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Preface

This dissertation was written by Johannes Pfeiffer while he was working with the ifo Institute for Economic Research. It was completed in November 2016 and accepted as a doctoral thesis by the department of economics of the University Regensburg in December 2016. The thesis studies unintended intertemporal reactions of fossil resource supply to climate policies, which often are subsumed under the notion of the green paradox, while taking into account the interrelationship between the resource and the capital market in a general equilibrium framework. Its specific contributions derive from three observations: First, resource markets, in particular of oil and natural gas, are often considered as not being truly competitive. Second, resource-rich countries invest in the international capital market and by now often hold substantial assets, for example in so-called sovereign wealth funds. Third, "green" energy technologies such as renewable energies mostly use physical capital to substitute fossil resources in energy generation, while generally capital and fossil resources are still seen as highly complementary in production. Overall, the thesis illustrates that general equilibrium approaches, particularly when accounting for these observations, can substantially alter the supply-side effects of climate policies.

Chapter 1 broadly introduces to the relationship between the use of fossil resources and climate change and gives a more extensive overview over the main line of reasoning and the main contributions of the thesis. The resource economics background and the predominantly partial equilibrium literature on unintended supply-side reactions are reviewed in Chapter 2. Chapter 3 provides an overview discussion about why partial equilibrium approaches may be too restrictive to comprehensively assess these supply-side reactions. It is argued that the interrelationship between the resource and the capital market is closer than captured in partial equilibrium approaches, which gives rise to feedback effects of policy induced resource supply shifts and establish additional transmission channels of climate policies. In Chapter 4, a general equilibrium framework is introduced, which captures the interrelationship of the resource and the capital market, the geographical concentration of resource stocks, and the capital investment of resource owners. Chapter 5 points out that, depending on the degree of internalization of the cross-market effects of resource supply in a general equilibrium setting, additional supply motives can substantially modify the supply behaviour of a resource monopolist. In particular, the monopolist, while having market power only in the resource market, may internalize the complementarity driven positive influence of resource supply on the return of her capital asset holdings. This gives rise to the so-called asset motive which in Chapter 6 is shown to establish a completely new transmission channel of climate policies: Climate policies induce adjustments in the capital investments of resource owners by redistributing resource rents to resource-poor countries and by the asset motive therefore can lead to postponement of resource extraction contrary to the familiar green paradox. Chapter 7 addresses the capital intensity of climate friendly substitutes to fossil resources by introducing such a energy technology to the model framework. Market power, even with the monopolist not pursuing additional supply motives, is again found to play a crucial role for the supply-side effect of climate policies. The reason is that in this modified general equilibrium setting a renewable energy subsidy (but not a carbon tax) also affects the price elasticity of residual resource demand. Finally, Chapter 8 concludes.

Keywords: climate policy, green paradox, complementarity, general equilibrium, market power, fossil energy resources, renewable energies, capital market, asset motive, sovereign wealth funds

JEL-Codes: D42, D50, D90, E22, F21, H23, Q31, Q38, Q42, Q43, Q54

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My present and former colleagues at ifo all contributed to a harmonic environment for research and work.Everyone in our group was there to help or just to talk whenever needed. Our regular coffee breaks always were an excellent opportunity to recreate. We also share some great memories from our department retreats and activities.

Parts of the thesis build upon joint work with my colleague Waldemar Marz whom I would like to thank for the fruitful collaboration and for the relaxed and – hopefully mutually – inspiring atmosphere in our shared office life. Waldemar often came up with new perspectives which helped me a lot to understand fundamental relationships and policy effects in more detail. Special thanks are also due to Niko Jaakkola, who put much effort into reading already preliminary results of my joint work with Waldemar, and considerably helped me to sharpen my understanding of many of the observations presented in this thesis. Moreover, I am highly grateful to Wolfgang Habla. Discussing our research (and life as doctoral students) always was fruitful and encouraging. In particular, Wolfgang provided indispensable input to the framing and modeling of my research questions as well as to the numerical analysis.

Last but not least, my family and friends stood by my side even though I could not always give all due attention and time to them. I am fully aware of that and deeply indebted to them for their understanding and encouragement. I dedicate this work to my parents and brother, who support me in all my endeavors at all times.

Fossil Resources and Climate Change – The Green Paradox and Resource Market Power Revisited in General Equilibrium

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1 Introduction

It is by now widely acknowledged in science and politics that managing and mitigating global warming and climate change is one if not the most central challenge of our time. Overwhelming scientific evidence has brought the Intergovernmental Panel on Climate Change (IPCC) to conclude in its recent report that the "warming of the climate system is unequivocal" as well as that the "human influence on the climate system is clear" (IPCC 2015). Global warming and climate change have, and will have, substantial implications for ecosystems, economies and, overall, living conditions. The consequences range from rising sea levels, which threaten coastal areas, changes in precipitation patterns and hydrological systems, which influence water supply, and shortfalls of crop yields from drought and heat to an increase in the number and likelihood of extreme and disastrous weather events such as phases of extreme heat, storms, or floods from extreme precipitation. The human influence is due to the emission of greenhouse gases (GHG). Since anthropogenic GHG emissions are only partly absorbed for example by the oceans and mostly have long atmospheric life-times, they accumulate in the atmosphere and, by increasing the energy uptake of the climate system, trap heat which leads to global warming and climate change. Emissions of carbon dioxide (CO_2) are the single most important driver for global warming, and the use of fossil resources the most important source of CO_2. The increase in CO_2 concentrations in the atmosphere contributed the most to the anthropogenic warming effect (radiative forcing) from 1750 to 2010 according to the IPCC (2015) (p. 44). Moreover, the IPCC states that anthropogenic CO_2 emissions accounted for over two third of the increase in GHG emissions from 1970 to 2010 and for 76% of total anthropogenic GHG emissions in 2010. A share of 65% of the total fell on the use of fossil resources in 2010, steadily increasing from about 55% in 1970. Overall, climate change therefore is closely related to the use, or combustion, of fossil resources for power generation, heating, industrial processes, and transport, and thereby to a major driver of the industrialization and the unprecedented growth in economic activities and income. This linkage, together with the aforementioned general characteristics of the global warming problem, has profound implications for its mitigation.

Anthropogenic climate change from an economic point of view basically represents a market failure, and there is little reason to put into question that it is actually "the biggest market failure the world has seen" (Stern 2008). In principle, this market failure can be internalized by setting a Pigouvian tax, or price, on GHG emissions, but determining and implementing the optimal price on GHG emissions differs for a number of reasons from the standard environmental economics textbook case. The most fundamental reasons are:

- The long-term damages from climate change and mitigation benefits are subject to substantial uncertainty. This is due to the complexity of the climate system, i.e. the relationship between the atmospheric concentration of GHGs, global warming and climate change, but also due to the complex and numerous impacts of climate change on ecosystems, living conditions, and economies. Moreover, uncertainty inevitably arises from the potential economic and technological developments over the long time horizons involved.

- Albeit complicated, conventional cost-benefit comparisons for the derivation of the "optimal" mitigation targets generally can account even for the large uncertainty on numerous levels of the climate problem by taking expectations and conducting sensitivity analyses. However, climate change also entails the risk of catastrophic events. Such catastrophic risks can considerably undermine the informative value of cost-benefit analyses, which either may be completely dominated by the damage of these extreme events, or may inappropriately disregard the disastrous outcome due to its typically low likelihood.

- Climate change necessarily raises inherently ethical questions about how to value cost and benefits of generations at very different points in time. These intergenerational trade-offs are typically reflected in the choice of the discount rate, which, over the long periods of time involved, can crucially drive the results of scenario comparisons.

- The warming effect does not depend on the place of origin of GHG emissions but only on the stock, or concentration, of GHGs in the atmosphere. Thus, while countries differ with respect to their vulnerability to climate change, they all more or less similarly contribute to global warming when emitting GHGs. Mitigation of climate change and the internalization of the global warming externality is therefore inherently a problem of international coordination between sovereign states and cannot be achieved unilaterally.

- The already big challenge to arrive at such an international worldwide agreement is aggravated by the fact that independent of the exact target climate change mitigation necessarily entails drastic reductions in the use of fossil resources. At the same time, fossil resources still are widely seen as fundamental drivers for economic growth and development. Obviously, finding an international cooperative mitigation strategy is therefore severely impeded by concerns about loosing national sovereignty and development potentials, by particularly strong incentives to free-ride on other states' mitigation efforts and additionally by various distributional conflicts. For example, due to the stock pollutant nature of climate change, one line of conflict is between industrialized countries, which clearly have contributed the largest share to the current concentration of GHGs in the atmosphere, and developing countries, which more or less call in their "fair" pollution share in the atmosphere for further economic development.

The natural exhaustibility of fossil resources does not help to overcome the coordination failure, rather to the contrary as will become clear in the following. To limit global warming with a probability of over 50% at the by now famous 2°C warming target, current scientific evidence suggests that cumulative CO_2 emissions over the years from 2011 to 2050 should be restricted to around 1.000 $GtCO_2$ (870-1,240 $GtCO_2$, cf. McGlade and Ekins 2015)[1]. This carbon budget implies that substantial parts of the fossil resource stocks must be left underground which is illustrated, for example, by the figures in table 1.1 and by figure 1.1. In contrast to the well-known limits to growth debate of the 1970ies, it is therefore not the natural availability underground but the limited capacity of the atmosphere to absorb GHG emissions without drastic warming and climate change which in the end must define the limits on the use of fossil resources. However, whereas the former is naturally given, the limits to the use of the atmosphere as a global public good have to be set politically.

This thesis addresses another implication arising from the crucial role of fossil resources for global warming. Since climate change mitigation inevitably entails a reduction in the use of fossil resources, it obviously is contrary to the economic interests of owners of fossil resources in the exploitation of their resource stocks underground. The thesis aims to extend the understanding of the supply interests and behavior of resource owners, and thereby contributes to the prospects of successful climate

1 See also the projections in IPCC (2014), and on the differences in carbon budget estimates Rogelj et al. (2016b).

Table 1.1: Regional distribution of reserves unburnable before 2050 for the 2°C scenarios without CCS (with CCS)

	Oil		Gas		Coal	
Country or Region	Billions of barrel	%	Trillions of cubic metres	%	Gt	%
Africa	28 (23)	26% (21%)	4.4 (4.4)	34% (33%)	30 (28)	90% (85%)
Canada	40 (39)	75% (74%)	0.3 (0.3)	24% (24%)	5.4 (5.0)	82% (75%)
China and India	9 (9)	25% (25%)	2.5 (2.9)	53% (63%)	207 (180)	77% (66%)
FSU	28 (27)	19% (18%)	36 (31)	59% (50%)	209 (203)	97% (94%)
CSA	63 (58)	42% (39%)	5.0 (4.8)	56% (53%)	11 (8)	73% (51%)
Europe	5.3 (5.0)	21% (20%)	0.3 (0.6)	6% (11%)	74 (65)	89% (78%)
Middle East	264 (263)	38% (38%)	47 (46)	61% (61%)	3.4 (3.4)	99% (99%)
OECD Pacific	2.7 (2.1)	46% (37%)	2.0 (2.2)	51% (56%)	85 (83)	95% (93%)
ODA	2.8 (2.0)	12% (9%)	2.1 (2.2)	22% (24%)	17 (10)	60% (34%)
USA	4.6 (2.8)	9% (6%)	0.5 (0.3)	6% (4%)	245 (235)	95% (92%)
Global	449 (431)	35% (33%)	100 (95)	52% (4%)	887 (819)	88% (82%)

Source: McGlade and Ekins 2015

policies for at least two reasons. First, the geographically asymmetric distribution of fossil resource stocks implies that in international negotiations about cooperative solutions to global warming there is a group of countries with special strategic interests from the exploitation of their resource wealth. The geographical concentration of resource stocks and the implications for the exploitation of these stocks arising from climate change mitigation are clearly illustrated by table 1.1, which shows that to reach with reasonable probability the 2°C warming target not only a substantial share of global fossil resource stocks must remain unexploited but also that this affects in particular only a rather small group of countries. Moreover, note that a strict carbon budget establishes a distribution conflict within the group of resource-rich countries about the allocation of the remaining extraction quantities. A more comprehensive view on the supply interests of these countries then allows for a better understanding of their position in international climate negotiations and thereby to develop negotiation strategies and mechanisms to integrate resource-rich countries into an international climate policy architecture. Second, while the natural scarcity does not attenuate the problem of global warming as argued before, it is by now well known from the economics literature that the scarcity, or exhaustibility, has fundamental economic implications for the supply of resources. Basically, since in contrast to ordinary goods the overall supply of such exhaustible resources over time is limited, resource owners explicitly account for the depletion of the stock when determining current extraction. In particular, and as already pointed out by Sinn (2008b), this intertemporal nature of resource supply may give rise to intertemporal supply reactions of resource owners which are completely detrimental to the intentions of policy makers and thereby result in what is typically known as a green paradox outcome. A more comprehensive understanding of the supply interests of resource owners and of how climate policies interfere with these interests therefore helps to develop and design truly effective climate policies.

One might argue that considering these questions is more or less obsolete after the international community, including the group of resource-rich countries, has adopted a climate mitigation agreement in Paris in December 2015. Even though the problem of climate change was already recognized with the establishment of the United Nations Framework Convention on Climate Change (UNFCC) in the early 1990ies, it took the international community of states another 25 years to finally come to an agreement about the mitigation target and about an architecture and route to implement this target, which clearly reflects the diplomatic complications by the strategic interaction of countries with often diverse interests in the mitigation of climate change and different vulnerability to climate change impacts. In the Paris Agreement all 195 nations un-

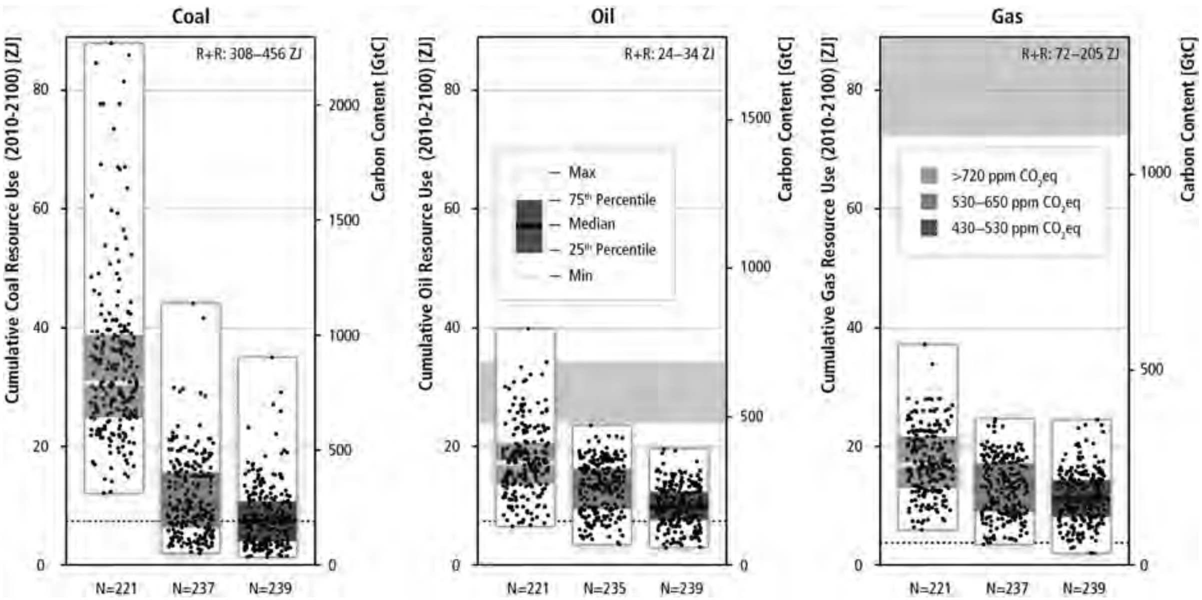

Figure 1.1: Comparison between cumulative global coal, oil, and gas use between 2010 and 2100 in baseline and mitigation scenarios and fossil reserves and resources available underground;
shaded areas correspond to the estimates of reserves and resources (R+R) and dashed black lines to historical cumulative use until 2010, while dots refer to scenario projections;
Source: IPCC 2014, Figure 6.15

der the UNFCC have given an answer to the complex weighting of cost and benefits of climate change mitigation by committing to “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change”. The long-term temperature target, which is even more ambitious than the famous 2°C target but generally seen as adequately addressing the impending damages from climate change (e.g. Schellnhuber et al. 2016), is not implemented by a global carbon price or emission cap but by a pledge and review process where parties are obligated to successively submit (increasingly) ambitious national mitigation pledges, or Intended Nationally Determined Contributions (INDCs), every five years. This bottom-up approach of voluntary mitigation pledges proofed useful throughout the negotiations to overcome concerns about the loss of national sovereignty which a more top-down climate policy architecture in form of a uniform carbon price would have implied. However, while it is widely acknowledged that the agreement itself represents a rather unexpected political breakthrough (Jacobs 2016), the bottom-up framework outlined therein for the implementation of the long-term temperature goal almost certainly fails to achieve a cost efficient mitigation solution from an economic point of view. The reason is that every country more or less voluntary sets its mitigation target while there is no mechanism to adjust mitigation costs internationally (Weimann 2016, Pethig 2016). Even worse, it remains to be seen whether the long-term temperature targets can be achieved in this bottom-up approach as the current mitigation pledges are definitely not sufficient and at best limit global warming to about 3°C (Schleussner et al. 2016). At the same time, however, the pledge and review process so far suffers from a lack of transparency and comparability of pledges (Aldy et al. 2016, Rogelj et al. 2016a) and leaves much, if not too much, discretion over mitigation efforts to the parties. In fact, it is not ensured that the parties will successively announce and commit to more ambitious pledges which are finally in accordance with the temperature target. Thus, the Paris Agreement at least defines minimum mitigation efforts but does not completely resolve the international coordination failure from the global warming externality, nor does it fully address the various distribution conflicts involved with climate change mitigation, which may become evident in the upcoming rounds of mitigation pledges. Thus, there is still room for supply reactions and strategic behavior of resource owners in future rounds of climate negotiations, which warrants a more comprehensive understanding of their supply interests.[2]

Supply Interests and the Green Paradox

To this end, the thesis takes on the supply-side perspective introduced in particular by Sinn (2008b) to the climate policy discussion. Sinn argues that due to the intertemporal nature of the supply of exhaustible resources the effect of climate policies, which intend to reduce the demand of resources, is especially dependent on the development of the policy intervention over time while its strength is generally of minor importance. In fact, he shows that the dire revenue prospects from policy schemes which aim to increasingly reduce resource demand over time can induce fossil resource owners to accelerate the extraction of their stocks. Contrary to the good intentions of policy makers, climate policies therefore may induce intertemporal supply reactions which even aggravate the market failure from an excessive use of fossil resources given the global warming externality and clearly are detrimental to climate change mitigation. The interference of climate policies with the supply

[2] In fact, one may even argue that due to the insufficient mitigation plans so far and the announcement of future rounds of mitigation pledges with more ambitious mitigation commitments, the Paris Agreement more or less provides exactly that framework which is often found to give rise to a green paradox.

interests of resource owners is thereby not reflected in negotiation strategies or positions but in the timing of resource extraction. One might object that climate policies targeting resource demand, in contrast to the underlying assumption in Sinn (2008b), reduce aggregate resource extraction, for example due to rising extraction costs or the availability of substitutive technologies at least in the longer run, and that in the end this restriction of cumulative emissions is crucial for the mitigation of climate change as reflected in the aforementioned carbon budget calculations for the 2°C target. Following this line of reasoning Gerlagh (2011) introduced a differentiation between two forms of green paradox outcomes to the literature. In case of a so-called weak green paradox, the reduction in cumulative emissions actually prevents an increase in cumulative climate damages from the intertemporal supply reaction and the accompanying rise in the short-term emissions, whereas a strong green paradox prevails if the supply reaction raises short-term emissions and cumulative climate damages. The unintended intertemporal supply reactions in any case at least substantially undermine the effectiveness of climate policies. Whether a strong green paradox arises or not, crucially depends on the climate damage function, i.e. on the relationship between CO_2 emissions, global warming, and climate damages. While ambitious temperature targets certainly require a restriction of cumulative emissions as reflected by the aforementioned carbon budget calculations (cf. also Rogelj et al. 2016b), short-term emissions still do play a role for reaching such targets. In fact, due to the long-term persistence of CO_2/GHGs in the atmosphere, sharp increases in short-term emissions can render long-term temperature targets infeasible even if resource use stops at some point.[3] There is also the risk that increases in short-run emissions, in particular if they lead to an overshooting of GHG concentrations or global temperature over the long-term targets, entail a passing of so-called tipping points in the climate system. These tipping points refer to nonlinearities in the climate system which generally arise from changes in the carbon cycle, i.e. changes in the capacity of the climate system to absorb GHG emissions, from self-enforcing feedback effects on GHG concentrations and warming, or from more or less persistent damages to the climate system, and limit the capacity of the Earth's system to recover even when emissions have stopped (for an overview, see e.g. Lenton et al. 2008).

[3] See also the projections in IPCC (2014) where an overshooting of GHG concentrations on the one hand reduces the likelihood that stabilizing GHG concentrations in 2100 at sufficiently low levels will limit global warming to for example 2°C, and on the other hand in many scenarios requires the use of negative emission technologies in the second half of the century. These technologies and their wide deployment are, however, controversially debated (e.g. Fuss et al. 2014, and Smith et al. 2015).

Why a General Equilibrium Approach Seems Reasonable

The contribution of Sinn (2008b) has triggered a whole strand of literature, which assesses the possibilities for the arising of the (weak and strong) green paradox. Chapter 2 will give a detailed overview over this literature building upon a review of the underpinnings of the green paradox from the resource economics literature. The central argument of this study to a more comprehensive understanding of the supply interests of resource owners, however, is that the partial equilibrium perspective of large parts of the literature, which is typically reflected in the assumption of a given and constant market rate of interest, may be too limited and oversimplifying. The line of reasoning presented in chapter 3 is basically two-fold.

First, it is well known already from the early literature on exhaustible resources starting with Hotelling (1931) that the supply of such resources, due to its intertemporal nature, is inherently linked to the capital market. The reason is that resource owners when choosing to leave resources underground effectively transfer wealth to the future while the alternative, or reference, option for such an intertemporal transfer of wealth obviously is given by the capital market. In equilibrium, as already noted by Hotelling (1931), both options must be equivalent, and fossil resources underground therefore must yield the capital market return given by the interest rate. However, we argue that there is an even closer interrelationship between both markets. In fact, the partial equilibrium perspective fails to adequately capture, albeit generally widely recognized, the still prominent role of fossil resources for economic growth and development. Economically, this prominent role is particularly reflected in a still high degree of complementarity between fossil resources and other factors of production and especially capital. The complementarity relationship introduces a positive dependence of the interest rate (or capital demand) on fossil resource supply on the one hand, and of resource demand on the capital stock on the other hand. Moreover, resource rich countries participate not only in the resource market but also in the capital market in which they invest (parts of) their proceeds from fossil resource trading. For example, in the first half of 2016, Saudi Deputy Crown Prince Mohammad bin Salman, entrusted with Saudi Arabian long-term oil extraction policy, presented Saudi Arabia's vision 2030,[4] which represents a detailed plan to drastically reduce the dependency of the country's state budget on oil revenues by heavily investing in all sorts of capital assets and by building up the world's largest sovereign wealth fund (SWF). While a number of resource rich countries have already accumulated large

[4] see Economist 2016 and http://vision2030.gov.sa/en.

SWFs, the role of these capital asset holdings for the effect of climate policies has so far, somewhat surprisingly, not been investigated. The investment activities of resource rich countries also, for example, imply that capital supply can to some extent depend on the investment activities from these countries and thereby in the end on the profits these countries earn in the resource market. All these considerations suggest that resource supply decisions have an influence on the capital market, and therefore, for example, that the intertemporal supply reactions of resource owners to climate policies can contrary to the literature induce changes in the interest rate, which feed back into the supply decision and thereby may alter the effectiveness of climate policies.

Second, as soon as one gives up the assumption of an exogenous interest rate or capital market equilibrium overall, new transmission channels of climate policies on the extraction decisions of resource owners come to the fore as climate policies also may induce resource supply reactions by influencing the capital market directly. We generally survey a number of such additional transmission channels in chapter 3 but focus on the redistributive effect of climate policies, or on the effect of climate policies on the savings of resource owners, and on the capital intensity of substitutive carbon free energy technologies. Climate policies by lowering resource demand obviously incur losses in the resource profits of resource owners, or resource rich countries in the international context, which directly represents the aforementioned conflict between the supply interests of resource rich countries and climate policies. In fact, it is the incentive to at least minimize this loss in resource profits which gives rise to the intertemporal supply reactions underlying the green paradox. When additionally considering the capital market, however, resource rich countries are very likely to also adjust their savings and therefore their investments in the capital market. Thus, if this change in the investment activities has an (dominant) influence on the capital market, climate policies will also change the interest rate and/or the overall capital stock in the world economy, which both, due to the intertemporal nature of resource supply and the dependence of resource demand on the capital stock by the complementarity of production factors, have an effect on the extraction policy as pointed out before (see also van der Meijden et al. 2015b). In general, such an influence on the capital market can arise either from a dominant position of these countries in the capital market, which however may not seem too plausible given the size and volume of the international capital market, or from differences in the savings behavior between resource-rich and -poor countries. The latter is due to the fact that the loss in resource profits incurred by climate policies actually entails a redistribution of income from resource owners to resource consumers, which in principle again is a rather well known result from the resource economics literature (see e.g. Bergstrom 1982). Hence, if resource consumers and owners differ in their savings behavior, climate policies via the income redistribution alter aggregate capital supply and thereby induce changes in the overall capital market equilibrium. For example, if aggregate capital supply falls due the income redistribution, the interest rate will rise, which creates an incentive for resource owners to adjust, and typically to accelerate, resource extraction.

The capital intensity of many of the mitigation technologies in the energy sector introduces another linkage between the capital and the resource market, which becomes relevant in the context of climate policies. There is a general consensus that the decarbonization of energy systems requires large capital investments, in particular due to additional infrastructure needs, additional provisions for the stability of energy systems given the intermittency of weather-dependent renewable energy sources and due to the lower utilization rates (capacity factors), as we will discuss in more detail in chapters 3 and 7. This implies that climate policies, directly or indirectly fostering the deployment of these technologies, not only reduce the demand for fossil resources in the energy market, which represents the familiar crowding out effect from the introduction of substitutive technologies, but also reallocate capital from resource-related applications to substitutive energy generation. The latter, for example, by the complementarity of production factors may lead to a further fall in resource demand. Moreover, due to rising investment needs for the transition to decarbonized energy systems, climate policies are likely to increase capital demand and thereby the interest rate.

Overall, this two-fold reasoning suggests that the partial equilibrium perspective of large parts of the literature on the supply reactions of fossil resource owners to climate policies misses important feedback effects and additional transmission channels of climate policies. To consistently capture the closer interrelationship between the resource and the capital market and to study potential new transmission channels arising from this interrelationship a general equilibrium approach is warranted. We introduce and extensively discuss such a framework in chapter 4, which is in particular constructed as to represent the asymmetry in resource endowments and production capabilities between resource-rich and -poor countries and to include a full representation of an international capital market with endogenous savings.

Contributions

There is small strand of literature investigating the effect of climate policies and potential green paradox outcomes in general equilibrium, which we survey in chapter 6. The implications of the feedback effects from the capital market, which are induced by adjustments in the resource supply path, and of the redistributive effects of climate policies for the arising of the green paradox have already been studied by van der Meijden et al. (2015b) and van der Ploeg (2015). We adapt and review their results in chapter 6 showing in particular that the green paradox may contrary to partial equilibrium be reversed if the savings reaction of resource-rich countries to the income redistribution is dominating. Basically, the reason is that in this case the income redistribution leads to an increase in the capital stock for reasons of consumption smoothing which, via the complementarity of fossil resources and capital, increases resource demand and thereby can create a sufficiently strong incentive to postpone extraction. This thesis, however, considerably extends their analysis by introducing and focusing on resource market power. To this end, we already devote special attention to the role of resource market power for the supply of an exhaustible resource and the effect of climate policies which so far has been identified in the literature in the review of chapter 2. Overall, with respect to the effect of climate policies resource market power so far has played only a minor role in the literature, even though very recently the imperfect competition case has attracted new attention in the literature due to the possibility and the special implications of limit pricing regimes with resource market power (cf. Andrade de Sà and Daubanes 2016, van der Meijden et al. 2015a). The thesis contributes to this newly arising interest in the role of resource market power for the effect of climate policies but takes a completely different approach by considering resource market power in general equilibrium. This proves to have considerable implications for the supply behavior, the role of the capital asset holdings of resource-rich countries and the effect of climate policies. In fact, to the best of our knowledge this is the first contribution to the literature which systematically discusses the supply behavior as well as the effect of climate policies with resource market power while taking into account the interaction of the resource and the capital market in general equilibrium.

The assumption of market power is motivated in particular with respect to the oil market, and may also be relevant for the natural gas market but certainly less so for coal, which at the same time due to its abundance is often seen as non-exhaustible and therefore less prone to give rise to a green paradox. In the oil market, the current and future market position of OPEC (Organization of the Petroleum Exporting Countries)

Table 1.2: Oil production and liquids by source (million barrel/day)

				New Policies			450 Scenario*	
	1990*	2000	2014	2020	2030	2040	2020	2040
OPEC	**23.9**	**30.8**	**36.7**	**38.5**	**44.3**	**49.2**	**36.4**	**33.1**
Crude oil	21.9	27.7	29.8	30.6	34.4	36.6	28.6	23.9
NGLs	2.0	2.8	6.1	6.5	7.8	9.5	6.3	7.1
Unconventional	0.0	0.3	0.7	1.4	2.0	3.0	1.4	2.1
Non-OPEC	**41.7**	**44.2**	**52.8**	**55.0**	**52.9**	**51.3**	**54.5**	**36.2**
Crude oil	37.7	37.8	38.1	36.7	33.5	30.1	38.0	21.5
NGLs	3.6	5.5	7.8	8.7	9.3	9.7	7.6	6.2
Unconventional	0.4	1.0	6.8	9.5	10.0	11.5	9.0	8.6
OPEC share	**36%**	**41%**	**41%**	**41%**	**46%**	**49%**	**40%**	**48%**

Sources: IEA 2015b (Tables 3.6, 3.7); *IEA 2014 (Table 3.5)

countries clearly demonstrates that the oil market is far from being truly competitive.[5] Even though the influence of OPEC has shrunk over the past years due to the market entry of producers of unconventional oil, its market share is still substantial, and is mostly expected to increase again in the future. For example, according to the projections of the International Energy Agency (IEA) the market share of OPEC will rise substantially from currently around 41% to around 49% in 2040 (see IEA 2015b and table 1.2). The last two columns in the table also illustrate that this development does virtually not depend on whether a more or less business as usual pathway in the so-called “New Policies Scenario” or an ambitious climate change mitigation pathway in the “450 ppm Scenario” is assumed. The market concentration is even more pronounced for oil reserves underground, which may be seen as an indicator for the future potential to control the supply side of the oil market (see table 1.3). This is not the least also indicated in the aforementioned study of McGlade and Ekins (2015) by the large share in the resource quantities unburnable under an ambitious climate mitigation target which falls upon the countries in the Middle East (see table 1.1). To simplify the exposition, instead of a certainly more realistic oligopolistic (or competitive fringe) market structure, monopoly power as the extreme opposite case to the competitive market is assumed throughout this study.

[5] This view is, for example, also supported by van der Ploeg and Withagen (2012a), Andrade de Sà and Daubanes (2016), and van der Meijden et al. 2015a.

