cent annually.

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[16] European Commission, October 2013, http://ec.europa.eu/clima/policies/ets/.

[17] Commission Decision of 30 June 2011 on the Union-wide quantity of allowances referred to in Article 3e(3)(a) to (d) of Directive 2003/87/EC of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowances trading within the Community, Brussels, June 2011. European Commission, The EU Emissions Trading System, August 2013, http://ec.europa.eu/clima/policies/ets/index_en.htm.

Switzerland, which had a share in global CO_2 emissions of 0.13 per cent in 2012, also adopted the common EU target to reduce greenhouse gas emissions by 20 per cent by 2020 compared to 1990 levels.[18] The chosen instrument is also a cap-and-trade system in which participation has been mandatory for large CO_2 emitters since 2013, while participation of smaller emitters remains voluntary. The system currently covers 55 large emitters from energy-intensive industries.[19] Companies can also use emission permits obtained via the UN trading scheme to meet their obligations. Similar to the EU ETS, the total emissions allowance will be reduced by 1.74 per cent annually.

As part of its Clean Energy Bill, Australia, which was responsible for 1.2 per cent of global CO_2 emissions in 2012, introduced a carbon tax of 23 AUD per tonne of CO_2 in July 2012.[20] However, the tax was abolished two years later in July 2014.[21] Nevertheless, Australia's target remains to reduce its greenhouse gas emissions by 5 per cent until 2020 in comparison to 2000 levels. The tax was abolished to keep the Australian economy competitive internationally and lower the living costs for households. Australia's neighbouring country New Zealand, which exhibited a share of 0.1 per cent in global CO_2 emissions in 2012, has introduced a price on carbon in all sectors besides agriculture.[22] New Zealand has the target of reducing its greenhouse gas emissions by 5 per cent by 2020 compared to 1990 levels and the country would increase this target up to 20 per cent conditional on the establishment of a global agreement. The long-term goal is to reduce the country's emissions by 50 per cent by 2050 compared to 1990 levels. Entities under regulation are obliged to hand in emission permits according to their duty, while emission permits can be purchased either on the international market via the UN trading scheme or from the New Zealand government at a fixed price of 25 NZD.[23] The system thus has a flexible cap, given that the number of permits sold by the New Zealand government is not constrained. Furthermore, some energy-intensive sectors have to hand in only one emission certificate for two tonnes of CO_2 released. New Zealand is willing to link its domestic trading scheme with other emerging schemes and establish a trans-regional scheme for the Asia-Pacific region.

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[18] Bundesgesetz über die Reduktion der C02-Emissionen (C02-Gesetz), Bundesversammlung der Schweizerischen Eidgenossenschaft, Dezember 2012. CO2 Emissions from Fuel Combustion (2013 Edition), IEA, Paris.

[19] Federal Office for the Environment, Schweizerische Eidgenossenschaft, 2014, http://www.bafu.admin.ch/emissionshandel/index.html?lang=en.

[20] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[21] Parliament of Australia, Clean Energy Bill 2011. Australian Government, Department of the Environment, August 2014, http://www.climatechange.gov.au/.

[22] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[23] Ministry for the Environment, New Zealand Climate change information 2013, http://www.climatechange.govt.nz/.

South Korea has a target of reducing its greenhouse gas emissions by 30 per cent by 2020 compared to the business-as-usual projections. The instrument to achieve this goal is a cap-and-trade system, which is expected to be launched in 2015 and is estimated to cover 70 per cent of the country's total carbon emissions. South Korea had a share of 1.9 per cent in global CO_2 emissions in 2012.[24] Another example of a regional emission trading system is the one introduced in the metropolitan region of Tokyo. Following the fashion of the EU ETS, the Tokyo Cap-and-Trade programme was the first emission trading scheme in Asia. In terms of CO_2 emissions, the Tokyo metropolitan region ranks along with Sweden and Norway, which themselves exhibited shares in global CO_2 emissions in 2012 of 0.13 and 0.11 per cent, respectively.[25] The mandatory scheme, which became effective in 2010, captures large greenhouse gas emitters in the Tokyo metropolitan area and is managed by Tokyo's Metropolitan Government. For the first compliance period from 2010 to 2014, the target is to reduce greenhouse gas emissions of the participating facilities by 6 per cent compared to the base-year emissions of a certain facility, representing an average of the past emissions of this facility.[26] For the subsequent period from 2015 to 2019, the cap is planned to be tightened to reach a reduction of 17 per cent of the participant's emissions compared to the respective base-year emissions.

Although these developments spur some hope, the world's major CO_2 emitters, except for the European Union, namely China, the US, India, Russia and Japan, have neither set out binding emission reduction targets under the Kyoto protocol nor have they undertaken significant voluntary efforts to reduce their emissions to date. In the US, which exhibited a share of 16 per cent in global CO_2 emissions in 2012, three regional initiatives to reduce CO_2 emissions are underway, but progress is made only gradually. The Regional Greenhouse Gas Initiative (RGGI) launched in 2009 is an attempt of nine states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont) to cap their CO_2 emissions. Until 2020, the annual cap of 91 million tonnes CO_2 imposed in 2014 is supposed to be reduced by 2.5 per cent annually.[27] Another regional initiative to cap emissions is the Western Climate Initiative (WCI), which initially comprised several states in the US and Canada. The initial common goal was to reduce CO_2 emissions of the participants

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[24] White Paper, Bloomberg New Energy Finance in cooperation with Ernst & Young Korea, 2013. CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[25] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[26] Bureau of Environment, Tokyo Metropolitan Government, Tokyo Cap-and-Trade, August 2014, http://www.kankyo.metro.tokyo.jp/en/.

[27] Regional Carbon Initiative, February 2013, www.rggi.org/, Summary of RGGI Model Rule Changes.

by 15 per cent by 2020 compared to 2005 levels.[28] However, the coalition more or less fell apart. Up to the present, the only significant action based upon this initiative is undertaken in California. As a member of the WCI, California has had a cap-and-trade system in place since 2012, while the period of mandatory compliance started in 2013. Operators of industrial facilities are obliged to participate in the California emission trading system, as well as electricity, gas, fuel oil and carbon dioxide suppliers.[29] The annual emissions allowance, which is set to about 2 per cent below the 2012 emissions level, will be reduced by about 3 per cent annually. California's long-term target is to reduce its CO_2 emissions by 80 per cent by 2050 compared to 1990 levels.

The Republic of China has the voluntary target to reduce its CO_2 emissions intensity per unit of GDP by 40 to 45 per cent by 2020 compared to 2005 levels. With a share of 25.9 per cent in global CO_2 emissions in 2012, China is one of the heavyweights regarding the fight against global warming.[30] In June 2013, China launched the first pilot project for a mandatory CO_2 emission trading scheme in Shenzhen with approximately 800 participating companies.[31] Six further pilot projects in Beijing, Tianjin, Shanghai, Guangdong, Chongqing and Hubei have subsequently been launched. The seven projects are supposed to cover around 700 million tonnes of CO_2 emissions by 2014, which amounts to approximately 9 per cent of China's total CO_2 emissions in 2011. The pilot projects exhibit different reduction targets and vary regarding their design in some respects because the Chinese government is keen to find a proper role model for the design of a national carbon market in the future. The major sectors included differ across projects to some extent, although the focus lies on electricity generators and energy-intensive industries. A nationwide roll-out of the programme is planned, but it remains to be seen when this will happen.

In 2008, the government of India released the National Action Plan on Climate Change, which sets out various targets including, among others, increasing energy efficiency and solar energy generation, enhancing the security of water supply and making agriculture sustainable.[32] India exhibited a share of 6.2 per cent in global CO_2 emissions in 2012.[33] As part of the 2009 Copenhagen Accord, India pledged to voluntarily reduce its CO_2 emissions

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[28] Western Climate Initiative, Statement of Regional Goal, August 2007.

[29] California Air Resources Board, August 2014, http://www.arb.ca.gov/homepage.htm.

[30] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[31] The Climate Institute, First pilot emission trading scheme in China kicks off Media Brief, June 2013. Environomist Ltd., China Carbon Market Research Report 2014, August 2014, http://www.southpolecarbon.com/public/140227_Environomist_China-ETS_ResearchReport.pdf.

[32] National Action Plan on Climate Change, Government of India, Prime Minister's Council on Climate Change, 2008.