Table 1.3: Total proved reserves of oil including gas condensate, natural gas liquids (NGLs) and crude oil

	At end 1995	At end 2005	At end 2014	At end 2015		
	Thousand million barrels	Thousand million barrels	Thousand million barrels	Thousand million barrels	Share of total	R/P ratio
World	1126.2	1374.4	1.700	1697.6	100.0%	50.7
OPEC	786.6	927.8	1211.1	1211.6	71.4%	86.8
Non-OPEC	339.6	446.6	488.9	486	28.6%	24.9

Source: BP Statistical Review of World Energy June 2016;
*Reserves: quantities with reasonable certainty recoverable in the future from known reservoirs under existing economic and operating conditions according to geological and engineering information, including gas condensates, natural gas liquids (NGLs) and crude oil; R/P-ratio: reserves-to-production ratio;

To investigate the role of resource market power, we follow in a first step the industrial economics literature (cf. Bonanno 1990) and point out in chapter 5 that the monopolist's supply behavior in general equilibrium crucially depends on her degree of information about the overall economy. The reason is that the supply decision of the resource monopolist in a general equilibrium framework has more widespread, cross market, effects, which the monopolist may or may not recognize and internalize into her supply decision. While this reasoning generally holds true for any monopolist in any general equilibrium setting, it seems to be particularly relevant and plausible due to the widely acknowledged still prominent role of fossil resources for the overall economic development that a monopolistic supplier of fossil resources, and especially oil, is able to oversee the more widespread effects of her supply decision. In this case, we demonstrate that additional supply motives arise from the interrelationship between the resource and the capital market, which add to the internalization of the familiar own-price effect by a monopolist but generally establish ambiguous incentives for resource extraction. Contrasting the modified supply behavior with seminal results from the standard resource economics literature on market power – the conservationist's bias and the neutrality of market power under iso-elastic resource demand – illustrates, however, that simply transferring the familiar monopolist's supply decision, based on the internalization of the own-price effect of resource supply, to general equilibrium can be completely misleading. In particular, we thereby identify a completely new linkage between the resource supply decision and the capital investments of resource-rich countries with (some) market power. Primarily due to the complementarity between capital and fossil resources, the monopolist may realize that supplying resources fosters the productivity of capital and overall economic activity and thereby can raise the return which her investments in the capital market yield. This so-called asset motive introduces an additional intertemporal trade-off to the resource supply decision, which crucially depends on the development of the asset holdings and of the strength of the influence of resource supply on capital return over time. Even though generally of ambiguous effect for the extraction path, we think that the asset motive overall can considerably contribute to a more comprehensive understanding of the supply interests of resource-rich countries, given the investments of many of the resource-rich countries and the still prominent role of fossil resource for economic growth.

The interplay of resource market power and capital investments introduced by the asset motive has in particular fundamental implications for the effects of climate policies, which is pointed out in chapter 6. While the green paradox in the competitive resource market may only be reversed with resource-rich and -poor countries differing in their savings behavior, we find that the redistributive effect of climate policies can give rise to a reversal even for symmetric savings preferences if the resource-rich country exerts market power in the resource market and thereby also pursues the asset motive. In fact, even though climate policies in this case are completely neutral with respect to overall capital supply, the individual investment positions of the resource-rich and the resource-poor country still change due to the redistribution of resource income. If the resource-rich country increases its savings to compensate the loss in resource profits from a credible announcement/tightening of climate policies for example for reasons of consumption smoothing, the larger capital holdings in the future have a leverage effect on the given positive influence of resource supply on capital return and render future resource supply more attractive. This positive effect from the linkage of resource supply to capital income can overcompensate the more dire revenue perspectives in the resource market completely so that the resource-rich country with market power and pursuing the asset motive is overall induced to shift resources no longer to the present but to the future. It is important to note that the asset motive and this completely new channel for a reversal of the green paradox do not require the resource-rich country to have additional market power in the capital market in the sense that its savings have a non-marginal effect on the aggregate capital stock and the interest rate. This also separates our analysis and the asset motive from the contribution by Hillman and Long (1985).

In addition to this new role of resource market power and capital assets in general equilibrium, the thesis considers another transmission channel of climate policies from the interrelationship between the capital and the resource market which is due to the capital intensity of climate friendly substitutive energy technologies. The leading example for such a technology is certainly renewable energy generation. Substitutive technologies and the effects of support schemes and of technological change have been extensively studied in the literature on the green paradox. The potential role of the capital demand of these new technologies, however, so far has been only briefly mentioned by Long (2015). The thesis provides to the best of our knowledge the first approach to capture the investment needs from the deployment of resource substitutes in a consistent general equilibrium framework and to study the implications of the capital intensity for the supply interests of resource-rich countries. The existing model framework is correspondingly extended in chapter 7 by assuming that there is technological change in the sense that the resource importing countries get access to a technology in the future which by use of physical capital is able to substitute fossil resources as energy carriers in production. This has the interesting implication that physical capital becomes complementary and substitutive to fossil resources at the same time since it is used in production and energy generation. Assuming simultaneous use of both energy sources in the future, we investigate the effect of climate policies – in this case of a carbon tax and subsidies – and of (exogenous) technological change, which further improves the substitutive technology, for both the competitive and the monopolistic resource market. While the availability of the capital intensive renewable energy technology does not have any implications for the effect of a carbon tax levied in the future, we find that the renewable energy subsidy (and technological change) necessarily gives rise to a green paradox only in the competitive resource market. In contrast, for a resource monopolist the green paradox may be reversed even though we let the resource monopolist only be aware of the reaction of her competitive fringe in the energy/resource market and not pursue the asset motive. The reason for the reversal in this case is that contrary to the carbon tax the renewable energy subsidy directly influences the investment equilibrium between investments in production, where capital is complementary to the resource, and investments in substitutive energy generation. With simultaneous use of both energy sources this investment equilibrium, however, fundamentally characterizes resource demand. In particular, the renewable energy subsidy therefore may increase the price elasticity of residual resource demand, which directly creates an incentive for the monopolist to shift resource extraction to the future as the negative own-price effect is reduced.

The structure of the thesis may already have become transparent throughout this overview over its main contributions. Chapter 2 surveys the basic insights from the resource economics literature on the supply of exhaustible resources and the role of market power therein as well as the partial equilibrium literature on the possibility and the implications of the green paradox. Chapter 3 discusses the limitations of partial equilibrium assessments of resource supply reactions to climate policies and gives an overview over potential additional transmission channels of climate policies in general equilibrium. The central analytical framework is presented in chapter 4. While chapters 2 and 3 provide more or less the broader background, chapters 5 to 7 contain the main contributions of the thesis and relate these more specifically to the literature which is most relevant for each research question. In chapter 5, the extraction decision of a resource-rich country with resource market power and the additional supply motives from the internalization of the cross market effects in general equilibrium are systematically studied. Chapter 6 builds upon these observations to derive the effect of climate policies on the resource extraction path. Finally, we introduce and discuss the additional interrelationship between the capital and the resource market and the additional transmission channel of climate policies from the capital intensity of substitutive technologies in chapter 7. Chapter 8 summarizes our central line of reasoning and our main observations.

2 The Supply of Exhaustible Resources and Climate Policy

By now it is well known that due to the supply reaction of fossil resource owners the credible announcement, or introduction, of future climate policy measures such as a unilateral carbon tax on imported fossil fuels may have consequences which are detrimental to the actual intentions of policy makers seeking to mitigate climate change. This has been pointed out by Sinn (2008b), who argues that the dire sales prospects from well intended future climate policies lead resource owners to exploit their deposits even faster than in an unregulated laissez-faire world. If this acceleration of extraction is harmful to the climate, well intended climate policies in the end can give rise to what he calls a "green paradox" outcome.

This chapter first reviews the central insights from the literature about the supply of exhaustible resources in a competitive and a monopolistic resource market. Building upon this short introduction to the economics of exhaustible resources, the chapter surveys the partial equilibrium literature on the green paradox. In particular, we thereby point out the role of resource market power which the literature so far has identified for the arising of the green paradox. The basic reasoning behind the economics of exhaustible resources and the green paradox is presented by use of a simplified two period model, which more or less represents the partial equilibrium counterpart to the general equilibrium framework introduced and studied later on.

2.1 The Supply of Exhaustible Resources: The Hotelling Rule

To discuss the supply of an exhaustible fossil resource and the role of resource market power we assume that there are two periods of time $t = 1, 2$ and a given stock of the fossil resource, which we denote by $\bar{R}$. Resource demand in both periods is represented by inverse demand

$$p_t(R_t) \qquad \text{with} \qquad \frac{\partial p_t}{\partial R_t} < 0 \tag{2.1}$$

and therefore a function of resource supply R_t, which possibly changes over time, for example due to technological change improving the efficiency in resource consumption. Finally, we assume that there is some exogenous market rate of interest i_2, which capital investments from the first period yield at the end of the second period.

2.1.1 Competitive Resource Market

In a competitive market setting, there is a competitively high number n of private firms, or resource owners in general, which have rational expectations regarding the future resource market price, the interest rate i_2, and the value added resource tax τ, which may be levied on resource use in the second period, for example for reasons of climate change mitigation. Each firm owns some share of the overall resource stock $\bar{R}$ so that

$$\bar{R} = \sum_{j=1}^{n} \bar{R}_j$$

We abstract from extraction costs for simplicity for the moment. This also implies that we generally need not specify the share which each firm holds in the total resource stock, but without loss of generality we may assume completely symmetric firms.

With positive resource prices in both periods and costless extraction, the individual resource constraint is necessarily binding because every resource extracting firm, in principle, wants to supply as much as possible to the market. However, in contrast to firms selling a reproducible good, resource owners have to take into account that their supply decision today will necessarily limit their supply tomorrow when they seek their profit maximizing supply strategy for given present and future resource market prices. This is a well known conclusion from the resource economics literature (see, for example, Dasgupta and Heal 1979). Profit maximization, therefore, requires firms to supply to the market not by just considering a single period but to plan supply dynamically or intertemporally, i.e. for the entire time horizon they are able to oversee.

In the two period setting, a representative firm j chooses the extraction policy as to maximize the present market value of selling resources in the first and the second period and thereby the overall present value of its resource stock

$$\max_{R_{1j},R_{2j}} p_1 R_{1j} + \frac{(1-\tau)p_2 R_{2j}}{1+i_2} \qquad \text{s.t. } R_{1j} + R_{2j} \leq \bar{R}_j \tag{2.2}$$

where we denote by R_{tj} the resource quantity sold by firm j in period $t = 1, 2$. With a competitive resource market, the representative firm is so small that given the high number of competing firms it has only a marginal influence on the market equilibrium, or at least does not recognize its actual influence on the market equilibrium outcome. Instead, the representative firm takes the equilibrium outcome of resource market prices in both periods and the interest rate i_2 as well as the resource tax as given.

From the first-order condition we observe that in the competitive market equilibrium the condition

$$(1 + i_2)p_1 = (1 - \tau)p_2 \tag{2.3}$$

must hold. This resembles the well known Hotelling rule (Hotelling 1931), which implicitly, given inverse resource demand in both periods, characterizes the optimal resource supply path (R_1^c, R_2^c) in the competitive market equilibrium. First, due to resource scarcity the competitive resource owners earn positive profits – a scarcity or resource rent – even without extraction costs. Second, according to the Hotelling rule the resource rent has to grow over time at the market rate of interest i_2, which resource owners use to discount future profits. This is intuitively plausible by recalling that the Hotelling rule essentially constitutes a non-arbitrage condition, which states that in market equilibrium the resource owners must be indifferent between extracting today and tomorrow (see Dasgupta and Heal 1979). Considering the representative firm again, the firm may extract an additional resource unit today, earn the market price p_1 at the margin, and invest this pure profit in the capital market, which yields a return i_2. Alternatively, the firm may conserve the resource unit underground for future extraction where it realizes the future period market price net of the resource tax τ. Thus, the representative firm, and any firm in the competitive market, will not have any incentive to deviate from its extraction decision if both options yield the same return, and therefore if an increase in the resource rent, given by the producer price in our setting, compensates for the foregone capital market return

i_2.[1] The Hotelling rule is graphically illustrated by figure 2.1 where the width of the diagram is defined by the resource stock available.

The introduction of extraction costs does not change this basic principle underlying the (competitive) market equilibrium with exhaustible resources. With positive extraction costs, the scarcity or resource rent just equals the (producer) market price, which resource owners are able to realize in each period in the resource market, net of extraction costs in the competitive case. This premium above marginal extraction costs still must rise with the rate of interest while the growth rate in the resource market price typically does not. In fact, with constant unit extraction costs the resource market price growths at a rate lower than the rate of interest. However, in general, extraction costs may also vary over time so that the resource rent may not only grow due to a change in the resource market price as in our admittedly rather simplified setting above. For example, if extraction costs depend on the remaining overall resource stock and increase with depletion of the stock, leaving resources underground is of additional value to resource owners as future extraction costs will be lower. In market equilibrium, the resource producer price then has to increase by less to the second period in order to keep resource owners indifferent, and, correspondingly, the resource rent has to rise at a slower rate than the interest rate in contrast to the standard Hotelling setting (see Levhari and Liviatan 1977). The cost advantage from current over future extraction also implies that there is an additional differential rent component in the overall resource rent, which is sometimes referred to as a Ricardian (stock) rent (Krautkraemer 1998). Similarly, if the extraction costs decrease over time with technological progress, the equilibrium resource producer price may not only rise at a rate lower than the interest rate but may over some interval of time even fall depending on the share of marginal extraction costs in the resource price and the rate of cost reducing technological change (see, for example, the discussion in Gaudet 2007). Finally, the relationship between the extraction rate and the interest rate can even be reversed if capital is needed for resource extraction so that extraction costs positively depend on the interest rate. The reason is that in this case, as shown for example by Farzin (1984), a decrease in the interest rate does not only reduce the

[1] Note that Hotelling rule (2.3) implicitly defines only the aggregate competitive extraction path as dependent on the market prices and the resource tax τ but does not uniquely determine the individual firm's extraction policy. In fact, an individual firm may even choose to completely exhaust its resource stock in the first or in the second period and would still be completely indifferent as long as the Hotelling equilibrium condition for the resource market holds. To uniquely define the individual firm's extraction policy in resource market equilibrium, we would have to introduce, for example, firm specific extraction costs.

opportunity costs of leaving resources underground, which creates an incentive to postpone extraction, but also extraction costs, which increases resource rents and thus establishes a counteracting incentive to accelerate extraction.

In the context of climate change mitigation and policies, substitutive low carbon technologies obviously are of particular importance. A perfect substitute, which supplies any quantity to the market with constant but high production costs, represents a so-called backstop technology following Nordhaus (1973). Such a backstop technology effectively introduces an upper price limit ("choke price"), above which demand for the exhaustible resource vanishes as the backstop technology enters the market and completely crowds out resources. If the resource is cheaper to extract throughout, the resource stock still will be completely exhausted, but the resource price path is shifted downwards so that the resource market price will reach the choke price exactly with exhaustion of the stock (see, e.g., Dasgupta and Heal 1979, or Stiglitz and Dasgupta 1982). However, stock depending extraction costs may render overall resource extraction endogenous if extraction costs rise with depletion of the stock above the choke price before exhaustion. In this case, which is often referred to as the Heal model (Heal 1976), since the perfect substitute becomes competitive before exhaustion, the fossil resource is no longer physically but only economically scarce in the sense that there is only a limited amount of low cost fossil resources available to the economy. Resource owners then do no longer earn a scarcity, or Hotelling, rent but still earn the differential, or Ricardian, rent from the cost advantage of extraction early in time or with a large resource stock left underground, which compensates them for the future increases in extraction cost incurred by the depletion of the resource stock in the current period (see Levhari and Liviatan 1977, and Hartwick 1982). Aggregate exploitation of the resource stock is also endogenized if resource owners have to invest in exploration and development of reserves underground. In the literature, for example, the implications of various resource stocks of different quality or the implications of uncertainty about future demand or resource stocks for the extraction patterns in a competitive resource have been investigated, too. A more comprehensive overview over this literature is provided by Krautkraemer (1998) or Gaudet (2007) while our focus in the following is more on the effects of resource market power.

2.1.2 Resource Monopolist

We now assume that resource extraction is controlled by a single firm, which again has rational expectations. As before, assuming a binding resource stock, the monop-

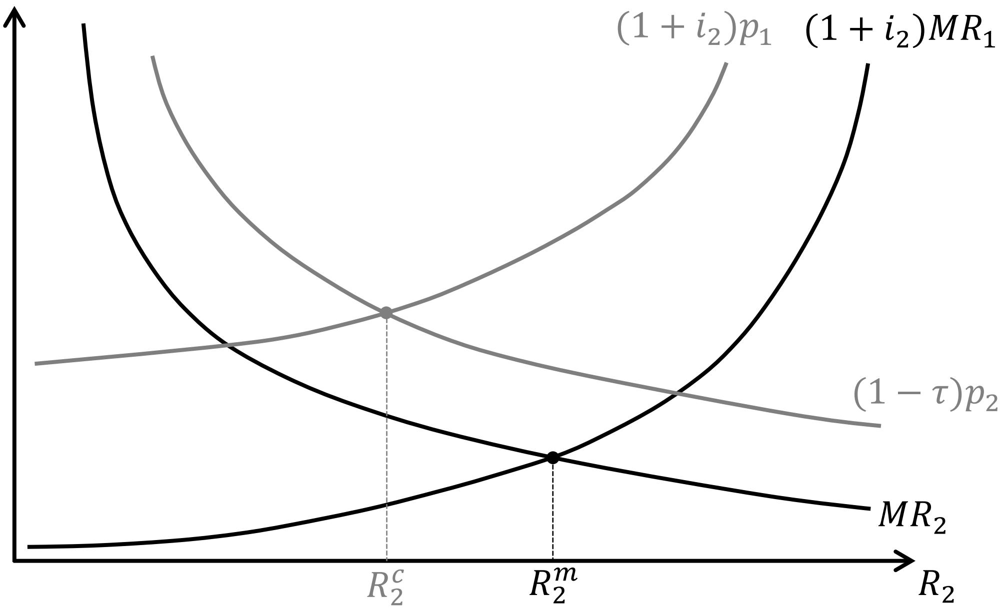

Figure 2.1: Graphical illustration of the Hotelling condition for the competitive market and the resource monopolist

olist has to internalize the negative effect of current resource supply on her future extraction possibilities, and therefore has to plan resource extraction by considering the entire time horizon of two periods. Thus, the optimization problem the monopolist faces, in principle, is directly comparable to the one of a representative firm under competition and reads

$$\max_{R_1,R_2} p_1(R_1)R_1 + \frac{(1-\tau)p_2(R_2)R_2}{1+i_2} \qquad \text{s.t. } R_1 + R_2 = \bar{R} \tag{2.4}$$

In contrast to the competitive setting, the dominant market position implies that the firm's supply decision has a non-marginal effect on market supply. Just as in the standard Cournot monopoly framework (see, for example, Mas-Colell et al. 1995), market power enables the resource owner to internalize the influence of its supply decision on market demand in each period, and therefore to account for the familiar negative own-price effect on the (infra-marginal) resource quantities sold, which arises for a marginal increase in resource supply in either period from the negative relationship between resource supply and the market price defined by inverse resource demand ((2.1)). Hence, combining the first-order conditions, the optimal monopolistic extraction path is characterized by Hotelling rule

$$(1+i_2)MR_1 = (1-\tau)MR_2 \tag{2.5}$$

which is the counterpart to (2.3) in the competitive setting. The marginal resource revenue MR_t is given by

$$MR_t = p_t + \frac{\partial p_t}{\partial R_t} R_t = p_t \left(1 - \frac{1}{\epsilon_{R_t, p_t}}\right) \tag{2.6}$$

where we negatively define the price elasticity of resource demand as

$$\epsilon_{R_t, p_t} = -\frac{\partial R_t^d}{\partial p_t} \frac{p_t}{R_t} = -\frac{1}{\frac{\partial p(R_t)}{\partial R_t} \frac{R_t}{p_t}} \tag{2.7}$$

Contrary to the competitive case the scarcity or resource rent does no longer derive from the producer market price but from the marginal resource revenue MR_t and exactly equals the latter without extraction costs. Still, Hotelling rule (2.5) obviously again constitutes the by now familiar non-arbitrage condition for the trade-off between current and future resource supply.

In this admittedly rather simplified setting, market power has only limited implications for the supply of the exhaustible resource. Rearranging Hotelling condition (2.5) to

$$1 + i_2 = \frac{(1-\tau)p_2}{p_1} \frac{1 - \frac{1}{\epsilon_{R_2, p_2}}}{1 - \frac{1}{\epsilon_{R_1, p_1}}}$$

illustrates that market power may even lead to the same extraction pattern, or speed of extraction, if resource demand is iso-elastic over time as pointed out by Stiglitz (1976) or Sweeney (1977). In this case, the second fraction on right just equals unity and Hotelling condition (2.5) in the end requires resource (producer) prices to increase with rate of interest just as in the competitive case.

If the price elasticity of resource demand increases over time, for example due to resource substitutes becoming available over time by technological developments, the monopolist will slow down extraction compared to the competitive case (Stiglitz 1976). Intuitively, the (negative) own-price effect is attenuated in this case over time, which raises the value of resource supply at the margin. This observation has given rise to the widely known notion of the monopolist being the conservationist's best friend brought forward by Solow (1974) and even earlier by Hotelling (1931), and is illustrated in figure 2.1, too. With stationary resource demand, such a flattening of the supply path compared to the competitive case arises if the price elasticity of resource demand negatively depends on resource consumption. In this case, the price elasticity of resource demand increases along a competitive resource extraction path falling over time so that again the resource monopolist has an incentive to deviate from the competitive market outcome by shifting resource extraction to the future. The monopolist will choose a more conservative extraction pattern even for iso-elastic resource demand if resource extraction comes at constant unit extraction costs or unit extraction costs which are constant in the extraction rate but falling over time (see also Gaudet 2007).

However, the conservative bias from resource market power does not generally hold true. Lewis et al. (1979) argue that the substitutability of a fossil resource in an economy likely depends on the resource price as for high prices the resource would be used only in sectors where the resource is actually essential, while for lower prices resources may also be used in sectors which, in principle, could substitute for the resource. Such a consumption pattern implies that the price elasticity of resource demand is not decreasing but increasing in resource consumption, which induces the monopolist to accelerate extraction over the competitive supply path (see also Lewis 1976). Similarly, Lewis et al. (1979) also demonstrate that if resource extraction incurs in each period some quasi-fixed costs, the monopolist will have a greater incentive to reduce total operative costs by reducing the time horizon of extraction and thereby to speed up extraction. The latter is somewhat similar to the more recent contribution by Fischer and Laxminarayan (2005), who consider a setting with more than one resource deposit and positive setup costs for opening each deposit. Market power then does not only influence the extraction policy for a given resource deposit but also the timing of the switch to the next deposit and, therefore, the length of the period over which a deposit is exploited. Even with iso-elastic demand and no unit extraction costs as in Stiglitz (1976) the monopolist then may choose a more or less conservative extraction policy than under competition depending on the number of deposits left for future exploitation.

Since there seems to be, if any, only a difference in the extraction pattern over time, Stiglitz comes to the conclusion “that there is a very limited scope for the monopolist to exercise his monopoly power” (Stiglitz 1976, p. 655). However, as for example pointed out by Tullock (1979), this assessment crucially depends on the more or less implicit assumption that the monopolist will actually extract the entire resource stock underground so that the overall supply over time is the same in the monopolistic and in the competitive setting. Clearly, this is in contrast to the implication of market power without scarcity, i.e. without a binding constraint on supply decisions, where a monopolist typically, by accounting for the own-price effect on infra-marginal quantities sold, reduces her supply in each period and therefore also on aggregate compared to the competitive market in order to yield a premium over marginal costs. In fact, Gaudet and Lasserre (1988) demonstrate that the scope for exerting market power is substantially increased if resource owners have to invest in exploration of the resource stock first. As expected, the monopolist in this case always reduces overall market supply over time compared to the competitive market to increase scarcity rents and to save on exploration costs.

We also implicitly assume in our simplified two period model that the resource constraint is actually so tight that marginal revenue is positive, even though marginal revenue is typically falling in supply and the monopolist, just as the competitive market, is "forced" to completely exploit the stock. With a fixed time horizon and marginal resource revenue decreasing in extraction, this, however, needs not necessarily be the case, in particular with unit extraction costs. Thus, while under competition the resource stock will always get completely depleted if substitution possibilities are limited and demand is positive even for very high resource prices, a resource monopolist might opt for leaving some resources underground if the marginal resource revenue became negative otherwise. In this case, the natural supply constraint from the resource stock given the fixed time horizon would effectively be less binding than the monopolist's incentive to reduce market supply for reasons of revenue maximization from the standard static Cournot monopoly setting. Note that Hotelling condition (2.5), in principle, does not exclude the marginal resource revenue being negative along the extraction path, but then obviously does no longer characterize a profit maximizing extraction policy as reducing resource supply in both periods would raise revenues in either period.

Moreover, this conventional approach for modeling resource market power relies on the assumption that resource demand is price-elastic ($\epsilon_{R_t,p_t} > 1$). Empirical observations, however, typically suggest that the price elasticity of (oil) demand is much lower and, in particular, well below unity as, for example, shown in Hamilton (2009). Kilian and Murphy (2014) take into account above ground crude oil inventories and find oil demand substantially more price-elastic than in previous studies but overall still rather price-inelastic. This inconsistency between theory and empirical observations is especially emphasized by Tullock (1979) while Stiglitz (1976) argues in a footnote that the monopolist's supply decision does not only depend on the short- but also on the long-run price elasticity of demand, thereby suggesting that the latter is much higher due to resource substitutes becoming more and more available over time. Still, albeit significantly higher than the short-run elasticity, the long-run price elasticity of oil demand is mostly estimated below unity (see for an overview Hamilton 2009). With price-inelastic demand, however, the monopolist again never chooses to fully exploit the resource stock within a given finite time horizon. Instead, the monopolist can increase resource revenue by continuously reducing market supply and driving up market prices, which, however, contradicts the developments in the oil market. This inconsistency is addressed by Andrade de Sà and Daubanes (2016). They argue that, instead of giving up the presumption of pure profit maximizing behavior in the resource market or just ignoring the dominant market position of some resource owners as, for example, OPEC in the oil market, profit maximizing behavior and market power can be reconciled with price-inelastic demand by understanding the resource market equilibrium as the outcome of a (permanent) so called limit pricing setting. The reason is that in such a setting the thread of the market entry of substitutive technologies constrains the monopolist in reducing period supply indefinitely and induces her to extract such that the market price stays just below the threshold from which on the substitutive technology would become competitive.[2]

The possibility of limit pricing phases with resource market power has been first pointed out by Hoel (1978), not with respect to the possibility of reconciling resource market power with price-inelastic demand but with respect to the adjustments in the extraction path arising from the presence of a perfect high cost substitute (see also Salant 1977, Gilbert and Goldman 1978, and Hoel 1983). Essentially, whereas in the competitive case the availability of such a backstop technology shifts the overall resource rent (price) path downwards so that the resource price reaches the backstop technology's price exactly when the resource stock is completely exhausted (see above), the monopoly's supply path is divided into two phases. In the first, the monopolist follows an extraction policy in accordance to the standard Hotelling rule from (2.5), but in contrast to the competitive market the monopolist may find it optimal that the resource market price reaches the (choke) price of the backstop technology before exhaustion of the stock. In this case, a second phase arises in which the monopolist takes advantage from her dominant market position by choosing extraction up to exhaustion of the stock such that the market entry of the backstop technology is deterred by keeping the resource market price slightly below the backstop's price. Hence, the present value of the monopolistic resource rent, i.e. the marginal resource revenue (net of extraction costs), is constant during the first phase but discontinuously jumps upwards to the limit price at the beginning of the second phase as the monopolist then no longer accounts for the negative own-price effect. The length of this second phase of limit pricing is determined by the fact that at its end, when the

[2] Note that such additional resource supply constraints may also arise from political economy lines of reasoning.

resource stock is completely depleted, the present value of the marginal resource rent given by the discounted limit price has to equal the present value of the resource rent from the first phase again (see Stiglitz and Dasgupta 1982).

The impending market entry of a substitute leads to higher resource market prices and lower resource supply in the short run as compared to a setting where the monopolist is completely unconstrained as shown, for example, by Gilbert and Goldman (1978). Moreover, referring back to our previous discussion about the speed of resource extraction note that such a phase of limit pricing entails that the monopolist chooses a more conservative extraction profile than the competitive market. The reason is that the limit price is reached earlier, and therefore that the resource stock is exhausted at a later point in time than under competitive extraction (Stiglitz and Dasgupta 1982). However, Katayama and Abe (1998) point out that this may not necessarily be true if the market entry of the backstop technology is uncertain and if the monopolist can only take into account that the probability of the market entry is non-decreasing in the resource market price. That the availability of a substitutive technology may induce the monopolist to choose a more conservative extraction policy is also illustrate by Hillman and Long (1982). They consider a more imperfect substitute which gradually arrives at the market and only partly crowds out the resource with increasing depletion of the resource stock. Thus, there is simultaneous use of the resource and the substitute up to exhaustion, but no phase of limit pricing. Since leaving resources underground increases residual resource demand tomorrow, a monopolist obviously has an incentive to postpone extraction if the monopolist, in contrast to a small resource owner under competition, internalizes this negative relationship between the remaining resource stock and production of the substitute into the supply decision.

2.2 Climate Policies and the Supply of Fossil Resources: The Green Paradox

The peculiarities of the supply of exhaustible fossil energy resources do not have any implications for the necessity to correct for the market failure and to internalize the negative externality from carbon emissions from a societal, or social planner, perspective. Due to the prominent role of fossil resources for economic growth and development and the still large utility from the use of fossil resources, the optimal mitigation of climate change is widely believed to require not an abrupt and immediate shift away from fossil resources but a less excessive exploitation of the resource deposits underground and a complete transition to carbon free economies in the medium or longer term. From an economic point of view, the first best approach to implement the social optimum is to set a global price on carbon emissions according to the Pigovian principle, either directly via a carbon tax or indirectly via an emissions trading system. Due to the long atmospheric life-time of GHGs, the optimal price thereby must be equal to the social costs of carbon, which are given by the discounted sum of all current and future marginal damages from emitting a ton of carbon to the atmosphere (see, for example, Hoel and Kverndokk 1996, or van der Ploeg and Withagen 2014).

However, as argued, for example, by Sinn (2008b) or van der Ploeg and Withagen (2015) governments are likely to fail to implement the first best climate policy. There are various reasons for government failure. Governments may refrain from pricing carbon emissions and instead subsidize substitutive carbon free technologies like renewable energies for political reasons. Moreover, there may be time lags in the implementation of climate policies, and governments may fail to implement a global climate policy due to the large coordination problem and the strong free-riding incentives involved with climate change mitigation. In such a second best world, the peculiarities of the supply side of exhaustible fossil resources can be crucial for the climate policy outcome because they can lead to unexpected intertemporal supply responses of the owners of fossil resources which are completely contrary to the intentions of policy makers and detrimental to the mitigation of climate change. This has been first and prominently brought forward by Sinn (2008b) and Sinn (2008a), who coined the term "green paradox" for such policy induced intertemporal shifts in resource supply which may cause even greater climate damages than under laissez faire.

2.2.1 The Green Paradox

The basic rationale for such a green paradox outcome can be understood within the simplified two period model of resource extraction of the previous section. It builds upon earlier results from the resource economics literature, which already studied the supply reactions to anticipated changes in resource taxes and showed that taxing the use of an exhaustible resources reallocates resource rents away from resource owners (e.g. Bergstrom (1982)) but does not necessarily lead to a change in the supply path as the latter crucially depends on the time profile of the tax policy (Sinclair 1994, Sinn 1982, Long and Sinn 1985, for a neutral tax policy scheme see also Dasgupta and Heal (1979)). To this end, we consider an (marginal) increase in the future value added resource, or carbon, tax rate τ. Given the initial market equilibrium defined by Hotelling condition (2.3), this may be interpreted either as the introduction of a (value-added) carbon tax in the future, or, given that there is a time constant value added resource tax rate in both periods initially, a tax policy which becomes stricter and stricter over time. We can capture the effect of such a (marginal) policy change by use of a comparative statics analysis, which we derive by totally differentiating Hotelling condition (2.3) with respect to the tax rate and the resource supply in both periods and by taking into account that $dR_2 = -dR_1$ as long as the resource constraint is binding:

$$\frac{dR_2^c}{d\tau} = \frac{-p_2}{-(1+i_2)\frac{\partial p_1}{\partial R_1} - (1-\tau)\frac{\partial p_2}{\partial R_2}} < 0 \tag{2.8}$$

The negative sign holds since for a falling inverse resource demand function $p(R_t)$ (see (2.1)) the denominator is unambiguously positive. It implies that in the competitive resource market resource owners will accelerate extraction if the future value added carbon tax rate increases. However, since climate damages arise from the accumulation of greenhouse gases in the atmosphere and since there is only a very low rate of decay of carbon in the atmosphere, carbon emissions earlier in time increase the overall climate damages, given that the overall resource stock is completely exploited in any case. Thus, the well intended tightening, or introduction, of the carbon tax in the future period in this case paradoxically leads to an increase in climate damages.

This green paradox outcome is due to the intertemporal supply response of resource owners, which directly follows from the economic peculiarities of the market supply of an exhaustible resource in comparison to an ordinary reproducible good or production factor. For a given future resource demand and given market discount rate i_2, the increase in the future carbon tax leads to a reduction in the present value of the future resource rent, which is directly observable from the numerator of the comparative statics. Obviously, since the scarcity of the fossil resource brings the resource owners to choose their extraction policy by trading off the (marginal) value of future and present resource supply, this policy induced decrease in the future resource rents directly creates an incentive to shift resource extraction to the first period. The supply response reduces the first period resource market price and increases the second period market price so that for given resource demand and a given market discount rate Hotelling condition (2.3) eventually holds again. The adjustments in the resource market prices are captured in the denominator of the comparative statics and influence the strength but not the direction of the supply response.

Following these observations for the effect of a rising value added resource tax, Sinn (2008b) anticipates that a green paradox may arise quite generally for any policy instruments or technical measures which decrease the present value of resource rents over time as long as there is no globally enforced cap on carbon emissions, for example within a global emissions trading system. He also points out that the climate policy debate almost entirely focuses on reducing resource demand over time thereby ignoring that this quite likely comes along with falling resource rents over time, too. These arguments have been scrutinized in the literature. The term green paradox is thereby often also understood more broadly as referring to outcomes of climate policies which are against the intentions of policy makers. In the following, we will give an overview over the literature investigating the possibilities and the welfare consequences of such green paradox outcomes.[3]

A green paradox like increase in emissions in the short term may also be due to time lags between the credible announcement and the implementation of a climate policy regulating carbon emissions. This has been shown, for example, by Di Maria et al. (2012), who additionally point out that if fossil resources differ with respect to their carbon intensity but are nevertheless completely exhausted, there will not only be a shift of overall resource use to the in-between time period, but there will also be an incentive to use the more carbon intensive resources in the period before the climate policy is actually implemented. The basic reasoning for the green paradox and the applicability of the Hotelling framework for the assessment of the effects of climate policies is criticized by Cairns (2014), who basically argues that resource owners simply are not able to shift resource extraction between periods of time at arbitrary amount. The reason is that the exploitation of resource stocks requires upfront investments in exploration and extraction facilities. Thus, there are, on the one hand, capacity constraints on extraction in the short term. On the other hand, this also implies that future climate policies may render further investments in resource exploration and extraction infrastructure unattractive so that these resource quantities will not be extracted at all. Similarly, Di Maria et al. (2014a) argue that, even though resource supply may strongly react to the announcement or tightening of future climate policies, the arising and especially the magnitude of the green paradox crucially depends on the demand side, too. In fact, for a substantial increase in short-term emissions, resource demand must be able to flexibly react to the shifts in resource

[3] Reviews of the literature on the green paradox are, for example, provided by van der Werf and Di Maria (2012), Jensen et al. (2015), and van der Ploeg and Withagen (2015).

supply or, correspondingly, to the fall in short-term resource prices.[4] Otherwise, only a small, or even no, green paradox may occur in market equilibrium. Di Maria et al. (2014a) also point out that the insensitivity of resource demand may explain the rather mixed results of their empirical assessment of the green paradox from the announcement of the US acid rain program in Di Maria et al. (2014b). Therein, they find that although coal prices considerably dropped after the announcement of the government program regulating the SO_2-emissions, the use of coal and, correspondingly, the emissions from coal significantly increased only for the subgroup of coal power plants which were not bound by long-term contracts in the coal market and thus were flexible to react to the drop in coal market prices. Stronger empirical evidence for a green paradox is presented by Curuk and Sen (2015), who study the oil trade between OPEC and OECD countries and the impact of spendings on research and development for renewable energies in OECD countries. They find that OPEC countries significantly increase their export volumes and lower their prices as a reaction to an increased R&D intensity (defined as the ratio of R&D-spendings to gross domestic product) in OECD countries, which directly corresponds to a green paradox outcome. However, apart from the contributions by Di Maria et al. (2014b) and Curuk and Sen (2015) there are to the best of our knowledge no other empirical assessments of the green paradox so far. Of course, this is also due to the problems to empirically identify the fundamental principles of resource supply according to Hotelling, which are discussed in more detail by Livernois (2009) (see also Hamilton 2012).

Cumulative Extraction and Backstop Technologies

The relevance of the intertemporal supply responses of the owners of fossil resources rests, in particular, on the assumption that even with rising costs of resource extraction the global stock of fossil resources will be completely exhausted in any case, which also implies that even in the long run there will be no substitutive technology available at competitive costs. However, given the technological developments in the past this view is at least extremely pessimistic. Letting new technologies at least in the long run substitute fossil resources introduces a setting which is typically referred to as the Heal (1976) model (see section 2.1.1). As pointed out before, with positive and possibly stock dependent, or generally over time rising, extraction costs there may be no longer pure physical but economic limits to aggregate resource ex-

4 The authors also point out that the flexibility of current resource demand depends on both, the price elasticity of demand and the willingness of consumers to shift future consumption to more present periods in time, and therefore on the intertemporal elasticity of substitution.

traction, which become binding as soon as extraction costs exceed the market price of the substitutive technologies. In the context of climate change, climate policies then may not only induce an intertemporal shift in resource supply, but may also alter and especially reduce cumulative resource extraction and thereby emissions. This brings Gerlagh (2011) to distinguish between a so-called weak green paradox, which refers to the immediate effects of climate policies and the increase in the emissions in the short run, and a strong green paradox, which arises if climate policies actually are detrimental to climate change mitigation by inducing supply responses which increase the cumulative damages from climate change in present value terms. The crucial role of the endogeneity of cumulative emissions for the overall assessment of environmental effects of carbon taxes is, for example, shown in Hoel (2012), who points out that the arising of the green paradox is generally the less likely the more the implicit improvement of the backstop technology's competitiveness in the long run via the rising carbon tax rates reduces aggregate extraction. However, even in case of constant extraction costs and no backstop technology available, Edenhofer and Kalkuhl (2011) note that a unit resource tax policy scheme with a rising tax rate may come along with such a "volume effect" on emissions if the initial tax rate is set sufficiently high so that the rising tax rate eventually will reduce the resource producer price below extraction costs.[5]

Whether or not the cumulative extraction and carbon emissions endogenously depend on the development of extraction costs and resource demand over time is also crucial for the assessment of technology policies which aim to foster the development and deployment of mitigation technologies. Subsidy schemes are politically much more feasible than the pricing of carbon emissions, and not least for that reason have been much more prominent in the climate policy agendas so far. Since such instruments, in contrast to a carbon tax or an emissions trading scheme, only indirectly internalize the negative externality from greenhouse gas emissions, they typically fail to implement the social optimum. Hence, similar to sub-optimally set carbon taxes, they must been seen as second best instruments which are likely to give rise to an acceleration of extraction and a (weak) green paradox, as argued, for example, by van der Ploeg and Withagen (2012a).

[5] Somewhat similar to Edenhofer and Kalkuhl (2011), Hoel (2012) also argues that setting the unit carbon tax higher than the initial resource rent excludes the arising of the green paradox by forcing resource owners to reduce their supply in order to increase the producer price over extraction costs.

As already anticipated by Sinn (2008b) (see above), a strong green paradox will inevitably arise if a substitutive backstop technology with constant production costs is subsidized but the resource stock is still completely exhausted as the extraction costs of fossil resource are still lower than the backstop's market price (cf. also Hoel 2008, and Gerlagh 2011). In this case, to mitigate climate change and slow down extraction, the use of the backstop technology would actually have to be delayed and therefore taxed. This, however, would not only be politically infeasible but also time inconsistent as there would be no reason (apart from governmental budget constraints) for taxing the backstop technology after exhaustion of the resource stock (van der Ploeg and Withagen 2012a). In fact, assuming that the resource stock gets completely exhausted in any case reduces the scope of climate policies to the timing of resource extraction and carbon emissions, and in the end more or less undermines the economic justification for supporting new technologies for reasons of climate change mitigation. This conclusion, however, can be different with endogenous technical change.

With economic limits to the depletion of the resource stock, subsidizing a carbon free backstop technology can render an even larger part of the resource stock unattractive to extract. Policies supporting the development and deployment of new technologies then may induce an acceleration of resource extraction but are less likely to give rise to a strong green paradox as they decrease cumulative emissions at the same time (Gerlagh 2011, van der Ploeg and Withagen 2012a). Similar effects can be derived if investments in the exploration of the resource stock have to be made upfront (van der Ploeg 2013). From a societal, or welfare perspective, however, the costs of financing such support schemes have to be taken into account in addition to their effects on cumulative climate damages. Yet van der Ploeg and Withagen (2012a) show that although the first best or the social optimum can generally only be implemented by the optimal carbon tax – as long as there is only the negative climate externality from carbon emissions – choosing the second best approach and subsidizing the backstop technology is likely to increase overall welfare if the backstop technology is not too expensive so that cumulative extraction can be reduced by improving the market competitiveness of the backstop technology. Even a substantial, "non-marginal", financial support for a rather expensive backstop technology can lead to welfare gains if this policy manages to keep resource owners from completely exhausting the fossil resource stock.[6] This, however, is strongly dependent on the functional relationship

[6] Moreover, van der Ploeg and Withagen (2012a) demonstrate that exogenous technological change, which reduces the costs of the backstop technology, is always welfare improving as long as the neg-

between the green welfare component and cumulative emissions and on how much cumulative emissions can be reduced by such a non-marginal subsidy scheme. Fischer and Salant (2012) also consider the effect of technology policies but assume that there is a given cost degression rate of the backstop technology's cost over time, which can be increased, for example, by supporting research and development. If the resource is scarce and the resource stock is always completely exhausted, accelerating the degression of costs of the backstop technology will give rise to a strong green paradox, just as a one time reduction in the costs of the backstop technology. If, however, the cost degression renders the backstop technology competitive in any case so that fossil resources are no longer (physically) scarce, a policy induced additional acceleration of the cost degression will solely reduce the duration of the fossil resource era and thereby cumulative emissions without leading to an intertemporal resource supply response.

Imperfect Backstop Technologies

The additional trade-off introduced by the endogeneity of cumulative extraction, and the potential reduction in cumulative extraction in particular, generally tend to render the intertemporal supply reactions of resource owners less relevant for the overall assessment of climate policies. Second best climate policies become more likely to effectively reduce climate damages, even though not as much as intended by policy makers without considering the supply reaction of fossil resource owners (see, e.g., also van der Ploeg 2013). Still, this optimistic conclusion has to be qualified as it obviously also relies on how easily the new carbon free technologies can substitute fossil resources. Compared to the perfect backstop technology in the sense of Nordhaus (1973), which provides any amount of energy at constant (marginal) generation costs to the market and perfectly substitutes fossil energy, two imperfections have been especially studied in the literature: First, rising marginal costs of energy generation from the carbon free technology, and, second, imperfect substitutability between the backstop technology and fossil resources.

With increasing (marginal) energy generation costs, a phase of simultaneous use of both, fossil resources and the substitutive energy source, may arise. For linear en-

ative externality from carbon emissions is efficiently internalized by the first best carbon tax at the same time, irrespective of whether cumulative extraction is reduced or not and although it always accelerates extraction. The reason is that such an exogenous cost reduction comes along with substantial income gains as it, on the one hand, depresses the resource price path and, on the other hand, reduces the cost of energy in the post resource phase.

ergy demand and constant extraction costs, Gerlagh (2011) shows that if both energy sources are used simultaneously before the fossil resource stock is completely exhausted and energy is solely provided by the backstop technology, a reduction of the costs of the backstop technology does not give rise neither to a weak nor a strong green paradox. The reason is that the fall in the generation costs reduces residual resource demand as well as the energy price level and thereby resource rents. But with complete exhaustion of the resource stock such a decrease in residual energy demand necessarily implies that the phase of simultaneous use is extended so that extraction and emissions are shifted to future periods. This observation is confirmed by Grafton et al. (2012). They, however, point out in particular that a (ad-valorem) subsidy to lower the backstop technology's cost induces a direct and a counteracting indirect effect on residual resource demand during the initial phase of simultaneous use of both energy sources. On the one hand, the subsidy reduces residual resource demand at each point in time so that fossil resources have to be used over a longer time period to fully exhaust the given resource stock. On the other hand, there is an indirect effect as a higher subsidy also lowers the energy market price at the time of exhaustion of the resource stock. This shifts the overall Hotelling-type resource price path downwards which tends to increase residual resource demand. Therefore, the phase of simultaneous use may generally be prolonged or shortened. The latter would give rise to a green paradox with complete exhaustion of the resource stock. For linear demand, the direct and the indirect effects of the subsidy exactly offset each other if the resource is costless to extract. With positive but constant extraction costs, the first direct effect will always dominate, and the green paradox is reversed, just as in Gerlagh (2011). If, however, energy demand is no longer linear, Grafton et al. (2012) show that the green paradox may arise so that the indirect effect outsets the direct effect of a higher subsidy rate.

A backstop technology with linearly increasing costs of energy generation and the effect of (exogenous) reductions in the generation costs is also considered by van der Ploeg and Withagen (2012a), again assuming linear energy demand. However, they allow for more general parameter constellations which imply that, preceding the phase of simultaneous use of fossil resources and the backstop technology, there may additionally arise a third phase where only the fossil resource is used. Moreover, van der Ploeg and Withagen (2012a) focus on stock depending extraction costs so that even for a high cost backstop technology the resource stock may not be completely exhausted. Overall, the scenarios analyzed by Gerlagh (2011) and Grafton et al. (2012), where a pure fossil resource era is excluded, constitute only one of the four possible scenarios which van der Ploeg and Withagen (2012a) distinguish. They show that a green paradox does not occur if both energy sources are used simultaneously and if the resource stock is only partially depleted. In this case, reducing the costs of the backstop technology crowds out the fossil resource at every point in time,[7] and therefore decreases overall extraction independent of how long the phase of simultaneous use lasts. They also confirm the observation by Gerlagh (2011) and Grafton et al. (2012) that a green paradox will not arise if the resource stock is completely exhausted in finite time throughout the phase of simultaneous use of both energy sources. However, with a third, pure fossil resource era beforehand, the climate mitigation effect of a, possibly climate policy driven, reduction in the market price of the backstop technology tends to deteriorate. With complete exhaustion of the resource stock in the second phase of simultaneous use, a reduction of the costs of the backstop technology then induces a shift of resource extraction to the first phase – a weak green paradox – and thereby also implies that the resource stock is overall exhausted over a shorter period of time so that even the cumulative climate damage are likely to rise (strong green paradox). If there are economic limits to aggregate extraction and the resource stock gets only partially exhausted, resource extraction will also be shifted to the preceding fossil resource era, but, as in the more simpler settings with constant generation costs of the backstop technology, there is a counteracting effect from the reduction in cumulative emissions since aggregate extraction falls with the backstop technology becoming more competitive in the second period. Hence, in general, the effect on the (present value of) cumulative climate damages is ambiguous in this case.

Even with increasing (marginal) costs of energy generation, the imperfect backstop technologies in these contributions are able to perfectly substitute fossil resources. Long (2014) deviates from the assumption of perfect substitutability and introduces a substitutive energy source which differs from fossil resources not only with respect to generation costs but also with respect to the utility it provides to energy consumers. With competitive markets and simultaneous use of both energy sources, there are different but nevertheless interdependent market demand functions for fossil and renewable energy[8] and, correspondingly, the market prices for fossil and renewable energy fall apart. The improvement of the imperfect substitutability between fossil and renewable energy sources then represents an additional form of technological

[7] This corresponds to the direct effect of a backstop subsidy pointed out by Grafton et al. (2012).

[8] Obviously, as also pointed out by Michielsen (2014a), the cross price reaction, for example of resource demand to changes in the market price of the backstop technology, can be seen as an indicator of the substitutability between both energy sources from the perspective of energy users.

progress which climate policies may aim to achieve. Investigating such an improvement in the imperfect substitutability under the assumption that there is a phase of simultaneous use of both energy sources beforehand in which the resource stock is completely exhausted, Long (2014) follows Grafton et al. (2012) and distinguishes counteracting direct and indirect effects on residual energy demand. If the indirect effect from the induced decrease in the resource price path dominates, residual resource demand will rise and a green paradox will occur. In contrast, if the direct effect from the improved competitiveness of renewable energy is stronger, residual resource demand will fall and the green paradox does not arise. For a linear-quadratic utility function, constant extraction costs, and increasing renewable energy costs, Long (2014) demonstrates that whether a green paradox arises or not depends on the initially given degree of substitutability. The higher the substitutability initially, the more likely the direct competitiveness effect dominates, and therefore the more likely a green paradox occurs. van der Meijden (2014) also studies an imperfect backstop technology in an (general equilibrium) endogenous growth model but focuses on the implications which different degrees of substitutability between both energy sources in the energy sector have on the transition from fossil resources to the backstop technology. Similar to Long (2014), he finds that the imperfect substitutability prolongs the phase of simultaneous use. Moreover, the availability of the backstop technology gives rise to an acceleration of extraction. However, an increase in the substitutability of both energy sources does not induce an acceleration of extraction. The reason is twofold. First, with a better substitutability between both energy sources, labour can be released from energy generation with the backstop technology to research and development which drives economic growth. Thus, fossil resources become more important for energy supply over a longer period of time which implies that resource extraction must be more evenly distributed over time and therefore lower in the beginning. Second, with higher economic growth, energy demand in the future is higher, too, which also creates an incentive to postpone extraction.

Overall, the intertemporal supply reactions of resource owners become less relevant for the mitigation and welfare effects of (second best) climate policies as soon as climate policies do not only affect the timing but also reduce the volume of resource extraction. But this conclusion obviously needs to be qualified if the carbon free substitutive technologies, which are explicitly or implicitly supported by climate policies, can only imperfectly substitute fossil resources so that the second margin of climate policies introduced by the endogeneity of aggregate extraction is attenuated.

Dirty Backstops

The role of the intertemporal supply reactions of resource owners for the overall effect of climate policies also heavily relies on the assumption that the development and the volume of carbon emissions directly and solely depend on the use of scarce and exhaustible fossil resources. However, as for example illustrated in the recent world energy outlook (IEA 2015b), fossil resources generally differ with respect to the extraction costs, the carbon intensity, and the availability or volume of resource stocks. In particular, coal is more carbon intensive and more abundant than oil or natural gas, and at the same often cheaper to extract. Regarding the discussion of the green paradox, this observation implies that intertemporal supply responses may be much less an issue for coal than for the more scarce fossil resources oil and natural gas, simply because the market supply of coal is likely not to be influenced by scarcity rents and intertemporal trade-offs. Instead, coal can be seen as an additional, rather cheap, but dirty backstop energy source (van der Ploeg and Withagen 2012b, and Michielsen 2014a). From this perspective, the environmental effect of climate policies depends heavily on whether they limit the use of the dirty backstop coal, and much less on whether they induce intertemporal supply responses of the owners of the scarce and less carbon intensive fossil resources. Even a substantial subsidy on carbon free (renewable) energy technologies then can lead to increases not only in green welfare – i.e. a reduction of the climate damages – but also in overall welfare if it renders the use of coal unattractive and ensures that the economy switches to the carbon free renewable technology in the long run instead of the carbon intensive backstop technology. van der Ploeg and Withagen (2012b) show that since the refinancing of the subsidy comes at additional welfare costs, this generally will hold true if the cost difference between coal and renewable energy is not too large, if coal is highly carbon intensive, and if future climate damages are not discounted too heavily for social welfare. Moreover, in contrast to the case without the dirty backstop as, for example, analyzed by van der Ploeg and Withagen (2012a), this even holds true with complete exhaustion of the stock of the less carbon intensive, scarce fossil resources and an acceleration of extraction (weak green paradox).[9] The notion of coal as a kind of a dirty backstop to oil and natural gas also leads Harstadt (2012) to argue that buying and sealing coal deposits can be seen as a promising effective and supply-side oriented climate policy

[9] In fact, van der Ploeg and Withagen (2012b) also show that technological progress reducing the costs of the renewable backstop technology accelerates the extraction of the less carbon intensive resource but nevertheless leads to welfare gains with the first best carbon tax policy implemented because the economy switches earlier from the dirty to the climate friendly backstop technology which lowers cumulative emissions.

approach, even though it does not necessarily exclude intertemporal resource supply shifts in contrast to the reasoning of Sinn (2008b). Michielsen (2014a) points out that with imperfect substitutability between fossil resources and given the availability of clean and dirty backstop technologies the effect of second best climate policies on cumulative emissions and of the development of emissions over time also crucially depends on the degree of substitutability between the fossil resource and the dirty backstop. In particular, due to potential substitution effects between the dirty backstop technology and the fossil resource, he demonstrates that a green paradox like increase in short run emissions may arise upon an introduction or tightening of future carbon taxes even if resource extraction is postponed. The reason is that with a high substitutability the carbon tax induces a substitution effect towards the less carbon intensive resource in the second period, which leads to a postponement of resource extraction, but at the same time to an increase in the use of the more carbon intensive dirty backstop in the first period. Similarly with a high substitutability between the dirty backstop and the fossil resource, even though a subsidy on the renewable energy always leads to an acceleration of resource extraction, short run emissions will not necessarily rise as the increase in fossil resource supply crowds out the dirty backstop. Moreover, even if there is a weak green paradox in this case, a strong green paradox will not necessarily arise because the subsidy on the clean backstop always reduces emissions in the longer run with simultaneous use of all energy sources.

Endogenous and Complementary Technological Change

It has also been pointed out in the literature that the assessment of climate policies, and technological support schemes in particular, can fundamentally change with endogenous technological change. Daubanes et al. (2013) abstract from reductions in cumulative emissions and focus solely on the speed of resource extraction but consider the effect of support schemes for research and development of carbon free production factors within a framework of directed technical change (Acemoglu 2002). They show that the conventional wisdom about the effect of technology subsidies with complete exhaustion of the resource stock does not necessarily hold true as an increasingly strong support for research and development of the carbon free production factor can actually raise the demand for fossil resources over time due to the endogenous distribution of research efforts and the accompanying changes in the production structure of the economy. Obviously, such an increase in resource demand excludes a green paradox and induces a postponement of resource extraction. Nachtigall and Rübbelke (2016) investigate the implications of endogenous reductions in the costs of a substitutive renewable energy technology arising from learning-by-doing. At first, with these learning-by-doing effects, a subsidy for the use of the renewable energy in the current period reduces residual resource demand in the current period but also the costs of renewable energies in the future and thereby future residual resource demand. If this indirect effect via learning-by-doing is strong enough, a (weak) green paradox will arise. In contrast, they also demonstrate that even a second best carbon tax policy may lead to a postponement of resource extraction with rising extraction costs. The reason is that future carbon taxation makes renewable energy producers anticipate a larger future market share and thereby larger benefits from learning-by-doing[10] so that they increase the deployment of renewable energies already in the current period. But this lowers the energy price in the present period which in turn induces the resource owners to postpone extraction. Again, if this indirect effect from the response of the renewable energy sector is stronger, the green paradox will be reversed.

Hoel and Jensen (2012) do not consider endogenous technical change but point out that new technologies implicitly or explicitly supported by climate policies may not only be substitutive to fossil resources but also complementary such as carbon capture and storage (CCS). In a second best setting, where a carbon tax is politically only feasible in the future, they show that fostering cost reducing technological change for such a complementary mitigation technology does not induce an acceleration but a postponement of extraction and therefore can be preferable to a technology policy targeting substitutive renewable energies, which indeed leads to an acceleration of extraction.[11] Similarly, Spinesi (2012) points out that climate policies may also induce technological improvements within the fossil resource sector. In particular, climate policies can create an incentive to develop and improve extraction techniques so that extraction costs fall over time. Since these reductions in costs counteract the tax induced losses in resource rents, a green paradox may no longer arise.

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[10] This crucially relies on the albeit plausible assumption that the benefit from learning from a higher deployment of the renewable energy technology in the current period is the greater the higher the renewable energy generation in the second period.

[11] However, if there is no carbon tax at all, subsidizing the development of substitutive renewable energy at least opens up the possibility that fossil resources might be crowded out of the energy market in the future whereas a subsidy of carbon capture and storage (CCS) only incurs additional costs.

Geographical Leakage

Government failure to implement the first best climate policy in all these contributions is related to political constraints which make politicians prefer subsidies over taxes, or related to informational and commitment constraints when designing and announcing long-term paths of carbon taxes. However, an even more prominent source of governmental failure in the context of climate politics is the lack of international cooperation and coordination due to strong free-riding incentives. In a world with various jurisdictions pursuing different climate policy goals, the effectiveness of unilateral climate policies is generally likely to be undermined by increases in resource use and emissions in non-abating regions, i.e. by geographical (carbon) leakage effects.[12] Most obviously, unilateral climate policies affect the world market price of fossil resources by reducing the demand from the abating regions so that the resource market price tends to fall which in turn raises resource demand from non-abating regions (see also Sinn 2008a). Geographical leakage effects also arise by globally operating firms choosing to relocate carbon intensive production activities to non-abating regions,[13] and from induced changes in the international trade patterns and factor (capital) movements (for example, Copeland and Taylor 2005, and Burniaux and Martins 2012). These static leakage effects – in contrast to intertemporal leakage effects from the intertemporal supply responses of resource owners – may even exceed 100%.[14] Thus, even in purely static frameworks with heterogeneous countries and international trade in goods and factors, climate policies may

[12] The literature has identified various channels which can give rise to carbon leakage. van der Werf and Di Maria 2012, for example, distinguish the following: The "energy market channel" refers to the reduction in the world market price for fossil resources from a unilateral climate policy tightening, which induces an increase in fossil resource demand from non-abating regions. The "terms of trade channel" captures the fact that climate policies do not only affect the relative world market prices of fossil resources but also of other goods whose production is carbon intensive, and thereby lead to a change in the international patterns of trade in these goods according to the comparative advantages of non-abating regions in the production of these goods. Another reason for carbon leakage is the mobility of production factors, and in particular capital. If climate policies reduce the return on investments in abating countries, capital will flow to the non-abating regions and may raise emissions there by fostering production and growth. Knowledge spillover effects from the abating to the non-abating countries, or endogenous technical change, however, may reduce the leakage rates as has been pointed out, for example, by Di Maria and van der Werf (2008).

[13] This represents the so-called pollution haven effect, see, for example, with a focus on the effect of environmental regulation in the U.S. Levinson (2010).

[14] For empirical assessments of geographical leakage effects, see, for example, Levinson (2010), or Aichele and Felbermayr (2012) and Aichele and Felbermayr (2015).

result in outcomes which are completely detrimental to the actual intentions of policy makers and therefore can be interpreted as a green paradox in a broader sense. However, geographical leakage effects and country heterogeneity with respect to climate policies can also have strong implications within more dynamic frameworks which include the intertemporal supply decisions of owners of exhaustible fossil resources. In this context, we may rather generally note that if the climate policy scheme comprises a cap on carbon emissions, i.e. a quantity based approach to regulating carbon emissions in contrast to price instrument such as a carbon tax, and if there is no implementation lag, an increase in global carbon emissions in the short term and thereby a green paradox outcome will only be possible with geographical leakage of carbon emissions to non-abating regions.

The role of country heterogeneity for the arising of the green paradox has first been pointed out by Hoel (2011). He demonstrates that increasing the subsidies for a perfect but only locally used backstop technology, when there is a global competitive resource market and there are low and constant unit extraction costs, does not necessarily induce a strong green paradox if there are multiple countries with different subsidy levels and the subsidy is increased in the country which supports the backstop technology already stronger initially. However, if the subsidy is raised in the country with a lower support level, a strong green paradox will arise because the resource stock will then be depleted over a shorter period of time. In contrast, within a singly country, the latter always holds true in such a setting as we already have discussed before (see, for example, Gerlagh 2011). Intuitively, different climate policies in this multiple country setting imply that the countries switch to the backstop technology at different points in time, while due to the global resource market the resource producer price must be equalized across countries. The climate damage mitigation effect of unilateral climate policy initiatives then generally heavily depends on whether the total exhaustion time of the resource stock gets prolonged or not, which in turn depends on whether the more ambitious country tightens its climate policy or not. In the subsidy example, if countries only differ with respect to the subsidy levels, and if the more ambitious country further increases its subsidies, this country will introduce the backstop technology more early in time but at the same time the resource producer price path will be shifted downwards. This implies, on the one hand, that emissions in the short term increase, and therefore that a weak green paradox arises. But on the other hand, the country with the lower and constant subsidy will use the resource longer so that the time up to exhaustion of the resource stock is prolonged which tends to reduce cumulative climate damages. In contrast, if the less ambitious country increases its subsidy, the total depletion time will be shortened and early emissions will increase by the reduction in the resource price level even though the latter also induces the country with the higher subsidy to use the fossil resource longer.

A very similar effect of such a unilateral backstop subsidy is found by Ryszka and Withagen (2016), who extend and generalize the analysis of Hoel (2011) by introducing different extraction costs of fossil resources and different backstop energy costs across the abating and non-abating regions. Specifically, they assume that the abating country has a comparative (cost) advantage in producing the backstop energy but a disadvantage in extracting its resource pool. While the global resource stock is again completely exhausted in any case under these assumptions as in Hoel (2011), the differences in extraction costs have, in particular, implications for the effects of a unilateral carbon tax policy. With uniform extraction costs, a unilateral tightening of the carbon tax policy may give rise to a strong green paradox if the region with the lower carbon tax increases the tax rate and resource demand is sufficiently price-elastic. In fact, in this case the higher carbon tax shifts the resource price path downwards which increases short-term emissions, extends the use of fossil resources in the region with a higher carbon tax, and overall shortens the time to exhaustion of the resource stock. Ryszka and Withagen (2016) point out that this rather pessimistic result does not carry over to the setting with differing but constant extraction costs where a unilateral rise in the carbon tax can induce a weak but no strong green paradox, irrespective of whether the abating or the non-abating country increases the tax rate.

Grafton et al. (2012) also briefly discuss carbon leakage by assuming a two country setting where the imperfect backstop technology with rising unit production costs is available only in one country. With linear aggregate energy demand, they show that in equilibrium fossil resources are first supplied to both countries and used simultaneously with the backstop technology before the more green country completely switches to the backstop technology and resources are only supplied to the non-abating country. Increasing the subsidy payments for the backstop technology, reduces residual resource demand from the "green" country and thereby shortens the first phase while the second phase is prolonged. Thus, the effect of the subsidy on the overall exhaustion time is ambiguous, in general, which is in contrast to the uniform country case with linear demand where the date of exhaustion is constant or postponed.

2.2.2 The Role of Resource Market Power

So far, there have been surprisingly few contributions to the literature on the green paradox which explicitly consider the effect of climate policies in a resource market with imperfect competition, although, for example, van der Ploeg and Withagen (2012a) note that markets for fossil resources are far from being truly competitive in reality. One reason for this minor interest in resource market power probably is that market power has relatively little consequences for the characterization of the resource extraction path in more standard Hotelling frameworks as shown in the previous section 2.1.2, and correspondingly does not seem to alter the effect of second best climate policies qualitatively in many of the settings discussed so far.

To see this, we again return to the simplified two period model of resource extraction introduced before. Completely analogue to (2.8), we can derive the response of the resource monopolist to an (marginal) increase in the second period (value added) carbon tax τ from differentiating the corresponding Hotelling condition (2.5). The comparative statics

$$\frac{dR_2^m}{d\tau} = \frac{-\left(p_2 + \frac{\partial p_2}{\partial R_2} R_2\right)}{-(1+i_2)\frac{\partial MR_1}{\partial R_1} - (1-\tau)\frac{\partial MR_2}{\partial R_2}} < 0 \tag{2.9}$$

is again of negative sign because with marginal resource revenue MR_t from (2.6) decreasing in resource supply the denominator is again unambiguously positive whereas the numerator again captures the loss in resource rents incurred ceteris paribus from a marginal increase in the carbon tax. Intuitively, the resource monopolist accelerates extraction as to evade the larger carbon tax burden in the second period. Thus, the green paradox necessarily arises from the second best climate policy which is represented by the increasing value added resource tax in this case, just as for the competitive market. Moreover, it arises exactly for the same reason as in the competitive resource market in this simplified standard two period model of resource extraction.

This conclusion is more or less confirmed by van der Ploeg and Withagen (2012a) and Grafton et al. (2012), who both consider the monopolistic case as an extension of their analysis of the effects which are brought about by reductions in the costs of a backstop technology. van der Ploeg and Withagen (2012a) thereby assume stock dependent and therefore over time rising extraction costs but constant marginal costs of the backstop technology, whereas Grafton et al. (2012) assume constant extraction costs but rising marginal costs of the backstop technology. Overall, however, they arrive at virtually the same results as in the respective standard setting with a competitive resource market. For example, van der Ploeg and Withagen (2012a) again find that if the level of the stock dependent extraction costs is low so that the last drop of oil is cheaper to extract than the backstop technology, the resource stock will be completely exhausted. In this case, lowering the backstop costs will shorten the period of time over which the resource stock is exhausted by the monopolist. Hence, a weak and a strong green paradox necessarily arises just as in the competitive market. If the last drop of oil is more expensive than the production costs of the backstop technology, lowering the competitive market price of the backstop technology will reduce cumulative extraction but also shorten the period of resource extraction. Thus, a strong green paradox will only arise if the reduction in cumulative extraction is not too strong, which again is more or less the same conclusion as for the competitive market case discussed before.