[33] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

per unit of GDP by 20 to 25 per cent by 2020 compared to 2005 levels.[34] The country seeks to achieve this goal via its 'Perform, Achieve and Trade' scheme for energy efficiency.[35] Via this scheme, the government sets mandatory, facility-specific energy conservation targets.[36] Participants receive energy saving certificates if they over-accomplish their conservation obligation and they can buy certificates if they fail to meet their obligation. These certificates can be traded between the participants. The system includes the aluminum, iron and steel, cement, pulp and paper and the textile industries, as well as thermal power plants.[37] On average, the facility-specific target is to reduce energy consumption per unit of production by 4.2 per cent by 2015 compared to the average of the past energy consumption per unit of production from 2007 to 2009. The first commitment period from 2012 to 2015 comprises 478 plants.[38]

In line with Japan and Canada, Russia refused to accept a binding emission reduction target for the second commitment period under the Kyoto protocol. Russia, which had a share of 5.2 per cent in global CO_2 emissions in 2012, has a voluntary target to reduce its CO_2 emissions between 15 and 20 per cent by 2020 compared to 1990 levels, as documented in the 2009 Copenhagen Accord.[39] However, ambitions towards a national cap on total emissions are not in sight. Moreover, with a share of 3.9 per cent in global emissions in 2012, Japan has no binding emission reduction target, although it pledged a 25 per cent reduction compared to 1990 levels conditional upon an international agreement that comprises the world's major economies, also in Copenhagen in 2009.[40] However, referring to the Fukushima catastrophe in 2011, the government announced by the end of 2013 that it would now strive to reduce emissions by 3.8 per cent by 2020 compared to 2005 levels.[41] With a share of 1.7 per cent in

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[34] United Nations Framework Convention on Climate Change, Copenhagen Accord 2009, Appendix I, Quantified economy-wide emissions targets for 2020.

[35] Climate and Development Knowledge Network, Creating market support for energy efficiency: India's Perform, Achieve and Trade Scheme, January 2013, http://cdkn.org/resource/creating-market-support-for-energy-efficiency-indias-perform-achieve-and-trade-scheme/.

[36] The legal base to set out targets to increase the energy efficiency was introduced in 2001 via the Energy Conservation Act. The Energy Conservation Act, 2001, Ministry of Law, Justice and Company Affairs, New Delhi, September 2001.

[37] Bureau of Energy Efficiency, Ministry of Power, Government of India, PAT Consultation Document 2010-11, January 2011.

[38] Press Information Bureau, Government of India, Union Power Minister Launches "PAT" Scheme under NMEEE Energy Intensive Industries to Benefit by Trading ESCerts Energy Saving of 6.6 million tonnes oil equivalent by 2014-15, July 2012, http://www.pib.nic.in/newsite/erelease.aspx?relid=85182.

[39] United Nations Framework Convention on Climate Change, Copenhagen Accord 2009, Appendix I, Quantified economy-wide emissions targets for 2020. CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[40] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[41] The New York Times, November 2013, http://www.nytimes.com/2013/11/16/world/asia/japan-shelves-plan-to-slash emissions-citing-fukushima.html?pagewanted=all&_r=0.

global emissions, Canada withdrew from the Kyoto protocol in December 2011 due to the protocol not being effective in fighting climate change.[42]

As part of its National Climate Change Plan, Brazil has the voluntary goal to reduce its CO_2 emissions between 36.1 and 38.9 per cent by 2020 compared to 1990 levels.[43] Brazil accounted for 1.2 per cent in global CO_2 emissions in 2012.[44] Besides several initiatives with respect to enhance energy efficiency and to counteract deforestation, the Brazilian Market for Emissions Reduction, which became operational in 2005, has been established. As part of the National Climate Change Plan, this market provides the base for the international trade of those carbon credits that projects undertaken as part of the Clean Development Mechanism generate.[45] The Clean Development Mechanism is defined in Article 12 of the Kyoto protocol and it provides countries with an emission target under the protocol the possibility to meet their obligation by reducing emissions in the developing countries rather than domestically.[46]

Kazakhstan, exhibiting a share of 0.7 per cent in global CO_2 emissions in 2012, launched an emission trading system in 2013 that covers carbon emissions from a variety of sectors including manufacturing, energy, mining, transportation, agriculture, as well as the metal and chemical industry, thereby covering approximately 80 per cent of the country’s total carbon emissions.[47] The first phase of full compliance is scheduled to start in 2014 and it will last until 2020. Also, Mexico with a share of 1.3 per cent in global CO_2 emissions in 2012 has set out the legal route to cap its emissions at some point in the future via its General Law on Climate Change, which was introduced in April 2012 and states the country’s voluntary goal of reducing emissions by 30 per cent by 2020 and 50 per cent by 2050, compared to 2000 levels.[48] Similarly, Taiwan with a share of 0.8 per cent in global emissions in 2012 aims to reduce its greenhouse gas emissions by 50 per cent by 2050 compared to 2000 levels and the