The resource monopoly case is also briefly examined by Long (2014) when studying the implications of changes in the imperfect substitutability between fossil and renewable resources for the extraction path and carbon emissions. He assumes that with simultaneous use of both energy sources the resource monopolist takes the position of the market leader and accounts for the supply decisions of the competitive fringe represented by the renewable energy producers. He finds that the threshold level of the degree of substitutability for the arising of the green paradox does not change with market power but that the monopolist exhausts the stock over a longer period of time. The latter may be seen as a representation of a conservationist's bias introduced by resource market power, which is also found by van der Ploeg and Withagen (2012a). Moreover, if the degree of substitutability is sufficiently high so that upon an increase in the substitutability the time up to exhaustion of the resource stock decreases and a green paradox arises, the monopolist will react more strongly and reduce the extraction time more strongly than in the competitive market case. Still, the overall effect of an increase in the substitutability between the fossil resource and renewable energies is qualitatively the same as under perfect competition.

However, in general, resource market power extends the ability of the resource owner to more strategically react to climate policies and to the threat of a future competitive backstop technology.[15] This is pointed out by van der Ploeg (2012) who demonstrates

[15] If the resource demand side is able to coordinate and thereby to strategically invest in substitutive technologies, the equilibrium resource supply path will no longer be characterized by Hotelling arbitrage considerations but by a kind of a modified limit pricing regime, which arises from the

that a resource monopolist will speed up extraction if she anticipates governmental support for research and development to increase the probability of an eventual technological breakthrough and to bring forward such a breakthrough in the development of a substitutive technology. If the resource monopolist has to invest in the exploration of the resource stock, this weak green paradox, however, is counteracted again since the monopolist at the same time responses to the eventual market entry of the backstop technology by reducing the exploration activities. Thus, cumulative extraction falls and the arising of a strong green paradox is less likely.

More recently, the implications of limit pricing regimes, and thereby also of resource market power, for the effect of climate policies have been studied in more detail by Andrade de Sà and Daubanes (2016) and van der Meijden et al. (2015a). Both contributions in particular illustrate that the assessment of climate policies can be altered completely by the arising of limit pricing regimes in the monopolistic resource market. van der Meijden et al. (2015a) first consider a setting where the resource monopolist is confronted with global but nevertheless second best climate policies, i.e. strong increasing carbon taxes over time and/or a subsidy scheme for a perfect backstop technology. They assume constant (but not prohibitively high) extraction costs and a perfect backstop technology with constant marginal production costs. Hence, they introduce a framework in which under competition the resource stock is necessarily completely exploited so that a weak and a strong green paradox necessarily arise from increases in future carbon taxes and from subsidizing the backstop technology (see above, or, for example, Hoel 2008, or Gerlagh 2011). In contrast, they show that in the monopoly case a weak green paradox is never induced, neither by the backstop subsidy nor a rise in the carbon tax. The reason is that there is a limit pricing phase before exhaustion of the resource stock during which the resource monopolist has to increase her market supply as to keep the backstop technology out of the market when climate policies are tightened. With complete exhaustion of the resource stock, however, this implies that there must be a postponement of extraction. But at the same time, cumulative climate damages may still increase because the monopolist depletes the resource stock over a shorter period of time. Thus, also in contrast to the competitive market, even though there is no weak green paradox, a strong green paradox may still arise. Second, van der Meijden et al. (2015a) give up the assumption of a single jurisdiction and distinguish two regions where one region is completely inactive with respect to climate policies. They show that the results from the single

interaction of the strategic incentives of the resource monopolist and the demand side as, for example, in Gerlagh and Liski (2011) or Michielsen (2014b).

jurisdiction case, in principle, transfer to the more general, or realistic, case of heterogeneous countries. Thus, unilateral climate policies do not induce a weak green paradox but may lead to an increase in emissions in later periods, or more specifically, in the medium term. The reason is that in this heterogeneous country setting two limit pricing phases may arise (depending on the size of the resource stock) as the monopolist, in addition to the familiar limit pricing phase before exhaustion of the resource stock, may also find it optimal in between to deter, or delay, the market entry of the backstop technology in the politically active region for some time by keeping the market price slightly below the subsidized price of the backstop technology there. Afterwards, the resource monopolist only supplies to the region where no climate policies are enforced at all, and the familiar second limit pricing phase towards exhaustion of the resource stock arises. Unilaterally tightening climate policies in the more ambitious region then obviously only affects the first limit pricing phase: The first phase of limit pricing is prolonged and the monopolist must increase its supply therein as to deter the market entry of the more strongly subsidized backstop technology in that region. But this requires a shift of resource extraction from the short term to later periods so that no weak green paradox arises. Additionally, van der Meijden et al. (2015a) demonstrate that unilateral climate policies also induce carbon leakage to the inactive region because this region is supplied with fossil resources over a longer period of time.[16] Overall, although short-term emissions decrease, unilateral climate policies may still give rise to a strong green paradox by the increase in emissions in the medium term and the longer term due to the induced carbon leakage to the inactive region in future periods.

As already discussed before (see section 2.1.2), Andrade de Sà and Daubanes (2016) consider a setting of permanent limit pricing (with constant and non-prohibitive extraction costs) to methodologically reconcile the assumption of resource market power with the empirical observation of price-inelastic resource (oil) demand. In such a setting, in contrast to the competitive market and more standard settings with price-elastic resource demand, carbon taxes, irrespective of their time profile, are purely distributional and completely neutral with respect to the extraction decision. Of course, this holds true only as long as the carbon taxes do not reduce the resource

[16] In fact, unilaterally tightening climate policies does not affect the second limit pricing phase but prolongs the time period during which the monopolist solely supplies to the region without climate policies but does not yet pursue a limit pricing strategy. Moreover, in case of speculating behavior in the resource market and a continuous resource price over time, van der Meijden et al. (2015a) show that this prolongation also comes along with an increase in the overall resource supply to the politically inactive region.

producer price below extraction costs where the resource monopolist would opt to leave the market completely. Subsidizing the perfect backstop technology reduces the limit price ("choke price") and thereby induces the monopolist to increase her resource supply in every period up to exhaustion. Hence, a weak and strong green paradox arises. Andrade de Sà and Daubanes (2016) point out, however, that this green paradox outcome does no longer result from an intertemporal supply response but is due to the monopolist's static objective to deter the market entry of the perfect backstop technology. Additionally, they allow for imperfect, or "ordinary", substitutes to fossil resources, which do not jeopardize the entire resource demand and therefore are not deterred by the monopolist. In this case, an intermediate regime of simultaneous use of both, fossil resources and ordinary substitutes, arises, which still is compatible with limit pricing. They demonstrate that if the climate policy supports these ordinary substitutes instead of the backstop technology, a green paradox like increase in emissions in early periods of time will not occur. The reason is that a subsidy for the ordinary substitute directly reduces residual resource demand and thereby the equilibrium resource use and carbon emissions so that the resource stock is depleted over longer period of time.

3 Limitations of Partial Equilibrium Assessments

The literature on the green paradox is sometimes criticized by putting into question the intertemporal decision making of resource owners in the Hotelling framework (see Hart and Spiro 2011, Spiro 2014, Cairns 2014). We do not follow this line of reasoning here. However, we argue in line with van der Meijden et al. (2015b) that the literature surveyed in the previous chapter misses potentially important feedback effects and transmission channels of climate policies. The reason is the underlying assumption that the capital market equilibrium, which is mostly just represented by some given market rate of interest, is exogenous and thus independent of the resource supply path as well as of climate change mitigation. In this chapter, we will generally discuss and give an overview why this assumption may actually be too restrictive, and therefore why a general instead of a partial equilibrium approach, which allows for simultaneous adjustments of the capital market equilibrium, is warranted.

First, we argue that due to rather standard assumptions regarding the structure of production and the savings behavior and due to the savings out of resource revenues of resource owners there is an even closer interrelationship between the fossil resource market and the capital market than captured in the most parts of the literature on the green paradox. This implies, in general, that the capital market is in fact not independent of the resource supply decision, and that intertemporal resource supply responses to climate policies may often induce adjustments in the capital market which feed back into the resource extraction decision.

Second, there is a general belief that effective climate policies will have profound impacts on the structure of economies so that they are likely to affect not only the market for fossil resources but also other factor markets and in particular the capital market. We will give an overview over potential direct impacts of stringent climate policies on the capital, and financial, market. These impacts are, at first, separate from the resource owners' extraction reaction. However, given the close interrelationship of the resource and the capital market pointed out before, they may establish additional transmission channels through which climate policies can have an influence on the extraction policies of resource owners.

3.1 Interrelationship Between Resource and Capital Market

In general, the resource and the capital markets are characterized by dynamic, i.e. intertemporal, decision making and forward looking behavior. In the capital market, savings decisions are typically made to transfer income between different periods of time as to smooth consumption over time, and investment decisions of, for example, private firms are built upon a comparison of the future returns of the investment project with the costs of capital. As pointed out before in section 2.1, owners of fossil resources, in principle, also make similar dynamic decisions by trading-off two options to transfer wealth between different periods in time. They may either keep resources underground and get a return from an over time increasing resource price (rent), or may extract and invest the proceeds today thereby earning the market interest rate as a return over time. In market equilibrium, resource owners must be indifferent between these two options so that all arbitrage possibilities are completely exploited and no incentive to deviate from the extraction decision exists. Hence, a fundamental interrelationship between the market for fossil (exhaustible) resources and the capital market is inherent even to the most standard Hotelling setting due to the exhaustibility of resource stocks and the intertemporal nature of resource supply.[1] In the following, we argue that this interrelationship is, however, even closer due to the complementarity relationship between fossil resources and capital, and due to the investment activities of resource owners in the capital market.

3.1.1 The Role of Oil in the Global Economy: Complementarity of Production Factors

The industrial revolution started over two centuries ago not the least due to the technical developments which allowed to increasingly substitute human labour force and animals by energy, and thereby mostly fossil resources, in production processes. The availability of fossil resources is still, even after unprecedented growth in economic activity and technological knowledge, seen as a major factor driving the business cycle and economic growth and development in industrialized as well as emerging economies. This prominent role of fossil resources for economic growth and devel-

[1] Additionally, as also already pointed out before (see section 2.1.1 and Lozada 1993, and Farzin 1984), the development of resource stocks and resource extraction is capital intensive. This implies that there is capital demand from the resource sector, and therefore that changes in the interest rate also affect the costs of extraction or exploration.

opment is illustrated, for example, by Stern and Kander (2012), who show that energy services have played a crucial role for economic growth and development in Sweden. The link to energy services is relevant as fossil resources have been and still are major carriers of energy (see e.g. IEA 2015b).[2] Similarly, Berk and Yetkiner (2014) empirically test the influence of energy prices on economic growth and arrive at the conclusion that energy prices have a significant and long-term negative impact on GDP (gross domestic product) per capita. There is also empirical evidence that oil price increases are in fact significant drivers for the business cycle, and recessive developments in particular (see Engemann et al. 2011, or Kilian and Vigfusson 2014, and for an overview over the literature Hamilton 2012).

From a more abstract (macro-)economic point of view, this widely recognized (still) prominent role of fossil resources indicates a substantial degree of complementarity of fossil resources to other core factors of production such as capital and labour. Complementarity is typically assumed in the literature on economic growth with exhaustible resources, from the seminal contributions by Solow (1974) and Stiglitz (1974) up to the more recent endogenous growth models in the context of climate change change mitigation as, for example, by Acemoglu et al. (2012). In fact, a rather common production structure in this literature is the familiar constant elasticity of substitution (CES) production function, which in case of three production factors, energy R_t, (physical) capital K_t, and labour L_t, is given by

$$F_t = F(K_t, R_t) = \left[\lambda R_t^{\frac{\sigma-1}{\sigma}} + \gamma K_t^{\frac{\sigma-1}{\sigma}} + (1-\lambda-\gamma) L_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{3.1}$$

2 The substantial dependence of economic growth and activity on energy services is in particular emphasized in the ecological economics literature, for example by Ayres and Voudouris (2014).

The parameter σ denotes the constant elasticity of substitution between production factors. Aside from the limiting cases $\sigma \to 0$ and $\sigma \to \infty$,[3] the production factors are complementary, which is captured by the positive and symmetric cross derivative[4]

$$\frac{\partial F_{tR}}{\partial K_t} = \frac{\partial F_{tK}}{\partial R_t} = F_{tKR} > 0$$

Hence, the complementarity of production factors implies that fossil resources have a (contemporaneous) positive influence on the marginal productivity of capital in production, and vice versa that there is a positive relationship between the (physical) capital stock and the marginal productivity of fossil resources.

With regard to the discussion of intertemporal resource supply responses to climate policies, taking into account such a complementarity relationship between fossil resources and capital has various implications. First, any shift in the resource extraction path alters the productivity of capital and therefore also brings about changes in the market rate of interest. The latter, as we already know, feed back into the resource supply decision, given their intertemporal nature in the Hotelling framework. Second, resource supply responses are likely to give rise to changes in the capital stock. On the one hand, this is due to the aforementioned complementarity driven influence of resource supply on the interest rate which directly induces substitution and income effects and thereby changes in savings decisions. On the other hand, due to the limited substitutability of fossil energy resources in production, intertemporal resource supply responses shift production and thereby income between periods of time. Since savings decisions typically include a consumption smoothing component, such changes in the time profile of income lead to reactions in savings and thereby capital supply, too. Such changes in the capital stock are relevant for the supply decisions of resource owners since with complementarity of fossil resources and capital the productivity of resources, and thereby resource demand, positively

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3 For $\sigma \to \infty$, the CES production function converges to the linear production function

$$F(R_t, K_t) = \lambda R_t + \gamma K_t$$

with perfect substitution possibilities, while for $\sigma \to 0$ there are no substitution possibilities at all and production is represented by the Leontieff function

$$F(R_t, K_t) = \min \{R_t, K_t\}$$

See, for example, the corresponding discussion of the CES production function in Barro and Sala-i-Martin (2004) or Dasgupta and Heal (1979).

4 Factor subscripts denote the first and second partial derivatives of the production function with respect to the respective factor(s) throughout the text.

depends on the capital stock invested in production. All these effects, which generally can be motivated by the prominent role of fossil resources for economic growth and development, suggest that intertemporal supply reactions to climate policies give rise to feedback effects from the capital market. However, they are not captured in the literature on the green paradox surveyed in chapter 2 where the capital market is typically just represented by assuming some given, i.e. exogenous, market rate of interest (i_2) and some resource demand function ($p_t(R_t)$ from (2.1)).

At least some of these interrelationships between the resource, or oil, market and the capital market from the complementarity of resources and capital can also be observed from the empirical literature on the influence of oil market shocks. In fact, while oil price shocks in the public debate typically are attributed to supply disruptions, they can actually also be due to fast growing economic activities, i.e. due to oil demand shocks (see e.g. Hamilton 2011), which again clearly reflects the interrelationship between economic activities and oil demand pointed out before. Kilian (2009) shows that the cause of an oil price shock is crucial for the magnitude and the persistence of its influence on the (U.S.) economy, thereby distinguishing between oil supply shocks, oil demand shocks driven by strong economic activity, and oil demand shocks arising from precautionary demand in expectation of future oil supply disruptions. Moreover, following this distinction, Kilian and Park (2009) find that an oil price shock from precautionary demand has a negative influence on U.S. stock returns while oil price shocks due to strong oil demand from an unexpected economic boom come along with rising stock returns. The intuitive reason is that in this case stock returns but also oil market prices are driven by the increase in economic activity, which is perfectly consistent with the complementarity of oil and capital. Cunado and Perez de Gracia (2014) find a significant negative influence of oil price shocks on stock returns in oil importing European countries, which is, again distinguishing between supply and demand driven oil price shocks but using a different methodology than Kilian and Park (2009), in particular true for oil supply shocks. Such a positive relationship between capital returns and oil supply is also what we would expect given the complementarity of oil to economic activity and capital. Similar observations are presented by Kang et al. (2014) for the returns in the U.S. bond market. The aforementioned reversed influence of economic activity on the oil market, which is consistent with the complementarity of oil and capital as well, is also illustrated by the findings in Kilian and Hicks (2013), who show that the surge in oil prices between 2003 to 2008 was primarily due to the increasingly strong demand from emerging economies, and China in particular (see also Kilian and Murphy 2014).[5]

3.1.2 Capital Investments of Resource Owners

Resource owners typically do not spend all the proceeds from resource extraction on consumption but invest some portion in the capital market. This is more or less already indicated by the Hotelling arbitrage principle underlying the intertemporal nature of resource supply decisions, too. These investment activities are obviously directly dependent on the development of the resource price, or more specifically on resource profits, and therefore introduce an additional interrelationship between both markets. So far, however, they have played only a minor role in the analysis of the extraction behavior of resource owners, and do not play a role at all in the literature on the green paradox. In fact, as pointed out by Hoel (1981), under perfectly competitive markets and without uncertainty, holding capital assets (abroad) does not influence the extraction policies of resource owners. Still, at least two examples from economic history have already revealed and illustrated this linkage between the resource market and the capital market via the capital outflows from resource exporting countries and the role of the capital investments from resource-rich countries for the global economy.

During the oil price crises of the 1970s, the sharp increase in oil prices created huge windfall profits among the OPEC countries (in the Middle-East). Since these revenues largely exceeded their capacity to invest and consume at home, the large current account surpluses of OPEC states led to a huge flow of capital from the oil exporting to oil importing countries. International and, due to advantageous regulatory provisions, especially British commercial banks (Kopper 2009) served as intermediaries to invest the resource profits, in particular because bank deposits allowed to hide the actual source of investments. This recycling of petrodollars is seen as a major source for the global macroeconomic imbalances in the 1970s and 1980s and the low interests rates during that period of time (see e.g. Sachs 1981). Moreover, the liquidity provided by oil exporting countries to commercial banks facilitated the lending boom to emerg-

[5] Fouquet (2014) also discusses this relationship in terms of the long run development of the income elasticity of energy demand over time and finds an inverse U-shaped development of the income elasticity of energy demand over time with an evolving U.K. economy and falling energy prices over time.

ing economies and thereby is also seen to have significantly contributed to the arising of the Latin American debt crisis in the 1980s.[6]

Resource exporting countries have had even larger current account surpluses during the more recent phase of surging oil prices between 2002 and 2007 than during the oil price crises of the 1970s (e.g. Economist 2006). The price increase has again led to a large redistribution of income from oil importing to exporting countries, and at least the oil exporters from the Middle East have invested a large portion of these revenues to increase their holdings of foreign assets (Higgins et al. 2006). Arezki and Hasanov (2013) argue that the accompanying huge capital outflows from resource exporting countries again had a great influence on sustaining and increasing the global imbalances after the Asian crisis in 1997 (see also Belke and Gros 2010), and directly or indirectly financed the current account deficits of the U.S. (see also Higgins et al. 2006). Belke and Gros (2014) additionally relate the recycling of petrodollars from the Middle East OPEC countries to the rather unexpected low interest rates during the phase of robust world economic growth between 2000 and 2008. They point out that if robust economic growth comes along with rising resource (oil) prices, the increase in windfall profits and savings of resource exporting countries may create excess liquidity which tends to reduce the interest rate even though high rates of economic growth, in principle, suggest the opposite. They also argue that the capital supply from the recycling of petrodollars, together with the increased capital supply from emerging economies as especially China, has contributed to the excessive risk taking of the U.S. and European financial sector which gave rise to the financial crisis in 2008, and to the surplus of global savings over investment possibilities in the industrialized countries – a phenomenon which is typically referred to as global savings glut (see also Bernanke 2005, Bernanke 2015, or more general on the debate of the low interest rates Economist 2015).

The investment strategies and deployment of capital from nearly all resource exporting countries but Norway are rather intransparent and hard to track (cf. e.g. Economist 2007, Higgins et al. 2006). In the 1970s, as already pointed out, resource exporting countries deposited their windfall profits predominantly in international commercial banks. The commercial banks served as intermediaries to hide the actual source of investments and to recycle the petrodollars, in the end to the resource importing countries to settle the current account deficits there. After a large share of

6 On the relationship between the petrodollar recycling of international commercial banks and the Latin American debt crisis, see, for example, Dooley (1994), FDIC (1997), or Theberge (1998)).

the wealth accumulated in the 1970s was lost during the Latin American debt crisis and due to mismanagement and corruption in the following years, many resource exporting countries, especially in the Middle East, have followed the example of Norway and have established new institutions, state owned sovereign wealth funds (SWF), to secure and transform current resource rents into income for future generations which is independent of the exploitation of the exhaustible fossil resource stock (Clark and Monk 2012). Nevertheless, as shown by Wiegand (2008), apart from the resource exporting countries in the Middle East, bank deposits still played an important role for the recycling of windfall profits to emerging economies during the phase of surging resource prices in the 2000s. The SWFs from resource exporting countries have reached immense volumes in the meantime. Table 3.1 gives an overview over the volume of the sovereign wealth funds held by OPEC countries based on estimates of the Sovereign Wealth Funds Institute as of June 2016. However, there is very little to no information available about the investment strategies, the investment structure, and the overall financial wealth of these funds, mostly because the resource exporting countries provide virtually no information about their investment activities. Moreover, the capital investments of these funds are typically channeled through intermediaries, again in particular in the city of London due to the historically existing close relationship (Chevalier 2009, Economist 2006, Economist 2007).[7]

In particular with respect to the implications for the international capital market equilibrium, it also has to be taken into account that high or increasing resource profits, which obviously lead to higher capital exports from resource-rich countries, always entail an income redistribution from resource net consuming to net producing countries. Thus, apart from the implications of the capital exports from resource-rich countries for global imbalances and financial stability, aggregate capital supply in an (perfect) international capital market, for example, does not necessarily change. There will, however, be a net effect on capital supply if resource consumers and producers have different savings ratios, and/or if the capital supply from resource exporting countries has a non-marginal influence on world savings and thereby on the overall capital market. The latter would imply that resource exporters could, to some extent, exert market power in the capital market. Whether this is plausible or not is to some extent dependent on the perspective and on the basis of comparison as noted by Kimmit (2008) with respect to the volumes of SWFs. At least it seems to be indis-

[7] The investment strategies of SWFs is discussed in more detail by Bernstein et al. (2013). Megginson and Fotak (2015) provide an extensive survey of the overall literature on SWFs.

Table 3.1: Sovereign wealth funds of OPEC countries related to oil and gas

Country	Billion US $
Algeria	50
Angola	5.0
Iran	62
Iraq	0.9
Kuwait	592
Libya	66
Nigeria	1.4
Qatar	335
Saudi Arabia	598.4 + 160
UAE Abu Dhabi	792 + 110 + 66.3 + 66.3
UAE Dubai	196
UAE Federal	15
UAE Ras Al Khaimah	1.2
Venezuela	0.8
World total gas and oil related	**4,286.3**

Source: Sovereign Wealth Fund Institute, Fund Rankings, Update June 2016 (http://www.swfinstitute.org/sovereign-wealth-fund-rankings/)

putable that SWFs by now already have a significant role in the financial system, and that this role is likely to increase over time. For example, Saudi Arabia just recently announced as its "vision for 2030" a detailed plan to establish the world's largest SWF with a volume of about $2 trillion as to reduce the country's dependence on oil revenues by investments in all sorts of capital assets.[8] Megginson and Fotak (2015) point out that especially Arabian Gulf-based SWFs invested about US$ 60 billion in stocks of American and European banks and thereby prevented the banking system to collapse in early 2008. They conclude that these "funds have thus collectively invested more new capital into the world's financial institutions recently than any other single entity except the entire United States government" (p. 741). Differences in the savings ratios, or behavior, between resource exporting and importing countries can generally also not be excluded. For example, Higgins et al. (2006) find that the resource exporting countries from the Middle East increased their savings ratios during the more recent phase of rising oil prices from 2000 onwards to about 50%, which is certainly substantial higher than the savings ratios of oil importing western countries like the U.S. or in the European Union.

In general, if for either of the aforementioned reasons savings from resource owners have an (net) effect on the capital market, the investment activities of resource owners establish a relationship between resource rents and capital supply. In this case, the capital market equilibrium, i.e. the interest rate and the capital stock, is no longer independent of resource supply decision. Taking into account the savings from resource exporting countries, therefore, may give rise to feedback effects for the resource supply decision via the adjustments in the investment activities of resource-rich countries and the thereby induced changes in the interest rate and the capital stock, but also may introduce additional transmission channels of climate policies as far as climate policies affect the savings behavior of resource-rich countries, which we will discuss in section 3.2.3.

3.2 Climate Policies and the Capital Market: General Equilibrium Transmission Channels

The observations in the previous section indicate that in contrast to standard partial equilibrium approaches the capital market equilibrium represented by the equilib-

[8] see Economist (2016) and http://vision2030.gov.sa/en.

rium interest rate and the equilibrium capital stock is not independent of the supply decision of resource owners. This implies first that supply responses of resource owners may very well induce more widespread effects in the economy than typically captured in the mostly partial equilibrium literature on the green paradox reviewed in section 2.2. Moreover, by the complementarity of resources and capital, the resource supply decision does not only depend on the interest rate but also on the capital stock or the capital accumulation over time. In this section, we point out and discuss that climate policies may impact the capital market equilibrium even separately of the supply responses of resource owners. Given the dependence of the supply decisions on the interest rate and capital stocks, this then introduces additional channels by which climate policies can lead to resource supply responses.

To the best of our knowledge, there is no systematic and in-depth discussion of the potential consequences of climate policies, and the decarbonization of economies, for capital supply and demand and the interest rate so far. This is also somewhat beyond the scope of the following discussion. Yet, we will present an overview over related discussions in the literature, which suggests that enforcing stringent climate policies to decarbonize the world economy is likely to affect the market for physical capital, i.e. the accumulation of capital over time and the (marginal) productivity of capital and thereby the interest rate. In the following analytical part of this study, we will in particular focus on the distributional effects of climate policies laid out in section 3.2.3 and the capital investment needs discussed in section 3.2.4.

3.2.1 Mitigation Costs and Limits to Growth

Mitigation of climate change and stringent climate policies are widely seen as to incur economic costs due to the necessary reduction in the use of rather cheap energy services from fossil resources and the necessary switch to more costly technologies. The latter, for example, may be illustrated by technologies to capture and store carbon (CCS), which, albeit to some extent attenuating the necessary reduction in fossil resource use, certainly come at additional costs compared to conventional power plants. These so-called first-order effects of climate change mitigation are largely causing the costs in form of losses in output (gross domestic product, GDP) and consumption (growth) compared to the baseline scenarios reported in IPCC (2014). In the idealized cost efficient mitigation scenarios, limiting the concentration of greenhouse gases in the atmosphere to 430 - 480 ppm CO_2eq by 2100 is estimated to reduce the annual average consumption growth rates by 0.06 to 0.17 percentage points through

2050 (median of 0.09), and by 0.04 to 0.14 percentage points over the century (median of 0.06) relative to the baseline scenarios, which project annual consumption growth rates of 1.9% to 3.8% until 2050 and of 1.6% to 3.0% over the century. The estimated losses in GDP range between about 1% to 10% by 2100. Obviously, if these mitigation costs in terms of output and income losses in the future are anticipated by households, this will be relevant in the consumption-savings decisions and may induce households to save more for reasons of consumption smoothing. This channel, for example, has been investigated with respect to its implications for the supply of fossil resources by Smulders et al. (2012), whose contribution will be discussed in more detail in section 6.1. At the same time, with losses in economic output and activity investment possibilities and returns may shrink with climate change mitigation over the century. However, there is some uncertainty with regard to the long-term consequences of climate change mitigation for economic growth and development and therefore also for capital accumulation and capital returns, which arises especially from the uncertainty about technological developments along such a mitigation pathway.

Much of the concerns about the economic costs of climate policies are essentially due to the necessary reduction in the use of fossil energy resources given their so far fundamental role for economic growth reflected in the substantial complementarity to other production factors and capital in particular, as previously discussed. Climate change, however, is not the first natural restriction which raises such concerns. In fact, the potential for economic growth with shrinking use of fossil energy resources has already been intensively discussed with respect to the exhaustibility of fossil energy resources in the course of the oil price crises in the 1970s (see, for example, the seminal contributions by Solow 1974, Dasgupta and Heal 1974, and Stiglitz 1974). As pointed out throughout the introduction, climate change "just" poses even stricter limits on the overall use of fossil resources than the available resource stocks underground so that the fundamental conclusions from this strand of literature about the role of factor substitution and technical change for long-term economic growth still can provide important insights when considering the potential economic consequences of climate change mitigation. In these (neoclassical) growth settings, the role of factor substitution is typically discussed by use of a CES production structure as introduced before (see (3.1)) where the substitution possibilities are directly captured by the elasticity of substitution σ (see section 3.1.1). While natural resources are not necessary for production for $\sigma > 1$ in the sense that $F(R_t = 0) > 0$, it is a well known result of the literature that particularly the accumulation of capital over time can overcome natural limits of a necessary input factor only if the substitution possibilities are still fairly high ($\sigma = 1$) and if production is more dependent on capital than on the scarce natural resource. The latter is thereby captured by the condition that the output elasticity with respect to capital is greater than the output elasticity with respect to the natural resource, which corresponds to the restriction $\gamma > \lambda$ in the CES function from above (see (3.1)). For lower substitution possibilities $\sigma < 1$ (and $\sigma = 1$ but $\gamma < \lambda$), the natural resource is not only necessary for production but also "essential" to the economy (Dasgupta and Heal 1979) which implies that capital accumulation and substitution for the natural resource cannot sustain a constant consumption level (even for a constant population) in the long run.[9] However, even if the natural limits to resource use do not pose such strict constraints on economic development and consumption for $\sigma = 1$, capital accumulation is likely to fall below the necessary level to sustain income in a market economy at some point in time because with permanent accumulation of capital the diminishing returns to capital more and more reduce the savings incentives.

In the end, a major conclusion from the literature is that to overcome (natural) limits to the use of a necessary input factor (and the problem of diminishing returns) technological change is key. This also implies that the consequences which are to be expected for economic growth, for capital accumulation, and for the return on capital from climate change mitigation crucially depend on to what extent and how fast technological change will reduce the dependency of the global economy on fossil resources, which is inherently subject to large uncertainty. The vital role of technological developments is supported by the findings in IPCC (2014) where the first best mitigation scenarios are contrasted with scenarios under limited availability of specific mitigation technologies. For example, without availability of CCS technologies mitigation costs are likely to substantially increase mitigation costs since the idealized IPCC scenarios for limiting global warming below 2°C entail even negative emissions and since CCS turns out to be a flexible and widely complementary technology. Similarly, Bowen et al. (2014) point out that the wide range of results from a comparison of

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9 The reason is, as Dasgupta and Heal (1979) show, that in this case, although the marginal productivity approaches infinity for a decreasing factor input, the average product of the production factor is limited from above because

$$\lim_{R_t \to 0} \frac{F_t}{R_t} = \lim_{R_t \to 0} \left[\lambda + \gamma \left(\frac{K_t}{R_t} \right)^{\frac{\sigma-1}{\sigma}} + (1 - \lambda - \gamma) \left(\frac{L_t}{R_t} \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} = \lambda^{\frac{\sigma}{\sigma-1}}$$

This implies that the maximal output over all periods of time is bounded from above, too, so that, given the limited use of R_t, at some point in time in the future output and consumption must decline to zero.

the implementation of the 2°C target in various integrated assessment models (IAMs) is largely due to the underlying assumptions about the future possibilities to substitute fossil resources. In the so-called WITCH model, which takes a rather pessimistic position regarding the technological developments, the 2°C target incurs a significant GDP loss, while in the REMIND model there is virtually no loss in GDP and an increase in macroeconomic investments since the decarbonization there is achieved predominantly by future resource substitution and not by a reduction in energy demand.

The vital role of technological change is also emphasized by Smulders et al. (2014) who discuss the potential for "green growth" in the context of (neo-classical) growth models. Green growth refers to the idea that the transition towards low-carbon economies will not come at costs in the end, but to the contrary will create new potentials for growth in income and consumption, which has been put forward, for example, by Bowen et al. (2009). The notion of green growth has got particular attention in the political arena after the financial crises of 2008 as it proposes a way to overcome and reconcile two of the main challenges of our time, the rather persistent instability of the world economy and climate change. There are different rationales for the possibility of green growth (for a review, see Jacobs 2013, and Bowen and Hepburn 2014), ranging from creating a (Keynesian) stimulus for economic growth by green government spending (e.g. Bowen et al. 2009, or Barbier 2010) to stirring a new green industrial revolution (Stern and Rydge 2012). Based on the economic growth theory, some proponents also argue that environmental and climate policies correct for market failures which so far have led the economy on a sub-optimal and inefficient growth path, for example by creating more efficient, or new, incentives for research and development. This line of reasoning is related to the so-called Porter hypothesis, which generally states that environmental regulation can foster productivity and growth by incentivising research and development, but is still controversially debated in the literature (see Ambec et al. 2013). In general, it is rather obvious that if this vision of green growth holds true, climate policies will have profoundly different implications for the capital market than under the familiar paradigm of climate policies as a drag on economic growth. In fact, climate policies will in this case, for example, spur new and attractive investment opportunities and thereby increase capital demand, but by a consumption smoothing argument may also tend to reduce savings. However, overall, all these conclusions about the consequences of climate policies for savings incentives, investment possibilities, and capital returns which derive from the potential influence of climate change mitigation on long-term economic growth and development in the end crucially depend on the highly uncertain availability and costs of new technologies which allow to substitute fossil energy resources and to foster the productivity of capital.

3.2.2 Climate Change Impacts on Capital Markets

There is not only uncertainty about the future development paths under effective climate policies but also about the counterfactual, i.e. the business as usual pathways upon which the assessment of mitigation costs, for example, in IPCC (2014) is based on. IAMs by now have been criticized for a number of limitations.[10] Especially relevant in the context of the potential consequences of climate policies for the financial markets seems to be that they are criticized to often severely underestimate the economic impacts of climate change.[11] This is, on the hand, due to the fact that the cost-benefit approach underlying IAM analysis typically builds upon the comparison of the expected utility in different scenarios. But, as already pointed out in the introduction, relying on the probability weighted average of outcomes is prone to yield completely misleading insights if there are catastrophic climate risks, i.e. if climate change leads to severe disruptions and welfare losses with a low probabilities, as assigning low probabilities to catastrophic outcomes is likely to understate the scale of potential damages (Weitzman 2011). On the other hand, for example Stern (2013) points out that IAMs often do not adequately capture the economic impacts of climate change even apart from these tail risks. The reason is that IAMs typically assume against growing scientific evidence[12] that climate change incurs losses in output flows but no damages to capital stocks and to the underlying drivers for economic growth such as factor productivities or processes of endogenous growth as, for example, learning effects. Hence, they often do not capture long-term and potentially persistent impacts of climate change on the growth process of economies and thereby disregard potentially substantial and long-run losses in income and welfare in the baseline scenarios, even though global warming along these baseline pathways is very likely to exceed 3°C and to lead to completely unknown climatic conditions.

[10] See, for example, Stern (2013) and Revesz et al. (2014), or for an overview over this discussion Farmer et al. (2015).

[11] See also the comment by Stern (2016) on the most recent IPCC report.

[12] There are, for example, empirical studies using panel data sets on temperature changes within countries over time which have found a much stronger influence of weather conditions on economic productivity and output than current models project. For a review over the empirical literature on the relationship between weather realizations and economic growth see Dell et al. (2014).

Dietz and Stern (2015) illustrate these drawbacks by comparison of the baseline results of the standard DICE IAM with extended versions including negative impacts of climate change on the capital stock and on the growth of total factor productivity. Both extensions substantially lower the growth in per capital consumption in the baseline scenario without mitigation efforts, and therefore put forward a much stronger regulation of carbon emissions along the first best mitigation path than projected in the standard framework. These findings are more or less consistent with Moore and Diaz (2015), who modify the famous DICE framework to integrate empirical estimates of the impact of temperature changes on economic activities and growth from Dell et al. (2012). They are also supported by Burke et al. (2015), who estimate a non-linear concave relationship between temperature and economic production based on the within country variation in temperature and economic activity over time and, building on these estimation results, project the impacts of global warming on economic activities and income.

What do these observations imply for the financial (capital) market? Abstaining from climate change mitigation may come at significant losses in the value of (financial) assets. In general, as argued, for example, by Dietz et al. (2016) capital assets may be subject to faster depreciation or may even get completely destroyed by climate change due to, for example, storms or inundations. Moreover, since asset values reflect future returns and in the end are backed by the overall development of the economy, a devaluation of assets may also be due to climate change damaging overall factor productivity and disrupting endogenous drivers of economic growth and growth in factor productivity. To capture the negative impact of climate change, studies typically determine the "climate value at risk", which represents the present value loss in some portfolio of assets over a specific period of time that climate change may incur with a certain probability. EIU (2015) and Dietz et al. (2016) use an extended version of the DICE IAM, in which climate change directly damages capital stocks, to project the climate value at risk up to the year 2100 thereby focusing on the returns on all manageable assets held by non-financial institutions. In EIU (2015), the average expected climate value at risk is estimated to be US$$_{2015}$ 4.2 trillion from a private investor perspective with discount rates falling from 5.5% to 4% over the century. Based on an estimated current value of assets of US$ 143 trillion in 2013, this implies that investors overvalue assets by about 3%. Taking a government perspective with discount rates falling from 3.8% to 2%, the mean climate value at risk rises to US$$_{2015}$ 13.9 trillion. Considering more extreme global warming scenarios of 5°C or even 6°C, which occur with a probability of about 10% and about 3% respectively, the present value of asset losses increases to US$$_{2015}$ 7.2 trillion or even US$$_{2015}$ 13.8 trillion in the private investor case, and to US$$_{2015}$ 18.4 trillion and US$$_{2015}$ 43 trillion from the government perspective. Thus, there are substantial tail risks, which highlights also the position brought forward by Weitzman (2011).[13] These estimates, albeit already substantial, only refer to the stock of current financial assets and the climate change impact on their future returns but do not include the depreciation or destruction of non-financial assets. For example, by direct destruction of capital and lower overall investments, climate change leads to a mean reduction in the future capital stock of about 9%, and a reduction of 28% with 6°C global warming, according to the projections in EIU (2015).

The substantial costs of inaction suggest that climate policies may incur lower incremental (mitigation) costs in terms of economic activity and growth compared to the business as usual pathway than so far often expected from IAMs, or that climate policies by mitigating severe disruptions of economic growth potentials may even lead to gains in future welfare and income compared to business as usual. The latter more or less resembles the line of reasoning of the famous Stern report (see also Stern 2008), which argued that climate change mitigation will come at some costs but that these costs will be considerably lower than the costs caused by climate change when sticking to the business as usual ("brown") growth path, and provides also a rational for the proponents of "green growth" discussed before. By a standard consumption smoothing argument, this would give rise to lower or even negative instead of positive savings incentives from effective climate policies in contrast to what was argued before (see also Stern 2013). Similarly, since there is still large uncertainty about the economic impacts of climate change and there are catastrophic risks at least in the tail of the distribution of outcomes, climate policies can also be considered as an insurance strategy against these uncertainties and catastrophic risks (Weitzman 2011). From this perspective, we may rely on a precautionary savings argument to argue that climate policies may actually lower savings incentives by households. The projections by EIU (2015) and Dietz et al. (2016) demonstrate that climate policies are able to considerably reduce the value at risk of financial assets, and in particular tail risks from 5°C or 6°C global warming. In fact, limiting global warming to 2°C with a 66% chance reduces the mean losses in manageable assets by US$$_{2015}$ 2 trillion in the

[13] Of course, these results again significantly depend on the specifications of climate change impacts. This is, for example, illustrated by Covington and Thamotheram (2015) who especially study the value at risk from global warming exceeding 3°C. While the climate damage function from the standard DICE framework yields an almost negligible value at risk at 3°C of 2% of the representative portfolio, the value at risk from further warming amounts to 35% if more direct impacts on the endogenous growth processes are included as proposed by Dietz and Stern (2015).

private investor case or almost 50% according to EIU (2015), and even by 75% in case that global warming reaches 6°C by 2100 (EIU 2015).[14]

The consumption smoothing or precautionary savings reasoning, however, only applies if future income and value losses from climate change along a business as usual pathway are correctly anticipated and internalized by financial markets. But, notwithstanding the scale and the systemic nature of these climate risks, they are still not, or much too little, recognized and taken into account by financial market participants (see EIU 2015, or Covington et al. 2016). Covington and Thamotheram (2015) argue that this is due to a combination of reasons ranging from the rather misleading negligible consequences of climate change in many of the currently most prominent IAMs, over the short-term losses that often would have to be borne from low carbon investments at the moment, to the tendency for shortsightedness and insouciance in financial markets given an investment environment with large uncertainties about both, future climate damages and climate policies. This lack of awareness is also reflected in the projections of EIU (2015) because another interpretation of the results is that market participants overvalue current manageable assets, according to the mean climate value at risk by about 3% (see EIU 2015, p. 41).

The combination of significant asset values at risk and the insufficient reactions of financial market participants can give rise to future financial instability. This, of course, could be prevented by climate policies, not least since the necessary reallocation of investments and adjustments of investment strategies in the financial market to a large extent fail to be implemented due to the collective action problem inherent to the global externality of climate change. To this end, as pointed out by ESRB (2016), it is important that the low carbon transition is started early so that the economy can gradually adjust. Otherwise, climate policies themselves may put the financial stability at risk by devaluating considerable assets in the fossil resource sector and other sectors, whose products and technologies heavily rely on fossil resources. Stranded carbon intensive assets from abrupt decisive climate policy regulation and induced disruptive technological change seem to be particularly likely given the aforementioned still low recognition of climate change in financial markets, which indicates

[14] Dietz et al. (2016) find that limiting expected global warming from 2.5°C below 2°C with a 2/3 probability reduces the expected (mean) value at risk from 1.8% to about 1.18%, which in absolute terms amounts to a US$ 0.8 trillion reduction given an estimated global value of non-bank financial assets of US$ 143.3 trillion in 2013. Moreover, climate change mitigation particularly lowers the substantial tail risks as the value at risk of 16.86% or US$ 24.2 trillion at the 99th percentile in the business as usual case decreases to 9.17% or US$ 13.2 trillion in the mitigation scenario.

that investors so far have not priced in neither potential climate damages nor the consequences of a transition to low carbon economies. In this context, CTI (2014) points out that solely the exploitation of the fossil reserves which are currently under control of companies listed in the stock markets is inconsistent with the 2°C temperature target. At the same time, conservatively estimated about 20% to 30% of the market capitalization, for example, at the London exchange is directly related to the extraction of fossil fuels. This illustrates the significant exposure of capital markets and investors to the risk of stranded carbon intensive assets sometimes subsumed under the term “carbon bubble”. According to CTI (2015) stabilizing the greenhouse gas concentration in the atmosphere at 450 ppm (parts per million) in accordance with the 2°C target might render exploration and exploitation projects of publicly listed fossil fuel companies of over US$ 2 trillion over the next decade up to 2025 uneconomic. IEA (2014) measures the risk of stranded assets in the fossil fuel sectors only by the costs for exploration and development of fields or mines which are developed only in the business as usual scenario, the so-called New Policies Scenario, but not in the 450 ppm scenario. In this case, investments of US$ 130 billion for oil, US$ 50 billion for gas, and US$ 4 billion for coal by 2035 are prone to strand if there is a switch from the New Policies path to a 450 ppm path which is not expected by fossil fuel companies. Moreover, there is also a risk of stranding fossil fuel power plant investments of about US$ 120 billion as a substantial share of new fossil power plants would no longer be able to fully recover their fixed investment costs before decommissioning in these IEA projections. Still, these are rather conservative estimates of the values at risk. For example, CPI (2014a) also includes foregone revenues from lower fossil resource prices which raises the value at risk in fossil resource assets to some US$ 15 trillion, again just over the period up to 2035.

ESRB (2016) concludes that, while the direct first round exposure of the EU financial system seems to be manageable, financial stability can be at risk due to negative feedback, i.e. second round, effects, for example due to the high degree of debt financing of fossil resource firms. A combination of the value at risk from unmitigated climate change (e.g. Covington and Thamotheram 2014) and the climate policy risks of stranded assets has lead a number of large institutional investors such as big insurance companies as Allianz or the Norwegian SWF to restructure their portfolios and at least partly divest from assets whose return is backed by fossil resources (see, e.g., for an overview Baron and Fischer 2015). This divestment movement can be seen as the beginning of the necessary reallocation of capital away from carbon intensive fossil fuel backed assets but over the short term can also pose considerable problems for the financing of the energy sector (see for a discussion of the divestment campaign

Ansar et al. 2013). In any case, the costs of climate change mitigation, i.e. in particular the devaluation of carbon intensive assets, can considerably reduce the benefits from climate policies from the financial market perspective. This is also illustrated by Dietz et al. (2016), who find that the net effect of climate change mitigation on the present value of financial assets is significantly reduced to a 0.22% gain in the mean value at risk but still is positive in the long run and if investors are more risk averse.

3.2.3 Distributional Effects of Climate Policies

Given the rather asymmetric geographical distribution of resource stocks, the devaluation of fossil resources has also strong distributional implications between different countries and regions in the world. This is directly illustrated by the study of McGlade and Ekins (2015), who investigate the regional distribution of fossil resources unburnable under the remaining carbon budget for the 2°C global warming target. They find, as summarized by table 1.1, that unsurprisingly large shares of the remaining reserves must be left underground, but especially that about half of the oil and gas reserves which are not to be exploited globally are located in the Middle East while for coal the quantitatively largest burden in terms of unburnable reserves has to be borne by China, India, the FSU and the U.S. Even more important from the distributional perspective is the fact that oil and gas reverses tend to yield higher profit margins or rents, and thereby are more valuable than coal reserves. This is the reason why, for example, CPI (2014a) estimates that from the overall $US\$_{2013}$ 15.1 trillion of fossil resource value at risk US$ 11.2 trillion fall upon the oil owners while only US$ 1.7 trillion are at risk from coal, even though over 80% of the carbon emission reductions in the mitigation scenario fall upon coal. The results in CPI (2014a) also show that in particular net oil consuming countries can benefit substantially from a transition to a low carbon economy while countries like Saudi Arabia or Iraq would loose (see figure 9 therein). Similarly, Bauer et al. (2016) find that the net present value of fossil resource rents between 2010 and 2100 is reduced by $US\$_{2005}$ 12.4 trillion under a 450 ppm climate policy target with a loss of $US\$_{2005}$ 5.7 trillion in oil rents, of $US\$_{2005}$ 3.6 trillion in gas rents and $US\$_{2005}$ 3.1 trillion in coal rents. Investigating the regional distribution of resource rent losses, they also show that the Middle East together with North African countries incurs the largest losses. These estimates include foregone profits from resources which can no longer be exploited over the given period of time and from lower market (producer) prices.

That consumers of exhaustible resources are able to capture at least part of the scarcity rents by levying taxes or tariffs is a well known result from the early resource economics literature. In fact, Bergstrom (1982) showed that in a setting without extraction costs the tax burden from a value added resource tax is entirely borne by the resource owner, irrespective of whether the resource market is competitive or monopolistic. The reason is that raising taxes in such a setting, if anything, influences just the timing of extraction whereas overall resource supply is fixed by the given resource stock and thus inelastic. Brander and Djajic (1983) distinguish between resource net importing and exporting countries and show that the importers' ability to capture resource rents by levying import tariffs is restricted when the net exporting countries can use the resource themselves at home. The rent extraction motive of environmental or climate policies in particular is noted, for example, by Amundsen and Schöb (1999), who show that it creates an incentive for cooperation between countries even if cooperation is not required from the pure environmental policy perspective. In a dynamic game setting between resource importing countries coordinately levying a carbon tax and a cartel of resource exporters, Liski and Tahvonen (2004) point out that the optimal carbon tax for the resource importing countries includes, in addition to the internalization of the negative externality from carbon emissions, a strategic tariff policy component which aims to transfer rents from the resource cartel to the resource importing economies. Since climate policies ultimately have to aim to restrict the exploitation of fossil resources below the available stocks underground – given that the possibilities for capturing and in particular storing carbon are seen rather limited – they effectively render fossil resources abundant but create new scarcity via the carbon budget of the atmosphere for effective climate change mitigation. Hence, for example Eisenack et al. (2012) and Kalkuhl and Brecha (2013) argue that effective climate policies in the end turn resource rents into so-called climate rents from the scarcity of the atmospheric carbon budget. In contrast to resource rents, which naturally accrue to resource owners, the distribution of these climate rents is, however, subject to political negotiations and depends on the climate policy instruments which are adopted to enforce the climate policy targets (see also Edenhofer et al. 2013a). For example, if the carbon budget is implemented by a emissions trading scheme, the climate rents in the first place accrue to the governments, which then may or may not grandfather emissions permits to resource owners in order to compensate them for the resource rent income losses. Kalkuhl and Brecha (2013) investigate whether the scarcity rents increase or decrease with effective climate policies. They show that climate rents tend to exceed resource rents so that compensation is, in principle, feasible for a broad range of parameter assumptions, but that compensation from climate rents is the more difficult the higher the growth rates in fossil resource demand and the lower the discount rates of resource owners, i.e. the longer the time horizon of resource owners effectively is. Bauer et al. (2016) find in their IAM study of resource markets under climate policy regulation that the implementation of the 450 ppm stabilization target generates substantial climate (carbon) rents of US$$_{2005}$ 31.9 trillion, which are sufficient for compensating the overall loss in resource rents, but they also find that full compensation of resource owners also requires some redistribution of climate rents between regions.

This strong rent redistribution component of climate policies between resource-rich and -poor countries at first implies that resource-rich countries are likely not only to react to climate policies with shifts in their resource supply but also with shifts in their consumption-savings decisions, i.e. their capital investment decisions. The recent announcements of Saudi Arabia to heavily divest from fossil resources by 2030 and to even more strongly invest in the capital market (see section 3.1.2) may be seen as such a savings reaction to the more and more concrete emergence of an international climate policy architecture. Hence, for the capital market, the redistributive effects of climate policies, in particular on a national level between resource-rich and -poor or net producing and net consuming countries and regions, are especially relevant with respect to capital supply, apart from the previously noted risks for financial stability. However, analogue to what we already have noted with respect to the capital exports of resource-rich countries in section 3.1.2, in the international capital market there will only be a net impact on capital supply, if resource producers and consumers differ in their savings behavior so that different shares of the income which is redistributed by lower resource producer prices or by transformation of resource into climate rents are spent in both country groups yielding a positive or negative net effect on aggregate savings. Moreover, as also already noted before, such a net effect on aggregate savings can also arise if the capital exports from resource-rich countries are so large that they have a non-marginal influence in the capital market. In this case, the resource-rich countries would, in principle, be able to exert market power in the capital market via their capital supply decision. Changes in their capital supply by the climate policy induced rent income redistribution then would also have a significant effect on the capital market equilibrium.

3.2.4 Climate Change Mitigation and Future Investment Needs

Finally, limiting global warming to or even below 2°C will only be possible with an almost complete decarbonization of the energy system, as for example argued in IPCC

(2014). This requires considerable investments in the deployment (and development) of carbon free (renewable) energy technologies and in the improvement of the energy efficiency of economies. Moreover, the investment needs in the energy system tend to rise due to the widely acknowledged high capital intensity of low carbon and especially renewable energy technologies (see for example IEA 2015b, p. 323) and their overall generation characteristics (on the economics of renewable energies, see Heal 2009, Borenstein 2012, Edenhofer et al. 2013b). Hence, abstracting from the possible implications of these additional investment needs and capital costs for economic growth, which we discussed before, stringent climate policies and climate change mitigation may also bring about an increase in capital demand which, for example, could result in rising interest rates.

The recent investigation of the investment implications of a 2°C mitigation target in IEA (2016) may further illustrate this line of reasoning, in particular since the underlying assumption therein is that neither climate change mitigation nor climate damages impact economic (and) population growth to simplify the comparability of scenarios. Contrasting the business as usual pathway ("6DS scenario") with the so-called 2DS scenario, which is constructed as to limit the long-term average global temperature increase to 2°C with a probability of at least 50%,[15] mitigation of severe climate change entails a substantially lower increase in overall energy demand, a shift in primary energy demand from fossil towards renewable energies and in final energy demand towards electricity as the dominant energy carrier, and an almost complete decarbonization of electricity generation[16] as to decouple the (exogenous) growth in economic activity from carbon emissions. To this end, additional $US\$_{2014}$ 10.7 trillion have to be invested in renewable energies, $US\$_{2014}$ 2.1 trillion for carbon capture and storage (CCS), and $US\$_{2014}$ 1.8 trillion in nuclear energy. In total, since at the same time investments in conventional power plants and in infrastructure due to lower demand can be reduced by $US\$_{2014}$ 4.2 trillion and $US\$_{2014}$ 2.1 trillion, additional investments of about $US\$_{2014}$ 8.9 trillion are required compared to the business as usual path.

A similar "investment gap" in the electricity sector between the business as usual pathway and the realization of the mitigation targets of the Paris Agreement is de-

[15] This corresponds to a global cumulative emissions budget between 2013 and 2050 of around 1,000 $GtCO_2$.

[16] According to the projections, the CO_2-intensity of global electricity generation is reduced from 528 gCO_2/kWh in 2013 to under 40 gCO_2 in 2050.

rived in Ceres and BNEF (2016) where the additional investments are estimated to amount to US$$_{2015}$ 5.2 trillion in the period between 2015 and 2040. This study refers to a different time horizon than the IEA forecast before, but in particular is based on more optimistic assessments of the future development of renewable energy costs, which induces already a larger deployment of renewable energies in the business as usual case than in the IEA scenarios.

In IEA (2016) there are also projections presented about the investment need for the necessary deceleration of energy demand growth and the restructuring of final energy demand towards electricity as the main energy carrier. For buildings and in the industry sector, investments have to increase by about US$$_{2014}$ 18 trillion while the global investments in the transport sector are projected to be even lower by US$$_{2014}$ 14 trillion due to a shift from privately owned vehicles to public transport. However, it is also pointed out (p. 71 therein) that to limit the long-term increase in temperature below 2°C, or even below 1.5°C as stated in the Paris Agreement, even more radical changes to the energy system and most probably higher investments are necessary than so far found for the less ambitious 2DS scenario.

However, while there seems to be a rather broad consensus that investments in power generation and energy efficiency increase after the implementation of stringent climate change mitigation policy, overall energy related investments need not necessarily rise. Generally, an increase in investments in energy systems is widely expected already along business as usual pathways (see, e.g., IPCC 2014, or the current policies scenario in IEA 2015b), mainly because of growth in energy demand in non-industrialized (non-OECD) countries. From a climate policy perspective, the main problem, however, is that a too large share of these investments will go into the supply of fossil resources and fossil fuel based energy generation along the business as usual pathways, which directly reflects the market failure from the global warming externality. It is, therefore, emphasized that first and foremost a redirection of investment flows to low carbon technologies and energy efficiency measures will be crucial for reaching the 2°C global warming target (see also Boissinot et al. (2016)). Such a change in investment patterns does not only imply lower investments in fossil fuel based power generation, as shown by IEA (2016), but also substantial lower investments in the exploration and exploitation of fossil resource stocks. Obviously, this is also directly related to our previous discussion about stranded assets in the fossil resource sector. For example, CTI (2015) estimates that along a decarbonization pathway new extraction projects of the top 200 publicly listed fossil fuel companies of about US$ 1.9 trillion between 2015 and 2025 become obsolete. To some extent,

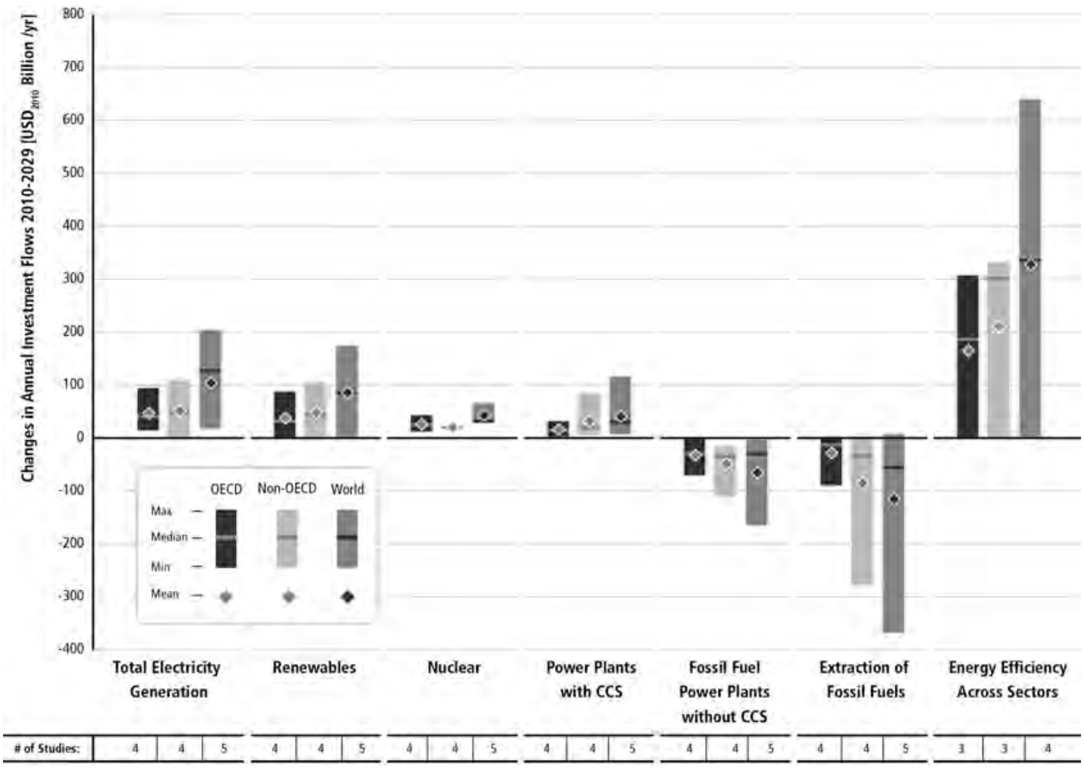

Figure 3.1: Change in annual investments when switching from business as usual to a 2°C mitigation pathway in the years from 2010 to 2029.
Source: IPCC 2014

this development is already reflected in the growing number of divestments from fossil resources and carbon intensive assets (see e.g. EIU 2015). The shift in investment patterns induced by stringent climate policies is, for example, observable from the scenario comparison in IEA (2015b). On the one hand, going from the so-called current policies scenario, in which only energy/climate policies enacted as of 2015 are taken into account in the projections for the period from 2015 to 2040, to the 450 ppm scenario, which represents a pathway towards limiting global warming to 2°C,[17] leads to a decline in cumulative investments in fossil fuel supply of about US$$_{2014}$ 14-15 trillion, but to an investment increase in the power supply sector of about US$$_{2014}$ 3-4 trillion, and to more than a doubling of the investments in end-use efficiency, which increase by about US$$_{2014}$ 16-17 trillion. On the other hand, overall cumulative investments rise rather moderately from about US$$_{2014}$ 66-68 trillion in the current

[17] The third scenario, the so-called new policies scenario, accounts for the climate pledges to COP21 as well as published energy policy intentions but still fails to limit global warming to 2°C. Interestingly, although there is already a significant shift in investment patters in the new policies scenario compared to the current policies scenario, there is virtually no change in overall cumulative investments which amount to US$$_{2014}$ 68 trillion in the new policies scenario.

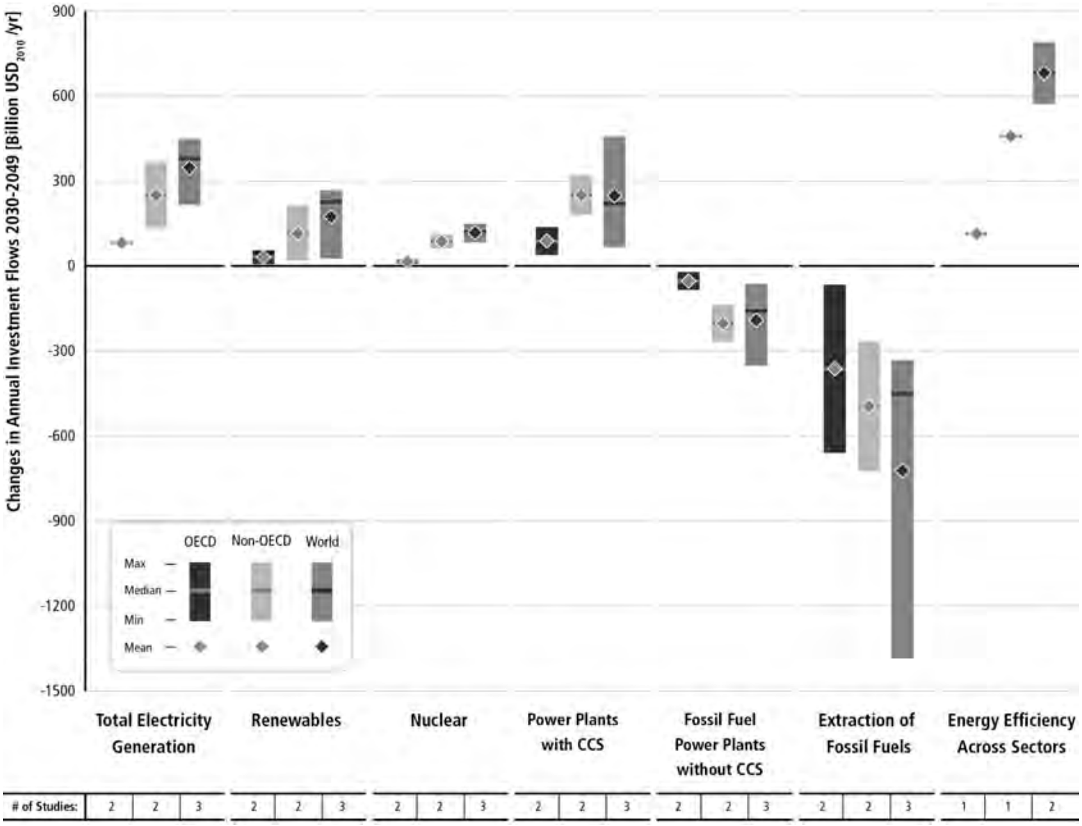

Figure 3.2: Change in annual investments when switching from business as usual to a 2°C mitigation pathway in the years from 2030 to 2049.
Source: IPCC 2014

policy scenario to about US$$_{2014}$ 75 trillion in the 450 ppm scenario.[18] In contrast, CPI (2014b) projects that, while capital investments in energy generation indeed increase, the transition to a low carbon energy system overall has a negative net impact on the capacity of the financial system by freeing up financial resources of about US$ 1.8 trillion due to the savings in energy systems' operating costs, i.e. in capital expenditures in the fossil fuel sector. However, most findings point to an, albeit rather moderate, increase in overall investment needs. This conclusion is supported for example by Boissinot et al. (2016) and by figures 3.1 and 3.2 from IPCC (2014) which give an overview over the range of projections from various studies.

[18] Note that these are rough estimates based on the visualization of the scenario projections in figure 2.6 of IEA (2015b).

4 A General Equilibrium Framework

To capture the interrelationship between the resource and the capital market and the potential role of the savings of resource-rich countries, we introduce in this chapter a general equilibrium framework of resource extraction and endogenous capital formation, which is virtually the same as in van der Meijden et al. (2015b). We therein differentiate between a resource-rich country and a resource-poor but producing country, or block of countries, as to represent the asymmetry in factor endowments and technological or production capacities which leads to one of the major distributional conflicts in climate negotiations. Similar general equilibrium models of trade in resources and capital have been developed by Dixit (1981), Svensson (1982), Marion and Svensson (1984), or Wijnbergen (1985), in particular to study the global imbalances from (exogenous) increases in oil prices and the possibilities of resource net importing countries to react to these imbalances by use of resource or capital tax policies.

Our primary objective in this chapter is to define the market equilibrium of the world economy conditional on some feasible resource extraction path and to derive the comparative statics of this conditional market equilibrium with respect to shifts in the resource extraction path. This approach is different to the line of analysis in the aforementioned contributions or also in van der Meijden et al. (2015b), but prepares for the following discussion of resource market power in such a (dynamic) general equilibrium setting.

4.1 Model

We consider a general equilibrium framework with two countries $m = E, I$ and a finite time horizon of two periods $t = 1, 2$. In each country, there is a representative household deriving utility from consuming a final good, which we choose as numeraire. Households have symmetric homothetic preferences represented by the life-time utility function

$$U(c_{1m}, c_{2m}) = u(c_{1m}) + \beta_m u(c_{2m}) = \begin{cases} \dfrac{c_{1m}^{1-\eta}}{1-\eta} + \beta_m \dfrac{c_{2m}^{1-\eta}}{1-\eta} & \text{for} \quad \eta \neq 1, \eta > 0 \\ \ln c_{1m} + \beta_m \ln c_{2m} & \text{for} \quad \eta = 1 \end{cases} \tag{4.1}$$

where $1/\eta$ equals the constant elasticity of intertemporal substitution and $\beta_m < 1$ denotes the utility discount factor for country $m = E, I$. For symmetric countries, we have $\beta_E = \beta_I$.

4.1.1 Resource Extraction

Country E owns the entire global stock of a fossil resource $\bar{R}$, which is costless to extract, just as in the very basic textbook model of resource economics. Resource extraction is controlled by some authority which we call the "sheikh", who benevolently distributes resource income

$$\pi_{tE}^{\tau} = \tilde{p}_t R_t \tag{4.2}$$

to his constituency, i.e. to the representative household in country E, where R_t denotes resource supply and $\tilde{p}_t$ the resource producer price.