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[42] Government of Canada, August 2014, http://www.ec.gc.ca/Publications/default.asp?lang=En&n=EE4F06AE-1&xml=EE4F06AE-13EF-453B-B633-FCB3BAECEB4F&offset=3&toc=show.
CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[43] Government of Brazil, Interministerial Committee on Climate Change, Executive Summary, National Plan on Climate Change, Brasília, 2008. The voluntary emission reduction target is confirmed in Law No. 12.187, December 2009.

[44] CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[45] International Business Structuring Association, Carbon Emissions Trading Brazil, October 2013, http://www.istructuring.com/knowledge/article/carbon emissions-trading-brazil/.

[46] United Nations, Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1998, Article 12.

[47] Emissions trading schemes around the world, Parliament of Australia, Department of Parliamentary Services. CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

[48] Ley General De Cambio Climático, Secretaría General, Secretaría de Servicios Paralmentarios, Mexico, June 2012. CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

country plans to regulate emissions via an emission trading scheme following the example of the European Union.[49]

The basic message underlying these developments is twofold. On the one hand, the regional initiatives undertaken are fortunate because they underline the ambitions of these regions to fight global warming. On the other hand, gradually establishing regional caps on emissions, which are planned to be tightened over time, offers exactly the potential to set the forces of the Green Paradox into motion. In fact, the planning of the cap-and-trade systems to be implemented around the world in the future implies that the future global fossil resource demand will be evermore reduced compared to the laissez-faire case as time proceeds. Admittedly, the major players who actually determine the global resource demand have not yet adopted any binding emission reduction targets nor have they implemented noteworthy regional caps on CO_2 emissions. But if the resource suppliers expect that these countries will also reduce their resource consumption below their laissez-faire consumption levels in the future, they will anticipate extraction from the future to the present if the expected demand reductions are sufficiently large. Ultimately, it is the speed at which the global community manages to impose a binding cap on global emissions that holds essential importance to effectively fight global warming. The global community has to secure the heavyweights in global carbon consumption into a system of binding emission constraints, not gradually but rather immediately.

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[49] Government of Taiwan, Environmental Protection Administration, Greenhouse Gas Reduction Management, August 2013, http://www.epa.gov.tw/en/NewsPrint.aspx?NewsID=1192. CO2 Emissions from Fuel Combustion (2014 Edition), IEA, Paris.

5 CONCLUSION

Our global economy heavily relies on the usage of the fossil resources that lie in the earth’s crust. From an intertemporal efficiency perspective, the global community currently extracts the global fossil resource stock too quickly because the competitive market does not internalise the advantage that leaving a resource unit in situ today implies for society in terms of lower output losses due to a less severe global warming problem tomorrow (cf. Sinn 2007, 2008a,b, 2012). The global warming externality induced by the combustion of each fossil resource unit is not internalised by the competitive market. Fixing this market failure requires slowing down the speed of global resource extraction compared to the laissez-faire case. However, the speed of global resource extraction is determined by the fossil resource owners around the world, who decide upon when to supply which resource quantity. This thesis demonstrates that in terms of the design of demand-reducing policy measures seeking to effectively slow down the speed of global resource extraction, it is essential to anticipate and take into account the intertemporal reaction of the resource supply side to these measures.

The good news from the present analysis is that if all countries would jointly decide upon their optimal resource consumption path over time, for instance, under the patronage of the United Nations, while the world’s fossil resource stocks remain the private property of competitive resource suppliers, this global coalition of the world’s countries would consume the global resource stock over time at the Pareto efficient speed. In the time-consistent solution, the global coalition internalises the global warming externality and its announced resource consumption path incentivises the representative competitive resource supplier to increase supply in the future at the expense of present supply, as is required to fight global warming. Hence, from an intertemporal efficiency perspective, the global community should strive to reach the global coalition. The Pareto efficient resource allocation can equivalently be implemented by levying a unit tax on resource consumption or by directly constraining the global resource flow over time to the efficient level; for instance, by imposing a respective time-path of caps on global greenhouse gas emissions.