Aggregate resource extraction over both periods must not exceed the given resource stock underground

$$R_1 + R_2 \leq \bar{R} \tag{4.3}$$

4.1.2 Final Goods Production

In the block of resource-importing countries I, there is a competitive final goods production sector. Final goods are produced by use of three input factors, capital K_t, resources R_t, and labour L, which is in constant supply from the representative household, with a CES production technology as already discussed in section 3.1.1

$$F_t = F(K_t, R_t) = A\left[\lambda R_t^{\frac{\sigma-1}{\sigma}} + \gamma K_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma-\lambda)L^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{4.4}$$

The parameter $A \geq 1$ represents total factor productivity, which is constant over time, and σ measures the constant elasticity of substitution between the two variable input factors. The constant elasticity of substitution between both production factors[1] is defined as

$$\sigma = -\frac{d\ln\left(\frac{K_t}{R_t}\right)}{d\ln\left(\frac{F_{tK}}{F_{tR}}\right)} > 0$$

The CES technology has constant returns to scale but decreasing returns to scale with respect to the variable production inputs capital and oil so that[2]

$$\Gamma_t = F_{tRR}F_{tKK} - F_{tKR}^2 > 0 \tag{4.5}$$

This ensures that a competitive market equilibrium with producers earning zero profits exists.

With profit maximizing competitive final goods producers the first-order conditions for optimal factor use (implicitly) define the market demand for the resource

$$R_t^d = R_t^d(p_t, i_t) \qquad \text{with} \qquad dR_t^d = \frac{F_{tKK}}{\Gamma_t}dp_t - \frac{F_{tKR}}{\Gamma_t}di_t \tag{4.6}$$

and for capital

$$K_t^d = K_t^d(i_t, p_t) \qquad \text{with} \qquad dK_t^d = \frac{F_{tRR}}{\Gamma_t}di_t - \frac{F_{tKR}}{\Gamma_t}dp_t \tag{4.7}$$

as negatively depending on the consumer resource price p_t and the capital cost/return i_t.

From labour supply, the representative household earns labour income, which in market equilibrium equals the residual profits of producing firms.

$$\pi_{tI} = F_t - p_tR_t - i_tK_t \tag{4.8}$$

We thereby implicitly assume that wages are fully flexible so that there is no unemployment.

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1 Intuitively, with competitive production so that the marginal productivity, or inverse demand, of either factor corresponds to its market price, the elasticity of substitution determines how strongly the optimal capital to resource ratio reacts to a (1%-) change in the relative factor market price (along a given production isoquant). If producers can easily substitute capital for resources, the relative factor input will strongly adjust with a change in the relative factor price and the elasticity of substitution is high, and vice versa.

2 Factor subscripts denote the first and second partial derivatives of the production function with respect to the respective factor(s).

4.1.3 Capital Supply

Capital supply directly derives from households savings in both countries for both periods. We assume that both, the resource exporting and the resource importing countries are “small” in the capital market in the sense that neither country can exert market power via its capital supply. Since we consider a discrete time framework, it proofs useful to point out the timing of savings decisions, i.e. investments in the capital market, and the returns from capital market investments. In the first period, the representative household in either country $m = E, I$ holds an exogenous capital endowment s_{0m}. For the second period, there is an endogenous savings decision of households. Capital endowments or savings are invested via the capital market in final goods production at the beginning of the respective period and get remunerated as a production factor throughout the period. At the end of the respective period, the households are paid the proceeds and their investments. For simplicity, we assume that capital does not depreciate. In the following, we discuss the endogenous savings decision of households, and then consider the aggregate capital supply for symmetric and asymmetric consumption preferences.

4.1.3.1 Savings Decision

Households choose savings as to maximize their life-time utility (4.1) subject to country-specific budget constraints. The savings decision of the representative households, therefore, generally derives from the familiar (utilitarian) consumption smoothing motive and depends on the interest rate i_2, which represents the market price of first period consumption in terms of second period consumption, and the first and second period income streams that accrue to the households in any case, i.e. independent of their savings decision. We assume that households have rational expectations and take these period income streams as well as the interest rate i_2 paid for capital investments in the second period as given.

Country I

In the first period, the representative household in country I earns labour income π_{1I} defined in (4.8) and capital income from given capital endowments so that the overall first period income stream is given by

$$y_{1I} = \pi_{1I} + (1 + i_1)s_{0I}$$

Without loss of generality, we assume for simplification that the resource importing countries may levy a value added resource tax on resource imports only in the second period so that $\tau_1 = 0$ and $\tau_2 = \tau \geq 0$. Later on in the context of climate change mitigation, the resource tax will be interpreted as a carbon tax. With lump-sum distribution of the tax revenue

$$T_2 = \tau p_2 R_2$$

to households, the representative household gets in the second period

$$\pi_{2I}^{\tau} = \pi_{2I} + T_2$$

separately of the capital income from savings, which are to be determined in the following. We concentrate on the value added tax case and only point out where a unit resource tax would have different implications. For the most part, the unit resource tax case is, however, completely analogue.

With these period income streams, the representative household in the resource importing country I has to obey the budget constraints

$$c_{1I} = y_{1I} - s_{1I} \qquad \text{and} \qquad c_{2I} = \pi_{2I}^{\tau} + (1 + i_2)s_{1I} \tag{4.9}$$

when choosing savings s_{1I}.

Country E

In country E, the representative household earns income from capital endowment and from resource profits. We again denote by

$$y_{1E} = \pi_{1E} + (1 + i_1)s_{0E}$$

the overall first period income available for consumption and savings. Resource profits π_{tE} have already been defined in (4.2) and equal resource revenue – in the second period net of taxes

$$\pi_{2E}^{\tau} = (1 - \tau)p_2 R_2$$

as we abstract from extraction costs for simplicity. The budget constraints for the consumption-savings decision then are given by

$$c_{1E} = y_{1E} - s_{1E} \qquad \text{and} \qquad c_{2E} = \pi_{2E}^{\tau} + (1 + i_2)s_{1E} \tag{4.10}$$

Savings Decision

With rational expectations regarding the interest rate i_2 and the period income streams y_{1m}, π_{2m}^{τ}, the representative households in both countries decide on savings s_{1m} as to maximize the life-utility (4.1) subject to the country specific budget constraints just introduced. From the first-order condition, optimal savings in both countries can implicitly be defined by the respective Euler equation

$$\frac{u'(c_{1m})}{\beta_m u'(c_{2m})} = 1 + i_2 \qquad \text{for country } m = E, I \tag{4.11}$$

as a function of the period income streams and the interest rate i_2

$$s_{1m} = s_{1m}(y_{1m}, \pi_{2m}^{\tau}, i_2) \tag{4.12}$$

Totally differentiating and simplifying by use of the respective household's budget constraints gives us the following marginal savings propensities with respect to changes in period income streams

$$\begin{aligned} \frac{\partial s_{1m}}{\partial y_{1m}} &= \frac{[\beta_m(1+i_2)]^{\frac{1}{\eta}}}{1 + i_2 + [\beta_m(1+i_2)]^{\frac{1}{\eta}}} > 0 \\ \frac{\partial s_{1m}}{\partial \pi_{2m}^{\tau}} &= \frac{\partial s_{1m}}{\partial \pi_{2m}} = -\frac{1}{1 + i_2 + [\beta_m(1+i_2)]^{\frac{1}{\eta}}} < 0 \end{aligned} \tag{4.13}$$

As intuitively expected by the underlying consumption smoothing motive, the household increases savings upon an increase in the first period income but reduces savings when its second period income rises. Since we assume homothetic consumption preferences, the marginal savings propensities are independent of the wealth level of the household. Instead, they are determined by the discount factor β_m, the intertemporal elasticity of substitution $\frac{1}{\eta}$, and the market interest rate i_2 only. This is also the reason why the influence of the second period income stream is qualitatively the same with and without the resource tax. However, note that the resource tax is likely to change the overall equilibrium of the world economy and thereby the interest rate i_2 so that the marginal savings propensities will differ quantitatively for different resource taxes or between a tax and a no-tax scenario.

From the total derivative of the Euler equation we also can derive the effect of the interest rate i_2 on savings as

$$\begin{aligned}\frac{\partial s_{1m}}{\partial i_2} &= SE_m + \frac{\partial s_{1m}}{\partial \pi_{2m}} s_{1m} \\ &= \frac{1}{\eta(1+i_2)} \frac{\pi^{\tau}_{2m} + (1-\eta)(1+i_2)s_{1m}}{1+i_2+[\beta_m(1+i_2)]^{\frac{1}{\eta}}} \gtrless 0\end{aligned} \tag{4.14}$$

Note first that due to π^{τ}_{2m} from (4.9) and (4.10) respectively it generally depends on the resource tax and the distribution of resource remuneration between both countries. Second, it is well known from economic theory that a change in the interest rate i_2 induces, on the one hand, a substitution effect, which is represented by the first term and defined as

$$SE_m = -\frac{\beta_m u'(c_{2m})}{u''(c_{1m}) + \beta_m(1+i_2)^2 u''(c_{2m})} = -\frac{\partial s_{1m}}{\partial \pi^{\tau}_{2m}} \frac{c_{2m}}{\eta(1+i_2)} > 0 \tag{4.15}$$

with $\frac{\partial s_{1m}}{\partial \pi^{\tau}_{2m}} < 0$ from (4.13). Since savings yield a higher return with an increase in the interest rate, the household is more willing to give up first period for second period consumption, and therefore to increase its savings. Or, put differently, with a higher interest rate the costs of first period consumption in terms of forgone second period consumption possibilities rise. On the other hand, a higher interest rate also implies that the household earns a higher capital income from existing savings in the second period so that the incentive to save for reasons of smoothing consumption over time is lower. This income effect is captured by the second term in (4.14).

Since the income effect counteracts the substitution effect, the savings reaction to marginal changes in the interest rate i_2 generally is of ambiguous sign. For $\frac{1}{\eta} > 1$, the substitution effect always dominates and (4.14) turns positive. This is intuitively plausible by recalling the definition of the intertemporal elasticity of substitution

$$\frac{1}{\eta} = \frac{d\ln \frac{c_{2m}}{c_{1m}}}{d\ln \frac{u'(c_{1m})}{u'(c_{2m})}} = \frac{d\ln \frac{c_{2m}}{c_{1m}}}{d\ln(1+i_2)}$$

where the second equality follows from the Euler equation (4.11). Thus, the higher the intertemporal elasticity of substitution the stronger reacts the optimal relation of second to first period consumption $\frac{c_{2m}}{c_{1m}}$ to a one percentage change in the interest factor $1+i_2$. If the household does not earn any second period income π^{τ}_{2m} from resource or labour income and the interest factor increases by one percent, the household can ceteris paribus increase second period consumption and thereby relative consumption by one percent, too. For $\frac{1}{\eta} > 1$, however, the optimal increase in relative consumption exceeds one percent so that the utility maximizing household must increase its savings. For $\frac{1}{\eta} = 1$, which implies logarithmic period utility functions in (4.1), the substitution and the income effect exactly cancel out, and savings do not react to changes in the interest rate at all.

Now consider the savings reaction to a change in the interest factor with positive second period income π^{τ}_{2m}. The one percent increase in the interest factor then translates into a less than one percent (ceteris paribus) increase in second period consumption. Thus, the substitution effect is strengthened and the household is induced to increase its savings even for $\frac{1}{\eta} = 1$ in this case.[3]

Finally note that so far we have only considered ceteris paribus changes in the period income streams and the interest rate and thereby, for example, neglected that labour income also depends on the interest rate i_2 according to (4.8). This, however, reflects the perspective of the representative households with rational expectations which just observe income streams and the interest rate as independent parameters of their consumption savings decision.

4.1.3.2 Aggregate Capital Supply

Aggregate capital supply in the first period is completely inelastic and just given by the exogenous capital endowments of households in both countries

$$K_1^s = s_{0E} + s_{0I} \tag{4.16}$$

Second period capital supply derives from the aggregated but endogenous savings of households in both countries, which due to our timing assumption do not add to the first period capital stock K_1. Instead, the existing capital stock is available for consumption (and savings) at the end of each period. For simplicity, we assume away any depreciation of the capital stock. Positive capital accumulation, therefore, implies that $s_{1E} + s_{1I} > K_1$ and not $s_{1m} > 0$.

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[3] Indeed, from the second line in (4.14) follows that with a positive second period income the intertemporal elasticity of substitution for which savings will not react to a change in the interest rate is not constant but always below unity as

$$\frac{1}{\eta} = \frac{(1+i_2)s_{1m}}{\pi^{\tau}_{2m} + (1+i_2)s_{1m}} < 1$$

Since aggregate second period capital supply is composed of the savings of households in both countries, it is generally a function of the period income streams y_{1m}, π^{τ}_{2m} and the interest rate i_2. However, while period income streams (and the interest rate) are taken as given in the consumption-savings decision of households, they in the end are functions of the factor market prices and the factor inputs (given the competitive final goods production sector). By decomposing changes in the period income streams, we show in appendix 9.1.1 that aggregate capital supply therefore can be represented as a function of factor market prices, of the resource supply path given a binding resource constraint, and the carbon tax

$$\begin{aligned} &K^s_2 = K^s_2(p_1, p_2, R_2, i_1, i_2, \tau) \\ &\text{with} \\ &dK^s_2 = \left(\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 - ID_2 \tau p_2\right) dR_2 + ID_1 R_1 dp_1 + ID_1 s_{0E} di_1 \\ &\qquad + ID_2(1-\tau) R_2 dp_2 + (SE + ID_2 s_{1E})\, di_2 - ID_2 p_2 R_2 d\tau \end{aligned} \tag{4.17}$$

First, we build upon the individual substitution effect in (4.15) and define the aggregated substitution effect, which is induced by a change in the interest rate i_2, by

$$SE = SE_E + SE_I = -\frac{1}{\eta(1+i_2)} \left(\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} c_{2E} + \frac{\partial s_{1I}}{\partial \pi^{\tau}_{2I}} c_{2I}\right) > 0 \tag{4.18}$$

Obviously, the higher the intertemporal elasticity of substitution, which determines how sensitive households are with respect to changes in the interest rate i_2, the stronger is the substitution effect. Second, we define the net effect of an income distribution from country I to country E in the first period on aggregate savings by

$$ID_1 = \frac{\partial s_{1E}}{\partial y_{1E}} - \frac{\partial s_{1I}}{\partial y_{1I}} \gtreqless 0 \qquad \text{for} \qquad \beta_E \gtreqless \beta_I \tag{4.19}$$

and correspondingly for the second period by[4]

$$ID_2 = \frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} - \frac{\partial s_{1I}}{\partial \pi^{\tau}_{2I}} \gtreqless 0 \qquad \text{for} \qquad \beta_E \gtreqless \beta_I \tag{4.20}$$

Intuitively, if the representative household in country E is more patient than its counterpart in country I so that its discount factor is greater $\beta_E > \beta_I$, it will be more willing to give up first period for future consumption than the representative household in country I. This obviously implies that the household in country E will save more from an increase in first period income. However, since the household has

4 Since both savings propensities, $\frac{\partial s_{1m}}{\partial \pi^{\tau}_{2m}}$ and $\frac{\partial s_{1m}}{\partial y_{1m}}$, are smaller than unity in absolute value by definition, we also know that $|ID_t| < 1$. Moreover, note that due to (4.13), we have $ID_2 = (1+i_2)ID_1$.

a stronger preference for future consumption, it will also reduce its savings by less than the household in country I upon an increase in second period income. Therefore, if income is redistributed from the household in country I to the more patient household in country E in either period, the net effect on aggregate savings is positive. In contrast, for symmetric time preferences, the income distribution between countries is completely neutral with respect to aggregate savings as the marginal savings propensities to changes in period income streams do not depend on the wealth level of households for homothetic preferences.

To intuitively understand the total derivative in (4.17), consider first the effect of an intertemporal shift in resource extraction from the first to the second period ($dR_2 > 0$). Such a shift implies a transfer of final goods production and thereby aggregate (world) income from the first to the second period ceteris paribus. In the total derivative, these production changes are represented by the market prices p_1 and p_2, which equal the marginal productivity of the fossil resource in the respective period due to profit maximizing competitive final goods producers. Since the CES production technology (4.4) exhibits constant returns to scale and production factors are paid their marginal productivity and since we hold all other factor inputs and prices constant by focusing on the first element in the total derivative, country E, in principle, completely captures these ceteris paribus production and income changes so that only savings of households in E are influenced. With a positive resource tax τ, the producer price, which country E receives, however, deviates from the marginal productivity of the resource and a share τ of the induced production increase in the future period does not accrue to the household in country E but is captured by the importing countries which levy the tax. Put differently, in this case the shift of resource extraction to the second period does not only imply a intertemporal reallocation of income but also a geographical reallocation from country E to country I, which is indicated by the last element of the resource supply effect. The intertemporal production shift unambiguously reduces savings and capital supply by increasing future income at the expense of present income as we can observe from the savings propensities in (4.13). This is obvious for the symmetric case ($ID_2 = 0$). However, even in the asymmetric country case, if country I is more patient than country E ($\beta_E < \beta_I$), the geographical reallocation of resource income by the resource tax will dampen the decrease in capital supply but can never reverse it.[5]

We next consider the effect of factor price changes. With a constant production factor labour, increases in the resource and capital market price p_t and i_t directly reduce the residual profits in final goods production ceteris paribus, and therefore according to (4.8) labour income. If the resource price in either period increases (for whatever reason), this income redistribution between production factors obviously implies a transfer of income from the resource importing countries to country E. The net effect on aggregate savings of a ceteris paribus change in the resource price, therefore, depends on the (a-)symmetry of the homothetic consumption preferences of households in both countries. In the second period, the induced income transfer to country E is reduced by the share in resource income which the resource importing countries are able to capture by taxing the imports of fossil resources.

In principle, the same reasoning also applies for changes in the price of capital. A rise in the interest rate i_1 increases the capital costs to final goods producers which ceteris paribus comes at expense of labour income since all factor inputs as well as the resource price are held constant. The representative household in country I, therefore, will be compensated for its loss in labour income by a higher capital income. However, since generally country E holds some part of the capital stock, labour income will also be redistributed to the representative household abroad upon an increase in the costs of capital. Whereas the income distribution from labour to capital income within country I obviously is completely neutral with respect to the savings decision, the net effect of the income transfer to country E again depends on the (a-)symmetry of consumption preferences.

In the second period, savings are endogenous and an increase in the interest rate generally induces a substitution and income effect as we have already discussed before for the individual household's decision. The aggregate substitution effect SE (see (4.18)) always induces households in both countries to save more upon a rise in the interest rate. In country I, the positive effect on capital income is completely offset by an accompanying loss in labour income whereas country E experiences an income

[5] This can be observed by writing

$$\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} - ID_2\tau = (1-\tau)\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} + \tau\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau}} < 0$$

gain from the increase in capital income. However, since this comes at the expense of labour income in country I, too, the induced income effect in country E from an increase in the interest rate i_2 appears in (4.17) only as the net effect of this geographical income redistribution. For asymmetric consumption preferences, aggregate savings will therefore always increase with the interest rate if this income redistribution has a positive net effect on capital supply for $ID_2 > 0$. In contrast, for $ID_2 < 0$, aggregate savings may fall with a rise of the interest rate i_2. In appendix 9.1.1, we further discuss the influence of the interest rate on aggregate savings for asymmetric consumption preferences. In contrast, for symmetric preferences, the income redistribution from labour to capital is not only neutral within country I but also geographically between country I and E. Hence, there is no income effect at all, and the interest rate unambiguously raises capital supply.

Finally, a change in the resource tax is ceteris paribus, i.e. for given factor inputs and factor prices, purely redistributive. The higher the tax rate the higher is the share in resource income (and profits, without extraction costs) which the resource importing countries are able to capture at home. The net effect of the resource tax on aggregate savings, therefore, directly depends on the (a-)symmetry of consumption preferences, too.

If we assume symmetric homothetic consumption preferences in both countries, any (geographical) redistribution of income is completely neutral with respect to aggregate savings as all the savings changes exactly offset each other. Capital supply is just a function of the resource supply path, represented by the second period resource supply R_2 for a binding resource constraint, and the interest rate i_2

$$K_2^s = K_2^s(R_2, i_2) \tag{4.21}$$

as the preceding discussion already has illustrated. Note that even a redistribution of capital endowments between countries does not influence aggregate savings in this case because it again just constitutes a pure transfer of wealth from one country to the other.

4.2 Conditional Market Equilibrium

We so far have introduced market demand for fossil resources, physical capital, and capital supply as functions of the factor prices, the resource supply (path) and the carbon tax. Without imposing more structure on the supply side of the resource market, we use these components in the following to characterize the market equilibrium in all three markets, the markets for resources, capital, and consumption goods conditional on some resource supply path which per assumption completely exhausts the given resource stock over the fixed time horizon of two periods.

This concept of a conditional market equilibrium then allows us to study the influence of shifts in the resource supply path on the market equilibrium of the world economy in a comparative statics analysis. We will close the model by imposing more structure on the supply side of the resource market in the next chapter when we discuss the optimal extraction policies in a competitive as well as a monopolistic resource market, and the implications of market power given the general equilibrium interactions between the resource and the capital market in our framework.

4.2.1 Definition of the Conditional Market Equilibrium

In this section, we briefly summarize the market clearing conditions for all three markets of the world economy.

Resource Market Equilibrium

The resource market equilibrium is characterized by the market clearing condition

$$R_t^d(p_t, i_t) = R_t^s \quad \text{for both periods } t = 1, 2 \tag{4.22}$$

for resource demand derived from competitive final goods production (4.6). To completely characterize the equilibrium in the resource market, we, in principle, need to specify the supply policy of country E and thus impose additional structure on the resource sector. However, as pointed out before, our aim for the moment is to derive the equilibrium relationships between the resource market, the market for physical energy and renewable energy generation which hold in a simultaneous equilibrium of all three markets for any choice of the resource supply path which exhausts the stock. To this end, we just consider some supply path (R_1^s, R_2^s) for which the additional intertemporal resource market equilibrium condition

$$R_1^s + R_2^s = \bar{R}$$

from (4.3) holds.

Capital Market Equilibrium

With fixed capital supply from aggregate endowments the capital market equilibrium condition in the first period reads

$$K_1^d(i_1, p_1) = K_1 = s_{0E} + s_{0I} \tag{4.23}$$

Capital demand is a function of the first period market prices of fossil resources and capital according to (4.7).

In the second period, the capital market equilibrium is characterized by the market clearing condition

$$K_2^d(i_2, p_2) = K_2^s(R_2, p_1, p_2, i_1, i_2, \tau) \tag{4.24}$$

Capital demand again derives from final goods production as a function of the resource and the capital market price. Capital supply from the savings of both countries is generally a function of the resource supply path represented by the second period resource supply R_2, the factor prices and the resource tax τ levied by the resource importing countries according to (4.17).

Final Goods Market Equilibrium

In equilibrium, aggregate consumption and savings has to equal aggregate consumption possibilities. Since we choose final goods as numeraire and assume by our timing structure of capital investments that the physical capital stock is paid back to households and available for consumption at the end of the respective period, the market clearing conditions for final goods in both periods are given by

$$\begin{aligned} c_{1E} + c_{1I} + K_2 &= F_1(K_1, R_1, L) + K_1 \\ c_{2E} + c_{2I} &= F_2(K_2, R_2, L) + K_2 \end{aligned} \tag{4.25}$$

where we set $K_2 = s_{1E} + s_{1I}$. By Walras' law we can conclude that if the resource and the capital market are in equilibrium, the market for final goods must be in equilibrium, too. This also directly follows from the fact that the representative households in both countries obey the period budget constraints in their savings decisions and have rational expectations with regard to period income streams and the equilibrium factor market prices in both periods.

4.2.2 Comparative Statics of the Conditional Market Equilibrium

The system of market clearing conditions laid out before in the end defines equilibrium factor prices and the equilibrium second period capital stock K_2 as functions of the resource supply path, which we deliberately have left rather unspecified so far. We now investigate by use of a comparative statics analysis how shifts in the resource supply path affect the conditional market equilibrium, and in particular equilibrium factor prices and the capital stock.

4.2.2.1 Comparative Statics: First Period

From the total derivative of (4.23) and (4.22) we observe that

$$\frac{dp_1}{dR_1} = \frac{\partial p_1}{\partial R_1} = F_{1RR} < 0 \tag{4.26}$$

due to the concavity of the production technology and

$$\frac{di_1}{dR_1} = \frac{\partial i_1}{\partial R_1} = F_{1KR} > 0 \tag{4.27}$$

by the complementarity of capital and resources in production.

4.2.2.2 Comparative Statics: Second Period

The comparative statics for the second period is derived by totally differentiating the resource and the capital market equilibrium conditions (4.22) and (4.24) while taking into account (4.18), (4.6), and (4.7) as well as dp_1 and di_1 from (4.26) and (4.27). We discuss the derivation in more detail in appendix 9.1.2.

We find that a postponement of resource extraction, which via the binding resource constraint is reflected by $dR_2 > 0$, influences the equilibrium second period capital stock according to[6]

$$\begin{aligned}\frac{dK_2}{dR_2} = & \frac{\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 - ID_2 \tau p_2\right) + \frac{\partial i_2}{\partial R_2}\left(SE + ID_2 s_{1E}\right)}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2(1-\tau)F_{2KR}R_2} \\ & + \frac{-ID_1\left(\frac{\partial p_1}{\partial R_1} R_1 + \frac{\partial i_1}{\partial R_1} s_{0E}\right) + ID_2(1-\tau)\frac{\partial p_2}{\partial R_2} R_2}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2(1-\tau)F_{2KR}R_2}\end{aligned} \tag{4.28}$$

To analyze whether such a postponement of resource extraction has a positive or negative effect on the capital stock, consider first the denominator, which generally captures the feedback effect of a change in the second period capital stock on savings incentives which arises in general equilibrium. A higher capital stock K_2 decreases ceteris paribus the marginal productivity of capital due to diminishing returns in final goods production (4.4) and thereby the interest rate i_2 in capital market equilibrium. This change in the interest rate induces, on the one hand, a substitution effect SE defined in (4.18). The accompanying income effect, on the other hand, as we already discussed before for the aggregate capital supply function (see secton 4.1.3.2), influences savings only insofar as the redistribution of labour income from country I to country E in form of capital income has a non-negative net effect on savings. By the complementarity of capital and resources in final goods production, an increase in the capital stock ceteris paribus also raises the resource market price ($F_{2KR} > 0$). Again, such a ceteris paribus increase in the resource factor price increases resource income at the expense of labour income in country I[7] and therefore has a net effect on aggregate savings only for asymmetric preferences and, with a positive resource (carbon) tax τ, only insofar as the income redistribution between factors implies a redistribution of income between countries.

Since households have rational expectations and always choose savings optimally for any market prices i_t and p_t, we can refer to the second-order condition for utility maximizing savings decisions of households with rational expectations to show that the denominator for (marginal shifts) in the resource supply path out of market equilibrium must be of positive sign, even though counteracting effects can arise from the

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6 We denote the ceteris paribus influence of the production factor $f_t = R_t, K_t$ on the interest rate and the resource market price as $\frac{\partial i_t}{\partial f_t} = F_{tKf}$ and $\frac{\partial p_t}{\partial f_t} = F_{tRf}$.

7 Recall that labour income is defined as the variable residual profit after resource and capital income is paid out. Since labour is in fixed supply, the wage variably adjusts throughout the comparative statics analysis.

income redistribution between both countries (see appendix 9.1.2). In the symmetric country case, the positive sign of the denominator is already ensured by the concavity of the production technology ($F_{2KK} < 0$) and the positive aggregate substitution effect SE from (4.18). The positive sign is also more or less intuitive as the denominator captures the feedback effect on the savings incentives of the households in both countries which arises from any change in the aggregate capital stock in the market equilibrium. If households get, for whatever reason, an incentive to save more in the first place, it seems plausible that the corresponding increase in the capital stock cannot induce households to save less in the end. Thus, the second-order condition implies that the feedback effect from the change in the capital stock may dampen or strengthen but cannot reverse the more direct savings incentives which are created by a change in the extraction path and are captured by the numerator.

The first element in the numerator of (4.28) is already known from our analysis of aggregate capital supply in section 4.1.3.2. It captures the change in aggregate savings which is induced by the accompanying ceteris paribus shift of final goods production and thereby aggregate income to the future period. At the margin, these income changes are measured by the marginal product of fossil resources in the respective period, i.e. by F_{1R} and F_{2R}, which equal the resource (consumer) prices p_1 and p_2 in market equilibrium. From the marginal savings propensities in (4.13), it is obvious that such an intertemporal transfer of income works towards lower savings. We also showed before that this holds true irrespective of whether the part of the production increase which the resource importing country I is able to capture via the resource tax (τp_2) plays a role for aggregate savings or not. In contrast to (4.17), the change in the equilibrium capital stock also is driven by the changes in capital and resource demand induced from such a shift in the extraction path. These changes in (inverse) factor demand and their influence on the aggregate savings are represented by the remaining elements in the numerator.

First, due to the complementarity of resources and capital in production a higher future resource supply ceteris paribus raises the marginal productivity of capital, or, in market equilibrium, inverse capital demand, which translates into a higher interest rate ($F_{2KR} = \frac{\partial i_2}{\partial R_2} > 0$). This (ceteris paribus) increase in the interest rate i_2 at first induces a substitution effect in both countries captured by SE (4.18). From a pure household perspective, as seen before, such an increase in the interest rate clearly also induces a counteracting income effect. However, from a broader economy-wide perspective, we now additionally must take into account that capital costs in final goods production rise with the interest rate, which fully comes at the expense of labour income in country I ceteris paribus, i.e. for a given resource consumer price. This does not only offset the familiar income effect from given savings within country I, but due to the transfer of labour income to country E even incurs an income loss in country I as far as country E owns part of the second period capital stock. Overall, the income effects are only relevant for asymmetric consumption preferences when geographical income redistribution has a net effect on aggregate savings. Since this net income effect may support or counteract the substitution effect depending on the time preferences in both countries, the second term in the numerator is generally of ambiguous sign (but of positive sign for $ID_2 \geq 0$).

Second, the last term in the numerator captures the induced change in (inverse) resource demand, or equivalently, the fall in the marginal productivity of fossil resources which arises from a higher second period resource supply due to diminishing returns in production. This implies that the (infra-marginal) resource quantities sold to the resource importing countries are paid less, and that resource income gets transferred to the resource importing countries – in our setting in form of additional labour income as the capital stock and the interest rate are held constant. The net effect of this income redistribution again depends on the (a-)symmetry of the consumption preferences. Similarly, in the first period, since first period resource supply is reduced by the postponement of extraction, first period resource demand, or the marginal productivity of resources, rises whereas (inverse) capital demand decreases. Even though the accompanying changes in resource and capital income are counteracting, the overall effect on the first period income of the representative household of country E is unambiguously negative because by the Euler theorem and the properties of the CES production technology we have

$$\frac{\partial p_1}{\partial R_1} R_1 + \frac{\partial i_1}{\partial R_1} s_{0E} = \frac{1}{\sigma} F_{1R} \left(\theta_{1R} + \theta_{1K} \frac{s_{0E}}{K_1} - 1 \right) < 0$$

Here, we denote the share of production factor's f remuneration in total output as $\theta_{tf} = \frac{F_{tf} f_t}{F_t}$. The net effect of this first period income redistribution from country E to the resource importing countries I on aggregate savings again depends on the (a-)symmetry of the consumption preferences.

Thus, overall, the reaction of capital accumulation to a postponement of extraction is ambiguous, in general. Due to the savings disincentive from the intertemporal shift of aggregate income to the second period and the positive savings incentive from the aggregate substitution effect, this, in general, holds even true for symmetric homothetic preferences ($ID_t = 0$). For the symmetric country case, however, we show in appendix 9.1.2 that assuming an intertemporal elasticity of substitution lower than the elasticity of substitution in final goods production

$$\frac{1}{\eta} \leq \sigma \tag{4.29}$$

is a sufficient condition for a negative relationship between postponement of resource extraction and the aggregate capital stock of the second period. Intuitively, this condition more or less ensures that the savings disincentives from the shift of income from the first to the second period dominate the complementarity driven substitution effect. This can be observed from the limiting case $\sigma \to \infty$, for which the CES production technology becomes linear. Resource supply then obviously no longer has an influence on capital demand so that the postponement of resource extraction induces no substitution effect at all (see also section 3.1.1) and reduces the capital stock by the intertemporal income shift irrespective of the intertemporal elasticity of substitution.