Furthermore, the analysis demonstrates that an incomplete coalition that comprises a subset of the world‘s countries and is of a stable size in terms of its member countries is also able to slow down the speed at which the global resource stock is depleted over time by unilaterally reducing its resource demand, thereby fighting global warming. It is shown that if an incomplete coalition levies a unilateral unit tax on its resource consumption, the growth rate of the unilateral unit tax determines the intertemporal supply reaction to the tax if the coalition and the fringe countries exhibit the same constant price elasticity of demand and if demand is independent of calendar time. Under these assumptions, a unilateral unit tax that grows at the market rate of interest is neutral for the speed of global extraction; indeed, this is also true in the presence of stock-dependent unit extraction costs. Furthermore, abstracting from extraction costs while allowing for time-dependent demand functions, it is demonstrated that a unilateral unit tax on resource consumption that grows at the market rate of interest remains neutral for the speed of global extraction if the coalition and the fringe countries exhibit the same constant price elasticity of demand and if the demand of the coalition and the demand of the fringe countries grows or shrinks at the same rate over time for exogenous reasons.

The decision problem of an incomplete coalition that suffers output losses from global warming is also analysed. The coalition leads in a Stackelberg differential game in which a representative competitive resource supplier and the passive fringe countries outside the coalition follow. Abstracting from extraction costs, the open-loop solution to the incomplete coalition’s decision problem is provided, whereby it is assumed that the coalition implements its preferred resource consumption path by levying a unit tax on consumption. As long as the incomplete coalition suffers output losses from global warming, it levies a unilateral unit tax on its resource consumption that decreases in present value terms. Hence, if the coalition and the fringe countries outside the coalition exhibit the same constant price elasticity of demand and if the demand of both groups grows or shrinks at the same rate over time for exogenous reasons, the unilateral open-loop unit tax chosen by the coalition unambiguously slows down the speed of global resource extraction compared to the laissez-faire case. Under the assumptions made, the incomplete coalition’s selfish open-loop policy thus increases the efficiency of the intertemporal resource allocation compared to the laissez-faire case.

Given that the European Union has a cap-and-trade system in place rather than a price instrument like a carbon tax, in a simplified two-period framework with zero extraction costs the analysis also shows that the incomplete coalition can equivalently implement the same intertemporal resource allocation that would result under a certain unilateral unit tax on resource consumption by directly regulating its consumed resource flow. Moreover, if the incomplete coalition abstains from its selfish open-loop policy and instead behaves altruistically in the sense that it certainly seeks to slow down the speed of global resource extraction compared to the laissez-faire case, it can always achieve this goal by constraining its present resource consumption below the laissez-faire level while not constraining its future consumption. Moreover, given that the incomplete coalition has announced a certain time-path of unilateral benchmark emission caps for the present and future, loosening the future cap slows down the speed of global resource extraction compared to the benchmark equilibrium. The same is true if the incomplete coalition tightens the present cap while maintaining the future cap at the benchmark level. Accordingly, tightening the future cap or loosening the present cap compared to the respective benchmark cap increases the speed of resource extraction compared to the benchmark equilibrium.

The conclusion is that establishing a global climate coalition that comprises all countries remains the target towards which the global community should strive, because the global climate coalition would dictate the Pareto efficient speed of resource extraction. As pointed out in Sinn (2008a,b, 2012), although dictating the intertemporal global resource extraction path via a time-path of global emission caps essentially constitutes a central-planning solution, the advantage of directly regulating the global fossil resource flow consumed over time against a globally applied price instrument like a unit tax on resource consumption is that the Green Paradox can certainly be avoided. Once the global coalition is established and a global cap on emissions is implemented, the expectations of the resource supply side become irrelevant. Tightening the global cap then unambiguously delays extraction from the present to the future. Moreover, establishing a global market for emission certificates on the grounds of the international trading scheme, which has already been established under the patronage of the United Nations, as laid out in Article 17 of the Kyoto protocol, could assure an efficient international distribution of emissions in each period.[1] However, it is most important that the global community implements a binding cap on global emissions as quickly as possible to avoid a long phase in which the resource suppliers around the world can sell off their resource stocks in the present in the fear of increasingly stricter future climate policy measures.

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[1] Kyoto Protocol Reference Manual on Accounting of Emission and Assignment Amount, United Nations Framework Convention on Climate Change, 2008.

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