For asymmetric countries, condition (4.29) needs no longer hold true. Moreover, since the various effects of income redistribution in the first and the second period are counteracting in general, we cannot resolve the ambiguity by just restricting the analysis on either the resource exporting country E or the resource importing country I having a lower preference for current period consumption, even though the net effect of an income redistribution is of the same sign in both periods as $ID_2 = (1+i_2)ID_1$.[8]

Given (4.28), we now can decompose the equilibrium changes in the second period factor market prices. We thereby distinguish between the directly induced change in the factor price which arises from the influence on the marginal productivity of the

[8] Recall that in the first period there is a unambiguous redistribution of resource income from country E to country I as

$$\frac{\partial p_1}{\partial R_1} R_1 + \frac{\partial i_1}{\partial R_1} s_{0E} = -\frac{F_{1R}}{\sigma} \left[1 - \theta_{1R} - \theta_{1K}\right] < 0$$

In the second period, in contrast, the induced income redistribution between both countries from the increase in resource supply R_2 is generally ambiguous. This can be observed by summarizing and rearranging the corresponding terms in the numerator of (4.28)

$$-\tau p_2 + (1-\tau)\frac{\partial p_2}{\partial R_2} R_2 + \frac{\partial i_2}{\partial R_2} s_{1E} = \frac{1}{\sigma}\left[(1-\tau)\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - 1 + (1-\sigma)\tau\right]$$

Since $ID_2 = (1 + i_2)ID_1$, the net effects of an income redistribution in the first and the second period will not counteract each other only if in the second period there is an income transfer from country I to country E so that the bracketed term is positive. Note that this is only possible for $\sigma < 1$ whereas for $\sigma \geq 1$ the bracketed term is unambiguously negative due to Euler theorem.

respective factor and the indirectly induced change in the factor price due to the influence on the equilibrium capital stock K_2. Due to the endogeneity of the capital stock and the generally ambiguous relationship between the capital stock and the second period resource supply, we observe from

$$\begin{aligned}\frac{dp_2}{dR_2} &= \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} \\ &= \frac{F_{2RR} - \Gamma_2\left(SE + ID_2 s_{1E}\right) + F_{2KR}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}p_2 - \frac{\partial s_{1E}}{\partial y_{1E}}p_1 - ID_2\tau p_2\right)}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2(1-\tau)F_{2KR}R_2} \\ &\quad - \frac{F_{2KR}ID_1\left(F_{1RR}R_1 + F_{1KR}s_{0E}\right)}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2(1-\tau)F_{2KR}R_2}\end{aligned} \tag{4.30}$$

that a higher resource supply may even increase the resource market price. However, if the capital stock shrinks with any postponement of extraction, the resource market price will always fall with higher resource supply because a reduction in the capital stock lowers the marginal productivity of the fossil resources and thereby the resource market price in addition to the negative own-price effect from the concavity of the production technology. Moreover, in the symmetric country case, the direct own-price effect $\frac{\partial p_2}{\partial R_2}$ always outweighs the indirect price effect from the endogeneity of capital accumulation so that the resource market price decreases with higher resource supply irrespective of how the capital stock K_2 reacts.[9]

Completely analogue, the equilibrium relationship between a postponement of resource extraction and the interest rate is given by

$$\begin{aligned}\frac{di_2}{dR_2} &= \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2} \\ &= \frac{F_{2KR} + F_{2KK}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}p_2 - \frac{\partial s_{1E}}{\partial y_{1E}}p_1 - ID_2\tau p_2\right)}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2 F_{2KR}(1-\tau)R_2} \\ &\quad + \frac{\Gamma_2 ID_2(1-\tau)R_2 - ID_1 F_{2KK}\left(F_{1RR}R_1 + F_{1KR}s_{0E}\right)}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2 F_{2KR}(1-\tau)R_2}\end{aligned} \tag{4.31}$$

Again, due to the ambiguity of the equilibrium capital stock reaction, the interest rate generally may increase or decrease with a higher second period resource supply. However, if the capital stock negatively depends on resource supply, the indirect effect via the endogeneity of capital accumulation will support the complementarity driven positive direct effect of resource supply on the market interest rate. As for

[9] The negative sign unambiguously holds since $F_{2RR} < 0$, $F_{2KK} < 0$ and $\Gamma_2 > 0$ due to the concavity of the production technology (see (4.5)), since $F_{2KR} > 0$ due to the complementarity of production factors and since $SE > 0$ from (4.18) as well as $\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} < 0$ and $\frac{\partial s_{1E}}{\partial y_{1E}} > 0$ according to (4.13).

the resource market price, we also can conclude that for symmetric countries the direct complementarity effect always dominates and the equilibrium interest rate will always increase with higher resource supply.

5 The Supply of Exhaustible Resources in General Equilibrium

In this chapter, we close the model by imposing more structure on the supply side of fossil resources where so far in the conditional market equilibrium we only have assumed that the resource constraint is binding. The chapter extends and revises the contribution in Marz and Pfeiffer (2015b). We first assume that there is a competitively high number of resource owners or resource exporting countries, which form the country block E, and demonstrate that the optimal extraction decision of competitive resource owners (with rational expectations) qualitatively does not differ from the competitive market solution in partial equilibrium. Second, we consider the extreme opposite of a single resource exporting country E with market power in the resource market. Assuming monopoly power is, of course, a simplification as real world resource markets are most probably best represented by an oligopolistic market structure. However, with the competitive market and the resource monopolist our analysis spans the entire spectrum of the possible supply-side structure in the resource market.

In contrast to a competitive supplier, a resource monopolist clearly observes its influence on aggregate market supply, which in a standard partial equilibrium setting of the resource market brings the monopolist to account for the price changes induced by a change in supply, as previously discussed in section 2.1.2. In a general equilibrium setting with interaction of different markets, however, shifts in the resource supply path, in principle, have more widespread cross market effects, which can directly be observed from the comparative statics analysis of the conditional market equilibrium before. The supply decision of a resource monopolist in such a general equilibrium setting, therefore, crucially depends on which of these additional effects the monopolist is assumed to account for.

We will systematically discuss the additional elements in the monopolistic supply decision which may arise from the interaction of the resource and the capital market in our general equilibrium framework and contrast the corresponding extraction policies with the familiar conclusions about monopolistic resource supply in partial equilibrium from section 2.1.2. In particular, we will identify the asset motive, which represents a new role of the previously discussed capital wealth of resource exporting countries and its development over time (see section 3.1.2) for the optimal extraction policy if a resource exporting country, or cartel, is not small in the resource market but can to some extent influence market resource supply.

5.1 Competitive Resource Market

With a competitively high number n of resource owners within country E, or a competitively high number of countries forming the resource exporting country block E, the resource supply side in the general equilibrium framework corresponds to the partial equilibrium setting introduced in section 2.1.1. We assume that the resource owners or firms, just as the households in both countries, have rational expectations regarding the market prices for fossil resources and capital in both periods.

In a competitive resource market, the representative resource extracting firm is so small that given the high number of competing firms it does not have a non-marginal influence on the market equilibrium, or at least does not recognize its actual influence on the market equilibrium outcome. This directly implies that even though resource supply has more widespread effects in general equilibrium, the representative firm's considerations, when planning resource extraction, do not differ from the partial equilibrium setting. In fact, just as in a standard partial equilibrium setting, the representative firm takes the resource market prices in both periods, the interest rate i_2 and the resource tax levied by the resource importing countries as given, irrespective of the interdependence of the resource and the capital market, which we discussed throughout the analysis of the conditional market equilibrium. The assumption of rational expectations ensures that the firms correctly foresee the equilibrium outcomes so that no incentive for revising the extraction decision arises. In our discrete time setting with two interest rates i_1 and i_2, note that the profit maximizing firm uses the interest rate i_2 to discount future resource profits because it represents the foregone return on today's resource profits invested in the capital market and thereby the opportunity costs of not extracting in the present period. This is again due to our assumptions on the timing of investments and investment returns in the capital market (see also section 4.1.3). Overall, the competitive market equilibrium and the competitive resource supply path are therefore still characterized by Hotelling condition

(2.5), which also can be interpreted completely analogue to the partial equilibrium setting (see, for example, van der Meijden et al. 2015b).

However, whereas we left the inverse resource demand function in our partial equilibrium framework completely unspecified (see (2.1)), it derives directly from the CES production technology (4.4) in our general equilibrium setting according to (4.6) and thereby also depends on the capital stock K_t by the complementarity of production factors. Thus, resource demand is not time constant but very likely to change over time with the capital stock. If we have capital accumulation in the sense that $K_2 > K_1$, at least part of the increase in resource prices (rents) necessary for Hotelling rule (2.3) to hold for a positive interest rate i_2 then will result from the upward shift in resource demand which is induced due to the complementarity of fossil resources and capital in production. Thus, capital accumulation causes the competitive resource extraction path to decrease more slowly or even to increase over time in contrast to a partial equilibrium setting with time constant resource demand.

5.2 Resource Market Power in General Equilibrium

We now assume that there is a single authority in country E, hereafter called the "sheikh", which controls the extraction of the entire world resource stock $\bar{R}$ and therefore has perfect monopoly power in the resource market. Market power generally enables the monopolist to internalize the reaction of the demand side, which in the familiar partial equilibrium Cournot approach of section 2.1.2 is reflected in the own-price effect on infra-marginal quantities sold.

In general equilibrium, however, a change in the supply of one factor typically induces more widespread effects in the overall economic system. In fact, the comparative statics analysis in section 4.2.2 has demonstrated that in our setting shifts in resource supply not only alter the resource market price but also savings and the return to capital investments, given the interdependency of the resource and the capital market from the complementarity of production factors and the endogeneity of savings. Naturally, the question then arises whether and to what extent a resource monopolist should account for these additional and more widespread transmission channels. This, however, is obviously not straightforward and unambiguously to answer. We argue that the internalization of these general equilibrium transmission channels in the end depends on the monopolist's information about the underlying economic relationships, and therefore foremost on whether the monopolist is seen to recognize the various effects or not. This reasoning, in principle, is just as in partial equilibrium. The internalization of the negative own-price effect into the supply decision is not only a matter of market power, which gives the monopolist control of aggregate market supply, but also a matter of her information about the price-quantity relationship defined by resource demand. While this is typically just implicitly assumed, there generally can be a range of supply scenarios in general equilibrium differentiated according to the transmission channels which the monopolist recognizes and internalizes into her supply decision. Thus, it is necessary to explicitly specify and discuss the underlying assumptions about the monopolist's information.

In the following, our aim is not to determine the most plausible supply scenario, but to systematically discuss the monopolistic extraction decision within our general equilibrium framework and to investigate what the potential modifications to the supply decision imply for the resource extraction path and for the role of resource market power as compared to the familiar standard setting from section 2.1.2. Instead of considering each possible supply scenario separately, we will first derive the supply decision of a truly omniscient monopolist, and then investigate how the different components, which directly can be attributed to the monopolist's level of information about the specific transmission channel, form its optimal extraction behavior. To this end, we choose the monopolist with the most restricted information from partial equilibrium as benchmark and investigate the incentives created by the additional general equilibrium supply effects to deviate from that supply policy since there is no explicit solution for the optimal extraction path.

Overall, this approach is possible, on the one hand, due to the additive structure of the optimal supply decision, which necessarily arises as we characterize the optimal supply decision by use of the first-order conditions of the corresponding maximization problem. On the other hand, we have already demonstrated in section 4.2.2 that the general equilibrium price reactions to resource supply can be linearly decomposed by separating "direct" effects from "indirect" effects arising from the endogeneity capital accumulation. The additive structure also allows us to attribute the different components of the modified supply decision to the sheikh's level of information about the various cross market effects of resource supply in general equilibrium. We thereby again follow the reasoning from partial equilibrium settings where the monopolist's information about the own-price effect and the reaction of resource demand is directly reflected in the partial derivative adding to the producer market price in (2.5). Finally, to illustrate the role of the interaction between the resource and the capital market most clearly, we will only study the symmetric country case and therefore abstract from additional general equilibrium effects via the influence of resource market power on the income distribution between the resource exporter and importers.[1]

5.2.1 Relation to the Literature: Market Power in General Equilibrium

The observation that decisions under imperfect competition in general equilibrium raise questions about the effects which the agent can or shall take into account are neither specific to the case of exhaustible resources nor new to the economic literature. In fact, in industrial economics there is a whole strand of literature considering decisions under imperfect competition in general equilibrium settings. The focus in the industrial economics literature is, in particular, on the equilibrium concept when the monopolist is not able to fully recognize the overall implications of her supply decision. In this case, the monopolist evaluates supply policies with missing or incomplete assessment of the induced market reactions. This basically implies that the monopolist is very likely to have an incentive to reevaluate and revise her supply decision ex post given the unexpected adjustments in her market environment. In general, and especially without learning, it is therefore not ensured that an equilibrium allocation, in which no party has an incentive to deviate, arises at least in the long run from the self-interest decision making of the monopolist and not only by chance. Negishi (1961), for example, develops an equilibrium concept much in line with the familiar process of tâtonnement. To this end, he suggests to think of the monopolist conjecturing market reaction functions based on her limited level of information and based on some expectation for the future capital market equilibrium. He then shows that if these conjectures of the monopolist fulfill specific consistency requirements, a stable equilibrium will arise if the monopolist constantly revises her supply decision. A comprehensive review and discussion of subsequent approaches to resolve these technical issues about the equilibrium definition with limited degree of information can be found in Bonanno (1990).

In the resource economics context the crucial role of the level of information about the equilibrium effects for the optimal supply decision has not yet been pointed out to

[1] This, however, may be of interest in particular in game theoretic settings where the resource demand side is able to more strategically react to the supply policy of the resource monopolist, for example, by use of import tariffs or the development of resource substitutes.

the best of our knowledge. Still, we think that it is particularly relevant in the context of exhaustible energy resources, and in particular for oil. The reason is, on the hand, the still prominent role of fossil energy resources for economic growth and development, which suggests that supply shifts are very likely to induce more widespread effects in the economy (see also section 3.1.1). On the other hand, the supply side of these fossil resources is generally far from being truly competitive, not least because of the geographical concentration of resource stocks, as we already argued in the introduction.

Albeit possible, we will not follow the approach of Negishi (1961).[2] Instead, we will, just as for the competitive resource owner, resort to the assumption of rational expectations regarding the second period factor prices and the second period capital stock. In this case, the monopolist with limited information evaluates her extraction policy based on consistent market outcomes but still incomplete assessments of the true general equilibrium relationship between her supply decision and the market prices. However, if the monopolist determines her extraction policy, rational expectations will ensure that the market outcome exactly corresponds to what the monopolist has taken as basis for her supply decision. Interestingly, the monopolist then does not have an incentive to deviate even though another extraction policy may be more profitable. In contrast, the fully informed, or omniscient, resource monopolist even does not need to have rational expectations. The reason is that the omniscient sheikh can derive the actual market equilibrium and actual market reactions for any resource supply path on her own and, therefore, can directly determine the resource allocation most profitable from her perspective.

Our general equilibrium framework introduced in chapter 4 is characterized by the asymmetry between country E and country I in the resource endowments and the ac-

[2] For example, in the case of a naive monopolist (see section 5.2.2.1), the consistency requirement of Negishi (1961) basically implies that the monopolist's conjectured future period price-quantity relationships must include the true equilibrium allocation. Graphically, the conjectured marginal revenue curves have to intersect the "true" marginal revenue curves, which include the adjustment in the capital stock for different resource supply paths, exactly for that resource supply path for which the conjectured/expected endogenous capital stock arises. For the naive monopolist, one can show that this consistency requirement holds. This implies that the naive monopolist will arrive at the equilibrium outcome if the monopolist constantly can revise and update her supply decision as soon as the market reaction reveals that her conjectures about the future capital market equilibrium are not consistent with her supply decision. Note, however, that the equilibrium solution in this case is not necessarily the optimal solution for the omniscient monopolist but only the optimal solution given the limited level of awareness.

cess to the final goods production technology, which in a partial equilibrium setting with an exogenous interest rate and the fossil resource as single factor of production has been studied by Kemp and Long (1979). As already indicated before, similar general equilibrium frameworks of resource extraction in discrete time have been developed by Dixit (1981), Sachs (1981), Svensson (1982), Marion and Svensson (1984) and Wijnbergen (1985). This strand of literature focuses on the effect of oil price shocks on the trade patterns between resource importing and exporting countries and their respective current account balances. Even though to a large extent motivated by the global imbalances aroused by the oil price crises of the 1970s, by the worries about the capabilities of the financial system to recycle the capital spending of resource-rich countries, and by the current and future position of OPEC member states in the world economy, these contributions almost entirely assume competitive resource markets and thus do not investigate whether the general equilibrium structure has any qualitative implications for the optimal supply decision of resource owners. For example, Marion and Svensson (1984) or Wijnbergen (1985) do not at all focus on the supply decisions of resource exporting countries but on the welfare implications of oil price increases for the resource importing countries in general equilibrium settings with adjustments in the interest rate and on the possibilities of resource importers to reduce the global imbalances by taxation of resource imports or international capital flows. One exception, however, is Dixit (1981). He studies the links between oil trade and capital accumulation that arise in general equilibrium and focuses on the role of savings out of oil revenues, which can influence the global allocation and ownership of the capital stock and thereby trade patterns, but at least briefly discusses a specific general equilibrium aspect for the role of resource market power. In contrast to our setting, the resource exporting country in his framework is able to produce final goods, but countries still differ in the endowment of production factors. He then points out that in general equilibrium the familiar conclusion that an improvement in the future substitutability of fossil resources restricts resource market power may be undermined if capital accumulation is dependent on the resource owner's savings out of oil revenues. However, this is an equilibrium result, which arises from the effect of capital accumulation on the future final goods market equilibrium, and does not follow from a potential modification of the monopolistic supply decision via the interdependency of different markets in general equilibrium.

There is a second strand of literature which considers general equilibrium settings with exhaustible resources but thereby focuses on the optimal extraction path of an exhaustible resource and the existence of a long-run steady state growth path given that there is endogenous formation of the capital stock, in particular. For example, the interaction of savings and the optimal depletion of a resource stock is analyzed by Aarrestad (1978), who, however, assumes perfect substitutability of fossil resources and capital in consumption. Chiarella (1980) studies the socially optimal extraction path for an exhaustible resource in a two sector model with endogenous accumulation of physical capital where the resource is used for both, the production of consumption goods and the production of physical capital. Geldrop and Withagen (1993) discuss the existence of a steady state general equilibrium trajectory of market prices under more general specifications of utility and production functions and conclude that the implicit assumption in partial equilibrium approaches of a constant and exogenous long run interest rate only holds under restrictive assumptions in general equilibrium – a sufficiently large resource stock with low extraction costs in combination with a sufficiently large rate of time preference. Obviously, however, all these contributions do not consider resource market power at all.

Our approach is also to some extent linked to the literature on the strategic interaction between resource-rich and resource-poor countries. As indicated before, we follow the Cournot-Nash monopoly approach where market power is generally represented by the ability of the supplier to take into account the reaction of the demand side. Following this reasoning, we may interpret the resource monopolist, and especially the omniscient sheikh, as a Stackelberg leader. Thus, there is strategic behavior only on part of the resource monopolist whereas all the other parties, i.e. households and final goods producers, just take the monopolist's choice of the extraction path as given. To consider strategic interaction, we would have to extend our framework by including a more "active" resource demand side. In particular, the demand side would have to recognize that it can influence the resource monopolist's choice of extraction, for example, via strategically levying import tariffs (see, for example, Karp and Newberry 1991, and for the case of a cartel on the resource supply side Wirl 1994) or by developing and employing substitutive technologies, which has been analyzed, for example, by Gallini et al. (1983), Dasgupta et al. (1983) or more recently by Gerlagh and Liski (2011) and Michielsen (2014b). Long (2011) provides an extensive survey of this strand of literature on strategic interaction of buyers and sellers of exhaustible resources in dynamic game settings. Since our focus is, however, on the implications of resource market power in a general equilibrium setting, we deliberately abstain from considering these options of the resource importing countries to actively influence the monopolist's supply decision to their advantage in order to keep the analysis as tractable as possible.

Most closely related to our analysis are probably Moussavian and Samuelson (1984) and Hillman and Long (1985). Moussavian and Samuelson (1984) also consider a resource monopolist in a general equilibrium framework but with an infinite horizon of continuous time and with a simplified endogenous capital formation process as the endogenous savings decision is replaced by a fixed savings ratio. With such a fixed savings propensity, they assume away the (ambiguous) influence of the interest rate on savings and focus on the savings reaction to intertemporal income shifts, which come along with a change in the extraction path. In contrast to our framework, this implies that in their setup a postponement of resource extraction always comes at the expense of current capital accumulation and therefore always leads to lower capital accumulation path. They argue that a resource monopolist should be considered as "naive" if she did not take into account this obvious relationship between resource supply and capital accumulation. They show that a non-naive monopolist in this sense is very likely to deviate from the standard partial equilibrium Hotelling rule. The reason is that the monopolist then not only trades off the present and the future value of resource supply but also the present value of different capital accumulation paths, which arise from an intertemporal shift in resource supply. For example, if the value of future increments to the capital stock from a postponement of resource extraction is much lower than in the present period, the non-naive monopolist will find it optimal to choose a faster extraction path. In our two country framework, we will identify a completely analogue effect from the endogeneity of the second period capital stock and the complementarity of production factors, which, however, is unambiguous in contrast to Moussavian and Samuelson (1984) due to the fixed time horizon of two periods.

Hillman and Long (1985) consider a two-country-two-period setting which is very similar to ours but assume that the resource-rich country not only has market power in the resource market but also in the capital market. The latter implies that the resource exporter can control the interest rate directly, whereas we investigate, in particular, the role of the complementarity driven positive influence of resource supply on the interest rate for the resource supply decision. Hillman and Long (1985) point out that due to the interdependency of the resource and the capital market the resource supply behavior of the resource-rich country influences its possibilities to exert market power in the capital market and vice versa. This leads to a modification of the supply decision compared to the standard resource monopolist. For example, without physical capital accumulation, joint monopoly power in both, the resource and the financial market, leads to a more conservative extraction path as to foster the demand for consumption financing in the resource importing countries and thereby to support the benefits from exerting market power in the capital market. With physical capital, however, the resource monopolist may also find it optimal to choose a less conservative extraction policy and even to subsidize the lending from resource importing countries if the accumulation of capital in production is particularly profitable to the resource exporter. However, Hillman and Long (1985) do not discuss whether the cross market effects of resource supply may give rise to modifications of the supply behavior of the resource monopolist in general equilibrium even without capital market power.

A resource monopolist in general equilibrium is also introduced by Hassler et al. (2010). Similar to the so-called asset motive pointed out in our analysis, they also argue that the ownership of capital affects the supply decision of the resource monopolist via the complementarity related influence of resources on the capital return, namely it gives an incentive to increase supply. However, their analysis is completely static and thus abstracts from the intertemporal trade-offs to be made with resource scarcity. The role of the positive influence of resource supply on the interest rate for the extraction decision has also been studied by Hoel (1981) who just postulates such a relationship in an otherwise standard partial equilibrium model of resource monopoly. Moreover, Hoel (1981) thereby only accounts for the endogeneity of the market discount factor but does not investigate the additional considerations which arise as soon as the monopolist holds assets in the capital market.

5.2.2 The Supply Decision of An Omniscient Benevolent Monopolist

Resource extraction in country E is controlled by some government authority which we call the sheikh. The sheikh is benevolent in the sense that she distributes resource income in both periods (4.2) to the representative household, or her constituency. Moreover, the benevolent sheikh cares for the well-being of her constituency and correspondingly chooses resource supply as to maximize the life-time utility of the representative household given in (4.1)

$$\max_{R_1,R_2} u(c_{1E}) + \beta_E u(c_{2E}) \tag{5.1}$$

Since we are interested in settings with resource scarcity, we again assume that the resource constraint (4.3) is binding, and therefore that the maximization of life-time utility is subject to $R_1 + R_2 = \bar{R}$.

The savings decision, in contrast, is still separately made by households, which have rational expectation regarding the sheikh's decision and the corresponding equilibrium outcome. This implies that the Euler equation (4.11) holds for any extraction path the sheikh chooses. Without changing anything in the following analysis, we could alternatively deviate from the structure of our economy and assume that the sheikh chooses both, savings and resource extraction, which would set the sheikh truly in the position of a social planner for country E but not necessarily for the world economy. We will point out in the following where the derivation of the optimal monopolistic supply path via the utility maximization differs from the familiar profit maximization approach as in (2.4).

Given that the sheikh maximizes life-time utility of households, she must obviously account for the budget constraints (4.10) when planning extraction. Moreover, the benevolent and omniscient sheikh is aware that in the conditional market equilibrium market prices and the second period capital stock as well as the savings of her constituency are functions of her supply decision

$$p_t = F_{tR}(K_t, R_t)$$

$$\text{with } \frac{dp_2}{dR_2} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} \qquad \text{from (4.30)}$$

$$i_t = F_{tK}(K_t, R_t)$$

$$\text{with } \frac{di_2}{dR_2} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2} \qquad \text{from (4.31)}$$

$$K_2 = K_2(R_2) \qquad \text{from (4.28)}$$

$$s_{1E} = s_{1E}(y_{1E}, \pi^{\tau}_{2E}, i_2)$$

$$\text{with } \frac{ds_{1E}}{dR_2} = -\frac{\partial s_{1E}}{\partial y_{1E}}\frac{\partial y_{1E}}{\partial R_1} + \frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}}\frac{d\pi_{2E}}{dR_2} + \frac{\partial s_{1E}}{\partial i_2}\frac{di_2}{dR_2} \qquad \text{from (4.11)}$$

Overall, we may think of the benevolent omniscient sheikh as the leader in a Stackelberg setting where the behavior of the Stackelberg followers is represented in these conditional market equilibrium relationships between the capital stock, the market prices of the resource and capital, and the resource supply path. To simplify the exposition and to focus on the implications of the general equilibrium effects of resource supply, we consider just the symmetric country case here as already pointed out before.

Since households with rational expectations in country E save optimally, the Euler equation (4.11) holds for any extraction decision. Hence, we can combine the first-order conditions and substitute for the marginal rate of substitution $u'(c_{1E})/\beta_E u'(c_{2E})$ to characterize the optimal resource extraction path by the modified Hotelling rule

$$(1+i_2)\left(p_1+\frac{\partial p_1}{\partial R_1}R_1+\frac{\partial i_1}{\partial R_1}s_{0E}\right)= \\ (1-\tau)\left[p_2+\left(\frac{\partial p_2}{\partial R_2}+\frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2}\right)R_2\right]+\left(\frac{\partial i_2}{\partial R_2}+\frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2}\right)s_{1E} \quad (5.2)$$

For the first period, the factor price reactions are given in (4.26) and (4.27). For the second period, we use the decompositions in (4.30) and (4.31) to split the factor market price reactions into the direct and the induced indirect effects of resource supply via the endogeneity of capital accumulation.

In principle, since the benevolent sheikh is confronted with an intertemporal trade-off, this condition resembles the familiar monopolistic Hotelling rule from (2.5). The optimal resource extraction path, which we denote by (R_1^o, R_2^o) with the superscript "o" referring to the omniscient sheikh, is characterized as that allocation of resources for which the present marginal value of resources in both periods to the sheikh is constant. However, in contrast to the standard setting, the marginal value of resource supply to the sheikh in either period is obviously extended. The own-price reaction in the second period includes the endogenous adjustment of the capital stock according to (4.30). Moreover, the marginal value of fossil resources in either period comprises not only the marginal resource revenue but in addition to this "resource income component" a "capital income component" due to the endogeneity of the return on capital investments of country E with respect to the resource supply path. In the first period, this endogeneity directly arises from the complementarity of both production factors (see (4.27)), whereas in the second period the complementarity effect is supplemented by the simultaneous adjustment in the capital stock according to (4.31). For future reference it also proofs useful to define this extended marginal resource value to the omniscient sheikh as[3]

$$MR_t^o=(1-\tau_t)\left(p_t+\frac{dp_t}{dR_t}R_t\right)+\frac{di_t}{dR_t}s_{1E} \quad (5.3)$$

[3] Recall that we assumed for simplification that the resource importing country I only levies a carbon tax in the second period so that $\tau_1=0$ and $\tau_2=\tau>0$ (see also section 4.1.3.1).

For unit carbon tax, the second period marginal resource value is instead given by

$$MR_2^o=p_2+\frac{dp_2}{dR_2}R_2-\tau+\frac{di_2}{dR_2}s_{1E}$$

where the factor price reactions are given by (4.26) and (4.27) for the first period, and by (4.30) and (4.31) for the second period.

It is worth noting that the reason for these differences to the familiar partial equilibrium monopolist is not that we have derived the modified Hotelling rule by letting the sheikh maximize the life-time utility of households instead of the present value of overall resource profits as in section 2.1.2. Even in the standard partial equilibrium setting, we could assume that the monopolist benevolently maximizes the households' life-time utility by choice of the extraction path and still would arrive at Hotelling rule (2.5), as long as households can separately smooth consumption over time by their savings decision. In fact, when the resource monopolist aims to maximize the life-time utility of households, the access of households to the capital market is crucial in partial as well as in general equilibrium to establish the familiar linkage between the return of conserving resources underground and the investment return in the capital market. Otherwise, the resource monopolist foremost plans extraction as to smooth consumption over time given the time preferences of her constituency, and the investment options and returns in the capital market do not play a role at all for the optimal extraction policy. Technically, this is reflected in the substitution for the marginal rate of substitution from the Euler equation (4.11) in the derivation of Hotelling condition (5.2).

The separate savings decision of households is also the reason why in the modified Hotelling rule (5.2) the intertemporal trade-off is weighted by the market discount factor $1 + i_2$, which does not include the influence of resource supply on capital return even though the sheikh explicitly internalizes that into her supply decision. In fact, just as in the standard Hotelling frameworks, the discount factor represents the opportunity costs of leaving resources underground in the extended general equilibrium setting, too. The benevolent sheikh, in principle, trades off the marginal utility gain from increasing households' consumption in either period by a shift in resource extraction from one period to the other. However, since households save optimally in any case, the return of conserving resources underground to the sheikh is in the end tied to the return in the capital market via the Euler equation. The alternative investment return, or the opportunity costs of leaving resources underground, would, however, be different if households (or the sheikh) could exert market power in the capital market in the sense that the savings from country E are non-marginal contributions to, or the only source of, world capital supply. In this case, the negative own-price effect in the capital market would explicitly be internalized into the savings decision, and thereby would also go into the discount factor relevant for the choice of the extraction path. This would exactly resemble the results in Hillman and Long (1985) who assume joint monopoly power in the resource and the capital market.

The informational requirements for the omniscient sheikh are, of course, quite high and can be criticized as unrealistic. Still, we think that it seems especially plausible in case of fossil resources to assume that resource owners with market power realize and account for at least some of the additional cross market influences of their fossil resource supply. The reason is the widely recognized still prominent role of fossil resources, and oil in particular, for the development and growth of both, industrialized and emerging market economies, which we already discussed before in section 3.1.1. Moussavian and Samuelson (1984) support this view by arguing that only a "naive" resource monopolist would not recognize and account for the obvious influence of resource supply on capital accumulation.

5.2.2.1 The Naive Sheikh

We adapt the terminology of Moussavian and Samuelson (1984) and refer to the completely naive sheikh as the monopolist who ignores all the additional cross market effects in our general equilibrium setting and just internalizes the familiar negative own-price effect from resource supply on the resource market price. Thus, all the additional components in (5.2) drop out, and the naive sheikh follows the familiar Hotelling condition

$$(1+i_2)MR_1^n = MR_2^n \tag{5.4}$$

as in partial equilibrium (see section 2.1.2). We denote the extraction decision of the naive sheikh by (R_1^n, R_2^n) where the superscript "n" stands for "naive". The definition of the marginal resource revenue MR_t^n exactly corresponds to the definition of marginal resource revenue in the partial equilibrium setting (2.6). However, there is now a concrete specification of inverse resource demand as it is derived from the marginal productivity of resources for the CES production technology (4.4). Denoting the share of total output which production factor f captures as remuneration in period t (before taxes) by θ_{tf} we therefore may write for the marginal resource revenue with $\tau_1 = 0$ and $\tau_2 = \tau \geq 0$

$$MR_t^n = (1-\tau_t)\left(p_t + \frac{\partial p_t}{\partial R_t} R_t\right) = (1-\tau_t)\frac{p_t}{\sigma}\left[\theta_{tR} - (1-\sigma)\right] \tag{5.5}$$

The price elasticity of demand is given by

$$\epsilon_{R_t,p_t} = \frac{\sigma}{1-\theta_{tR}} \qquad \text{with} \qquad \frac{\partial \epsilon_{R_t,p_t}}{\partial R_t} = \frac{\sigma-1}{1-\theta_{2R}} \frac{p_t}{F_t} \gtreqless 0 \qquad \text{for} \qquad \sigma \gtreqless 1 \tag{5.6}$$

Even though there is obviously no qualitative difference in the supply decision between partial and general equilibrium, we now, given resource demand derived from CES final goods production, have to take into account that the second period capital stock K_2 is very likely to deviate from first period aggregate capital endowments. Again, having the growth path of the world economy since the industrial revolution in mind, we want to focus on positive accumulation of physical capital over time in the sense that $K_2 > K_1$, although we generally cannot exclude that the capital stock shrinks over time. Via the complementarity of fossil resources and capital, fossil resources then become more valuable over time or, put differently, there is an upward shift in (inverse) resource demand. For the competitive resource market, we already have pointed out that this development tends to raise future resource extraction and might even lead to an increasing competitive supply path over time $R_1^c < R_2^c$ if capital accumulation is sufficiently high. We now will assess the role of capital accumulation for the supply decision of the naive sheikh.

First, the complementarity driven upward shift in resource demand leads to an increase in marginal resource revenue. This can analytically be verified for resource demand derived from the CES production technology as[4]

$$\left.\frac{\partial MR_t^n}{\partial K_t}\right|_{R_t} = (1-\tau_t)\frac{2-\sigma}{\sigma}\left(\theta_{tR} - \frac{1-\sigma}{2-\sigma}\right) F_{tRK} > 0 \quad \text{for all } \sigma > 0 \tag{5.7}$$

The positive sign holds true at least as long as $MR_t^n > 0$ from (2.6), which is a reasonable restriction in our setting. The reason is that otherwise the resource would not be scarce from the naive monopolist's perspective, which would contradict our assumption of a binding resource constraint.[5] Thus, the naive monopolist is generally

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[4] We use the notation $|_{f_t}$ to explicitly indicate that production factor f_t is held constant in the derivation of the respective term.

[5] Note that the restriction ensures that $\theta_{tR} > 1-\sigma$, and therefore that

$$(2-\sigma)\theta_{2R} - (1-\sigma) > 0 \quad \text{as} \quad \begin{cases} \theta_{tR} > 1-\sigma > \frac{1-\sigma}{2-\sigma} & \text{for } \sigma \leq 1 \\ 1-\sigma < 0 < 2-\sigma & \text{for } 1 < \sigma < 2 \\ -(1-\sigma) > 0 & \text{for } \sigma = 2 \\ 1-\sigma < 2-\sigma < 0 & \text{for } \sigma > 2 \end{cases}$$

which confirms that the sign of (5.7) does not depend on the elasticity of substitution $\sigma > 0$.

also induced by capital accumulation to supply more resources in the second period compared to the setting with constant resource demand over time.

Second, capital accumulation can influence the extraction bias which is introduced by market power in comparison to the competitive market outcome. We know from section 2.1.2 that this extraction bias is directly linked to the development of the price elasticity of demand over time along the competitive extraction path. However, whether the price elasticity of resource demand increases or decreases with resource consumption solely depends on the elasticity of substitution σ according to (5.6), and in particular not on the capital stock. Thus, the monopolistic extraction bias qualitatively does not change in our general equilibrium setting, as long as the competitive extraction path exhibits the same time pattern and as long as the relationship between resource consumption and the price elasticity of resource demand is the same as in the partial equilibrium setting. For example, in partial equilibrium we know that the resource monopolist will choose a more conservative extraction policy if there is a falling competitive supply path and the price elasticity of resource demand is falling in resource consumption (see section 2.1.2). With resource demand derived from the CES production technology, the latter is the case for $\sigma < 1$ according to (5.6). Thus, in this case, if the competitive resource extraction path is still falling over time in general equilibrium, we know that the naive sheikh will also choose a more conservative extraction path in general equilibrium, irrespective of the development of the capital stock over time.

Whether the respective extraction bias is exacerbated or attenuated by a higher second period capital stock is generally not clear. The accumulation of capital on its own affects the price elasticity of resource demand as we can observe from

$$\begin{aligned}\left.\frac{\partial \epsilon_{R_t,p_t}}{\partial K_t}\right|_{R_t} &= -\frac{\sigma}{(1-\theta_{tR})^2}\frac{\partial \theta_{tR}}{\partial K_t} \\ &= (\sigma - 1)\frac{\theta_{tR}}{(1-\theta_{tR})^2}\frac{F_{tK}}{F_t} \gtreqless 0 \quad \text{for } \sigma \gtreqless 1.\end{aligned} \tag{5.8}$$

This isolated effect of the capital stock on the price elasticity of resource demand, just as the effect of resource consumption (see (5.6)), crucially depends on the elasticity of substitution σ being greater or lower than unity. In particular, we observe that resource consumption and the capital stock increase the price elasticity for $\sigma > 1$ and decrease the price elasticity for $\sigma < 1$. For iso-elastic demand and $\sigma = 1$, both have no influence at all.

Considering the familiar conservationist's bias for $\sigma < 1$, these results suggest at first that capital accumulation tends to induce the monopolist to extract the resource even more conservatively than for a constant capital stock, and therefore that the conservationist's bias is exacerbated. Whereas this definitely holds true in comparison with the competitive extraction path without capital accumulation, for a full quantitative comparison we would also have to take into account that with capital accumulation the resource stock is depleted more conservatively in the competitive market, too. But since explicit solutions for the extraction path are excluded even in the competitive case, we cannot draw a general conclusion about the magnitude of the monopolistic extraction bias with and without capital accumulation. Since the price elasticity of resource demand changes with capital accumulation according to (5.8), we can, however, conclude that the naive sheikh will deviate from the competitive market solution for $\sigma \neq 1$ even if in the competitive market the resource supply is constant in both periods due to the increase in the future resource market price from capital accumulation.

Note that if the accumulation of capital over time leads to an increasing competitive supply path ($K_1 < K_2$ and $R_1^c < R_2^c$), or if we have a reduction in the capital stock and a decreasing competitive supply path ($K_1 > K_2$ and $R_1^c > R_2^c$), by (5.6) and (5.8) the effects of the capital dynamics and the resource consumption pattern on the price elasticity of demand ϵ_{R_t,p_t} are counteracting. This implies that the incentive for the naive monopolist to deviate from the competitive outcome and therefore the extraction bias is completely ambiguous in these cases, in general.[6]

For $\sigma = 1$ and Cobb-Douglas technology, resource demand is iso-elastic and the price elasticity of demand is not affected by changes in the capital stock. By (5.6) and (5.8) the naive monopolist's and the competitive extraction path then coincide with and without capital dynamics.

6 Note that a scenario $K_1 > K_2$ and $R_1^c < R_2^c$ is excluded because with a shrinking capital stock the necessary growth in the resource rent for Hotelling condition (2.3) to hold requires that second period resource supply is lower than in the first period.

5.2.2.2 The Asset Motive

If the benevolent sheikh recognizes in addition to the own-price effect the direct complementarity driven impact of resource supply on the market return on capital investments, the optimal extraction path is characterized by the condition

$$\begin{aligned}(1+i_2)\left(p_1+\frac{\partial p_1}{\partial R_1}R_1+\frac{\partial i_1}{\partial R_1}s_{0E}\right)=\\ (1-\tau)\left(p_2+\frac{\partial p_2}{\partial R_2}R_2\right)+\frac{\partial i_2}{\partial R_2}s_{1E}\end{aligned} \tag{5.9}$$

The complementarity of production factors introduces a capital income component to the benevolent sheikh's supply decision, which we call the "asset motive" in the following. The sheikh realizes that additional resource supply in either period increases the marginal productivity of capital and thereby, in market equilibrium, generates a higher return on the investments which her constituency holds in the capital market. The asset motive adds to the standard monopolistic motive represented by the negative own-price effect and increases the marginal resource value – note the distinction between the marginal resource revenue and the marginal resource value which includes all components the sheikh is aware of – to the sheikh whenever her constituency has positive capital holdings abroad $s_{(t-1)E} > 0$, i.e. no debt positions. For future reference it proofs useful to define this extended marginal resource value as

$$\begin{aligned}MR_t^{na}&=(1-\tau_t)\left(p_t+\frac{\partial p_t}{\partial R_t}R_t\right)+\frac{\partial i_t}{\partial R_t}s_{(t-1)E}\\ &=\frac{p_t}{\sigma}\left(\theta_{tR}+\theta_{tK}\frac{s_{(t-1)E}}{K_t}-(1-\sigma)\right)\end{aligned} \tag{5.10}$$

where again $\tau_1 = 0$ and $\tau_2 = \tau$ without loss of generality (see also section 4.1.3.1). The superscript "na" stands for "naive sheikh with asset motive" since the sheikh here is still naive with respect to the capital dynamics. The second transformation holds due to the standard properties of the CES production technology.

From a static perspective, the asset motive clearly creates an incentive to increase period resource supply, which generally for positive capital holdings has also been noted by Calvo and Findlay (1978) and Hassler et al. (2010). In a dynamic setting with resource scarcity and positive capital holdings in both periods, increasing resource supply in both periods is obviously not a feasible strategy. The asset motive, therefore, introduces an additional trade-off to the supply decision and presents a new perspective on the role of the by now large capital holdings of resource-rich countries even according to the officially available information about the volume of the sovereign wealth funds (see the discussion in the section 3.1.2).

A relationship between the capital asset holdings and the (dynamic or intertemporal) supply decision of resource owners has recently also been pointed out by van den Bremer et al. (2014). However, they consider a competitive resource market and show that with uncertain but correlated future resource prices and capital market returns the value of the resource stock underground should optimally be considered as part of the asset portfolio which resource-rich countries hold. This implies that the selection of the capital asset portfolio should account for the development of the resource asset underground for reasons of risk diversification and portfolio optimization. Moreover, and more important in our context, they also demonstrate that the standard Hotelling rule for a competitive resource market is modified with a positive (negative) correlation between the capital asset return and the resource price so that the resource is extracted more slowly (faster) than in the standard case. Intuitively, if there is a positive correlation between the future resource prices and capital returns, decelerating extraction will allow resource owners to realize not only high resource profits when the resource market price is high but at the same time also high capital returns from investing these resource proceeds. However, this reasoning clearly is completely different to the asset motive, which we will analyze in more detail in the following.

Note that with accounting for the complementarity effect on capital return planning resource extraction by maximization of life-time utility is no longer equivalent to the extraction policy of a private monopolistic resource firm, which maximizes the present value of resource profits and has access to the capital market. As pointed out before, this equivalency holds for the naive sheikh who takes the capital return as given. In fact, since households with rational expectations make a separate savings decision, the naive sheikh effectively chooses resource extraction as to maximize the present value of resource rents for a given interest in any case (see also the corresponding discussion in Hoel 1981). However, as soon as the monopolist accounts for the cross market influence of resource supply on the marginal productivity of capital, the equivalency of both approaches breaks down. The reason is that the utility maximizing benevolent sheikh then does not only consider resource income but also capital income of her constituency and therefore pursues kind of a two pillar strategy. Since the intertemporal arbitrage in this case is linked to the market interest rate only via the separate savings decision, the influence of resource supply on the market discount factor is not reflected in the extraction policy of the sheikh, as already previously pointed out. In contrast, a profit maximizing resource monopolist, who recognizes the complementarity based influence on the market interest rate, directly takes into account that shifting resource extraction from the first to the second period increases the alternative investment return in the capital market – the opportunity costs of leaving resources underground – but does not account for her influence on households' income from savings.[7]

Since we cannot explicitly solve for the optimal extraction path, we will assess the effect of the asset motive in the following by taking the purely naive monopolist's extraction decision as the benchmark case and by studying if and under which conditions the sheikh is induced to revise the extraction decision. This will also include an assessment of the monopolistic extraction bias in comparison to the competitive market outcome defined by Hotelling condition (2.3).

We start with investigating when the internalization of the direct complementarity effect does not lead the sheikh to revise the supply decision. Equating Hotelling rules (2.5) and (5.9), we observe upon rearranging that pursuing the asset motive will be exactly neutral compared to the naive monopolist if

$$\frac{F_{2KR}s_{1E}}{F_{1KR}s_{0E}} = \frac{(1-\tau)\left(p_2 + \frac{\partial p_2}{\partial R_2}R_2\right)}{p_1 + \frac{\partial p_1}{\partial R_1}R_1} = 1 + i_2 \tag{5.11}$$

where we also set $\frac{\partial i_t}{\partial R_t} = F_{tKR}$ in market equilibrium. Intuitively, pursuing the asset motive in both periods does not lead the sheikh to adjust the supply path if the present value of the capital income component in the overall marginal resource value MR_t^{na}, just as the resource income component given by the marginal resource revenue MR_t^n, is constant over time. If the marginal value of the resource in terms of the gains in capital income grows stronger over time than the marginal resource revenue, future resource supply will be more valuable to the asset motive pursuing sheikh than to the naive monopolist. Pursuing the asset motive then will create an incentive to shift more resource to the second period starting from the extraction decision (R_1^n, R_2^n) of the naive monopolist, and vice versa.

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[7] In fact, the Hotelling rule for such a profit maximizing, non-naive monopolist reads

$$(1+i_2)\left(p_1 + \frac{\partial p_1}{\partial R_1}R_1\right) = (1-\tau)\left(p_2 + \frac{\partial p_2}{\partial R_2}R_2\right) - \frac{(1-\tau)p_2R_2}{1+i_2}\frac{\partial i_2}{\partial R_2}$$

The second term on the right captures the effect of a marginal increase in the market discount factor, which reduces the value of second period resource supply.

We now further investigate the development of the capital income component $F_{tKR}s_{(t-1)E}$ over time. In general, the capital income component may rise or fall over time due to a change in the capital holdings of households and/or a change in the sensitivity of the interest rate with respect to resource supply. However, the latter is not independent but closely related to the marginal resource revenue MR_t^n from (5.5) as both directly derive from the final goods production technology. In fact, if we take the extraction path chosen by a naive monopolist according to Hotelling condition (2.5) (R_1^n, R_2^n) as reference point, the neutrality of the asset motive just depends on the development of the foreign capital holdings. The reason is that, as we know from our analysis of the conditional market equilibrium, the resource extraction path uniquely determines the market prices and the capital stock in the second period for symmetric countries (see (4.28), (4.30), and (4.31)) and given factor endowments $\bar{R}$ and K_1. In the end, choosing the naive sheikh's extraction path as reference unambiguously determines every variable but households' savings s_{1E}. Households' savings depend on the extraction path, too. But since they are a function of income streams y_{1E} and π_{2E}^{τ} according to (4.12), we may change savings by altering the distribution of the overall capital endowments K_1 between both countries, which is purely redistributive and hence without any effect on aggregate capital accumulation for symmetric homothetic consumption preferences (see also section 4.1.3.2). The latter, in particular, implies that we may have different allocations of capital endowments and thereby different savings s_{1E} while our reference extraction path represented by the extraction decision of the naive sheikh does not change.

The Role of the Distribution of Capital Endowments

To isolate the role of the capital endowments distribution for the comparison between the asset motive pursuing sheikh and the naive monopolist, we solve neutrality condition (5.11) for the ratio of country E's asset holdings

$$\frac{s_{1E}}{s_{0E}} = \frac{\frac{(1-\tau)\left(p_2+\frac{\partial p_2}{\partial R_2}R_2\right)}{F_{2KR}}}{\frac{p_1+\frac{\partial p_1}{\partial R_1}R_1}{F_{1KR}}} \equiv \Phi(R_1^n, R_2^n) \tag{5.12}$$

For symmetric homothetic preferences, the threshold Φ is just a function of the resource extraction path for a given resource tax τ and completely independent of the distribution of capital endowments K_1 between country E and I as we argued before. Moreover, by construction Φ is defined for the reference resource supply policy of the completely naive monopolist (R_1^n, R_2^n). The influence of the resource tax is studied in the next chapter 6.

Condition (5.12) first illustrates that it is not the absolute amount or value of capital holdings but their development over time which is relevant for the influence of the asset motive on the extraction decision. In particular, it suggests that if there is a sufficiently strong increase in the asset holdings of country E so that $\frac{s_{1E}}{s_{0E}} > \Phi$, the asset motive pursuing sheikh will revise the naive monopolist's extraction decision and choose a more conservative path. In this case, the capital income component, due to the strong increase in capital holdings, grows faster over time than the resource income component represented by the marginal resource revenue so that it creates an incentive to postpone extraction. Obviously, for $\frac{s_{1E}}{s_{0E}} < \Phi$, the opposite holds true.

A redistribution of capital endowments to country E lowers the ratio of asset holdings. To show this, we first note by (4.13) and (4.14) that since the overall market equilibrium does not change, the marginal savings propensities to changes in period income streams or the interest are insensitive to a redistribution capital endowments, too. Thus, for any given extraction path and given K_1, we can decompose the second period asset holdings of country E as a linear function of its endowments

$$\begin{aligned} s_{1E}(s_{0E}) &= s_{1E}(0) + \frac{\partial s_{1E}}{\partial s_{0E}} s_{0E} = s_{1E}(0) + \frac{\partial s_{1E}}{\partial y_{1E}} \frac{\partial y_{1E}}{\partial s_{0E}} s_{0E} \\ &= s_{1E}(0) + \frac{\partial s_{1E}}{\partial y_{1E}} (1+i_1) s_{0E} \end{aligned}$$

We denote by $s_{1E}(0)$ the savings level without any capital endowment. The savings reaction to increases in the first period income y_{1E} is a positive constant (lower than unity) for a given extraction path as we noted before. Using this relationship between capital endowment and savings, we get for the effect of a capital endowment redistribution on the ratio of second to first period capital holdings[8]

$$\left. \frac{\partial \frac{s_{1E}}{s_{0E}}}{\partial s_{0E}} \right|_{K_1} = \frac{1}{s_{0E}} \left[\frac{\partial s_{1E}}{\partial y_{1E}} (1+i_1) - \frac{s_{1E}}{s_{0E}} \right] = -\frac{s_{1E}(0)}{s_{0E}^2} < 0 \tag{5.13}$$

This implies that upon redistributing capital endowment to country E the monopolist's incentive to postpone extraction will be more and more reduced and eventually be reversed if the ratio of second to first period capital holdings falls below Φ. By increasing first period capital holdings, the redistribution of endowments disproportionally strengthens the capital income component in the first period over the one of the second period and thereby lowers the return in terms of capital income which the sheikh can get from conserving resources underground. The reason is that since

[8] We again use the notation $|_{K_1}$ here to point out that we consider a redistribution of capital endowments without an increase in aggregate capital endowments.

households save only some fraction of the additional first period income – recall that the savings propensity to first period income changes is positive but lower than unity according to (4.13) – the ratio of asset holdings decreases, which leads to a slower increase in the capital income component over time. In turn, the incentive to postpone extraction is the strongest if country E does not own any capital assets in the beginning ($s_{0E} = 0$) but holds positive shares in the future capital stock. Obviously, in this case the asset motive only adds to the second period marginal resource revenue and thereby creates an unambiguous incentive to postpone extraction.

Finally, we can use the fact that the maximal capital endowment redistribution to country E is necessarily limited by the given first period capital stock K_1 so that there is a lower bound on the ratio of asset holdings.[9] By (5.13), this observation allows us to conclude that the neutrality condition (5.12) cannot be met for any $s_{0E} > 0$ if

$$\Phi \leq \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1) = \lim_{s_{0E}\to\infty} \left.\frac{s_{1E}}{s_{0E}}\right|_{K_1}$$

In this case, we always have $\frac{s_{1E}}{s_{0E}} > \Phi$ and the asset motive pursuing sheikh will always supply more resources in the second period than the naive monopolist for any $s_{0E} \leq K_1$.

The Asset Motive and the Conservationist's Bias

What does the asset motive imply for the effect of market power in resource markets? In general, since pursuing the asset motive may create an incentive to accelerate or slow down the speed of extraction, the previous conclusions about the effect of market power may no longer hold true. To gain more intuition, we proceed along the lines of the comparison to the naive monopolist. Equating the respective Hotelling

9 For the limiting cases of the capital asset ratio we have

$$\lim_{s_{0E}\to 0} \left.\frac{s_{1E}}{s_{0E}}\right|_{K_1} = \lim_{s_{0E}\to 0} \left[\frac{s_{1E}(0)}{s_{0E}} + \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1)\right] = +\infty$$
$$\lim_{s_{0E}\to\infty} \left.\frac{s_{1E}}{s_{0E}}\right|_{K_1} = \lim_{s_{0E}\to\infty} \left[\frac{s_{1E}(0)}{s_{0E}} + \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1)\right] = \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1)$$
$$\lim_{s_{0E}\to K_1} \left.\frac{s_{1E}}{s_{0E}}\right|_{K_1} = \frac{s_{1E}(K_1)}{K_1} = \frac{s_{1E}(0)}{K_1} + \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1) > \frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1)$$

conditions (2.3) and (5.9), the asset motive pursuing sheikh will choose exactly the competitive supply path if

$$F_{1KR}s_{0E}\left(\frac{F_{2KR}s_{1E}}{F_{1KR}s_{0E}}-(1+i_2)\right)=(1-\tau)p_2\left(\frac{1}{\epsilon_{R_2,p_2}}-\frac{1}{\epsilon_{R_1,p_1}}\right) \tag{5.14}$$

holds with equality for the competitive extraction path (R_1^c, R_2^c). The price elasticity of resource demand ϵ_{R_t,p_t} is defined in (2.7). First, by neutrality condition (5.11) the left side will be exactly zero if the extraction paths of the asset motive pursuing sheikh and the naive monopolist coincide. Moreover, from our previous discussion of the influence of the capital endowments distribution we know that the left side is more likely to be of negative sign if we increase the asset endowments of country E. Second, regarding the right side, we can rely on our discussion of the naive monopolist in general equilibrium (see sections 5.2.2.1 and 2.1.2). For simplicity and better comparability with the familiar partial equilibrium results, we focus here on the case where the competitive extraction path is falling over time so that $R_1^c > R_2^c$ even though we may have capital accumulation in the sense that $K_2 > K_1$. In this case, we know that market power will imply a more (less) conservative extraction path compared to the competitive outcome if the price elasticity of resource demand ϵ_{R_t,p_t} is greater (lower) in the second period than in the first period along the competitive extraction path (R_1^c, R_2^c), and therefore if the right side is negative (positive). Obviously, if the negative own-price effects induces the naive monopolist to extract more (less) conservatively than the competitive market, the asset motive pursuing sheikh will only want to choose the competitive extraction path if the capital income component grows at a lower (higher) rate than marginal resource revenue over time. Put differently, the asset motive must compensate for the bias introduced by the own-price effect to let the sheikh choose the competitive extraction path. Since the initial distribution of capital endowments does not affect neither the competitive nor the naive monopolist's extraction path for symmetric and homothetic consumption preferences, this again depends on the distribution of capital endowments, too. For example, to counteract or maybe even reverse the familiar conservationist's bias in the naive monopolist's extraction policy, we can redistribute capital endowments from country I to country E which does not influence the overall market equilibrium but strengthens the first period compared to the second period asset motive and thereby induces the sheikh to accelerate extraction towards the competitive market solution.

For iso-elastic resource demand (i.e. $\sigma = 1$ with a CES production technology), the naive monopolist exactly chooses the competitive extraction path. However, for the asset motive pursuing sheikh, this conclusion does not necessarily hold true. In fact, with the asset motive, the sheikh will only follow the competitive extraction path if the marginal value of fossil resources in terms of the capital income component grows at the same rate as the resource income component represented by the marginal resource revenue. In this case, the right and the left side of condition (5.14) are exactly zero and there is no difference between the competitive market solution, the naive monopolist and the asset motive pursuing sheikh. Regarding the left side, since for $\sigma = 1$ the CES production technology corresponds to a Cobb-Douglas technology of the form $F_t = K_t^{\gamma} R_t^{\lambda} L^{1-\gamma-\lambda}$ so that the income share θ_{tf} of production factor f is given by the respective constant exponent, this requires that

$$\frac{s_{1E}}{s_{0E}} = (1-\tau)\frac{K_2}{K_1} \qquad \text{or} \qquad \frac{s_{1E}}{K_2} = (1-\tau)\frac{s_{0E}}{K_1}$$

Thus, the share of the capital stock which is held by the households in country E has to increase over time if the resource importing countries levy a resource tax (τ) in the second period. Otherwise, if there is no resource tax or a time constant value added resource tax, the share of capital assets in the aggregate capital stock has to be constant over time. The role of the capital asset share in the capital stock can also be observed by setting $\frac{\partial p_t}{\partial R_t} = F_{tRR}$ and $\frac{\partial i_t}{\partial R_t} = F_{tKR}$ and rewriting Hotelling condition (5.9) to

$$\frac{(1-\tau)p_2}{p_1}\frac{\theta_{2R} - (1-\sigma) + \frac{\theta_{2K}}{1-\tau}\frac{s_{1E}}{K_2}}{\theta_{1R} - (1-\sigma) + \theta_{1K}\frac{s_{0E}}{K_1}} = \frac{(1-\tau)p_2}{p_1}\frac{\lambda + \frac{\gamma}{1-\tau}\frac{s_{1E}}{K_2}}{\lambda + \gamma\frac{s_{0E}}{K_1}} = 1 + i_2$$

where the second transformation follows for the Cobb-Douglas case. This directly demonstrates that only for $\frac{s_{1E}}{K_2} = (1-\tau)\frac{s_{0E}}{K_1}$ the asset motive pursuing sheikh will follow the competitive extraction path defined by Hotelling rule (2.3).

Overall, a general conclusion about the effect of market power in resource markets and the role of the asset motive is not possible. In particular, pursuing the asset motive may reverse or even exacerbate the conservationist's bias. Moreover, the equivalency of the monopolistic and competitive extraction path for iso-elastic resource demand and without extraction costs may no longer hold true.

The Asset Motive, Capital Accumulation, and Aggregate Resource Extraction

When discussing the differences between monopolistic and competitive resource supply in partial equilibrium in section 2, we already pointed out that in contrast to Stiglitz (1976) the monopolist may indeed opt to leave resources underground in a finite time horizon setting without extraction costs and thereby opt to limit aggregate market supply compared to the competitive even without exploration investments

(Gaudet and Lasserre 1988) if the price elasticity of resource demand depends on resource consumption and resource demand becomes price-inelastic when exhausting the stock. Given resource demand derived from the CES-type final goods production, we can scrutinize this line of reasoning further and thereby also illustrate the role of the asset motive for aggregate resource extraction.

For $\sigma \geq 1$, resource demand is always price-elastic according to (5.6). Hence, even the naive monopolist always exhausts the resource stock completely without extraction costs in this case. However, for $\sigma < 1$, the price elasticity of resource demand is falling in resource consumption. Thus, for a sufficiently high resource stock, if we "force" the naive sheikh to exhaust the stock over the given time horizon of two periods, marginal resource revenue MR_t^n from (5.5) will become negative but Hotelling condition (2.5) is still met. In fact, using (5.5), we can show that

$$MR_t^n \gtreqless 0 \qquad \text{for} \qquad R_t \lesseqgtr \left(\frac{\sigma}{1-\sigma} \frac{\lambda}{\gamma K_t^{\frac{\sigma-1}{\sigma}} + (1-\lambda-\gamma) L^{\frac{\sigma-1}{\sigma}}} \right)^{\frac{\sigma}{1-\sigma}}$$

First, since physical capital and resources are complementary in production, the monopolist can supply more resources for a larger capital stock K_t, before the negative own-price effect on the infra-marginal resource quantities sold turns the overall marginal revenue negative for $\sigma < 1$. Second, even though Hotelling condition (2.5) is still met, such an extraction path is clearly not optimal. Instead, the naive sheikh in this case would prefer to leave some resources underground. Thus, given the finite time horizon of two periods and some aggregate resource demand over that time horizon, the available resource stock is actually not scarce from the monopolist's perspective due to the negative own-price effect. Again by (5.5) and the properties of a CES production technology, the maximal stock of fossil resources which the naive profit maximizing monopolist is willing to completely exhaust is given by

$$\begin{aligned} \bar{R} \leq & \left(\frac{\sigma}{1-\sigma} \frac{\lambda}{\gamma K_1^{\frac{\sigma-1}{\sigma}} + (1-\lambda-\gamma) L^{\frac{\sigma-1}{\sigma}}} \right)^{\frac{\sigma}{1-\sigma}} \\ & + \left(\frac{\sigma}{1-\sigma} \frac{\lambda}{\gamma K_2^{\frac{\sigma-1}{\sigma}} + (1-\lambda-\gamma) L^{\frac{\sigma-1}{\sigma}}} \right)^{\frac{\sigma}{1-\sigma}} \end{aligned}$$

and obviously positively depends on the capital stocks in the first and the second period. With positive extraction costs, this threshold is lower because the resource rent then equals marginal revenue net of marginal extraction costs. In contrast, in the competitive market without extraction costs, the resource owners will always completely exhaust the resource stock because the resource rent, which then equals the marginal productivity of resources without extraction costs, is non-negative even in the limiting case $\bar{R} \to \infty$.

With positive capital holdings, the asset motive adds to the marginal resource revenue and thereby generally establishes an incentive to increase extraction in each period. Thus, the asset motive pursuing sheikh is also willing to extract a larger aggregate quantity of resources than the naive monopolist given that the aggregate capital stocks K_t are same, or, for example, constant. In this case, the asset motive reduces the bias in aggregate resource supply, which is introduced by market power. This can be observed from[10]

$$MR_t^n + \frac{\partial i_t}{\partial R_t} s_{(t-1)E} \gtreqless 0$$

$$\text{for} \qquad R_t \lesseqgtr \left[\frac{\sigma}{1-\sigma} \frac{\lambda}{\gamma \left(1 - \frac{1}{1-\sigma} \frac{s_{(t-1)E}}{K_t}\right) K_t^{\frac{\sigma-1}{\sigma}} + (1-\lambda-\gamma) L^{\frac{\sigma-1}{\sigma}}} \right]^{\frac{\sigma}{1-\sigma}}$$

The threshold on the right side, however, also illustrates that a higher capital stock K_t does no longer necessarily increase the willingness to extract more if the sheikh pursues the asset motive. In fact, this will only be the case if $1 - \sigma - \frac{s_{(t-1)E}}{K_t} > 0$. The reason is that a ceteris paribus increase in the capital stock K_t can lower the cross derivative $\frac{\partial i_t}{\partial R_t} = F_{tKR}$ so that for given savings the asset motive is attenuated.[11]

5.2.2.3 Internalizing the Capital Dynamics

In addition to the complementarity driven change in the interest rate i_2, the omniscient sheikh also recognizes and internalizes into her supply decision that there are indirect effects in our general equilibrium setting which arise from the endogeneity of the second period capital stock according to (4.28). The decomposition of the factor price reactions in (4.30) and (4.31) suggests that these feedback effects will have implications for the own-price effect of resource supply and, given that the sheikh also realizes the influence on the interest rate, for the asset motive. In the following, we will discuss these implications separately before we consider the overall effect of the endogeneity of the capital stock on the sheikh's supply decision. We focus on the case

[10] The threshold on the right is greater than the corresponding term for the naive sheikh since for $\sigma < 1$ we have $1 > 1 - \frac{1}{1-\sigma} \frac{s_{(t-1)E}}{K_t}$.

[11] We have $\frac{\partial F_{tKR}}{\partial K_t} = \frac{1}{\sigma} F_{tKR} \left((2-\sigma)\theta_{tK} - 1 \right) \gtrless 0$.

where the second period capital stock decreases with a postponement of resource extraction, but also point out for which of our results this restrictive assumption is crucial.

The Endogeneity of Future Resource Demand and the Addiction Motive

Assume first that the sheikh only realizes that the second period capital stock and, via the complementarity of production factors, second period inverse resource demand depend on his supply decision. At the same time, the sheikh shall not be aware of the influence of her supply decision on the market interest rate, neither from the direct complementarity effect nor from the indirect effect by the endogeneity of the capital stock. In this case, since all the effects from the induced change in the interest rate drop out from (5.2), the sheikh will extract the resource stock such that Hotelling rule

$$(1+i_2)\left(p_1+\frac{\partial p_1}{\partial R_1}R_1\right)=(1-\tau)\left[p_2+\left(\frac{\partial p_2}{\partial R_2}+\frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2}\right)R_2\right] \tag{5.15}$$

holds. Thus, in contrast to the naive sheikh, who is just confronted with different resource demand functions over time due to different capital stocks K_1 and K_2, the sheikh now explicitly internalizes the reaction of the second period capital stock and the corresponding change in resource demand via the complementarity of both production factors into her supply decision. Intuitively, the sheikh now takes into account that there will be a shift in the inverse resource demand when supplying more resources in the future period, just as the non-naive monopolist which Moussavian and Samuelson (1984) consider.

To investigate the effect on the sheikh's supply decision, which arises from the internalization of the endogeneity of capital accumulation, we contrast the modified Hotelling rule (5.15) with the naive monopolist's supply path defined by Hotelling rule (5.4). Since the indirect effect from the capital dynamics obviously only affects the second period marginal resource value, we can restrict the analysis to the second period. In particular, there is no additional intertemporal trade-off introduced so that we do not need to derive an intertemporal neutrality condition as before for the characterization of the asset motive.

In Moussavian and Samuelson (1984) a postponement of extraction unambiguously leads to a lower capital accumulation path because they assume that a fixed share of present income is saved and adds to the existing capital stock. Thus, accelerating extraction always increases the future capital stock without depreciation while postponing extraction always reduces present income and thereby savings. In contrast, since in our framework savings are a function of first and second period income and the interest rate (see (4.12)) and the latter generally induces counteracting income and substitution effects, the second period capital stock may positively or negatively depend on second period resource supply according to (4.28), in general.

From (4.30) we know that the future resource market price always negatively depends on resource supply or, equivalently, that the future inverse resource demand is always falling in resource supply for symmetric homothetic preferences. This implies that in any case there still is a negative own-price effect of second period resource supply. The relationship between the capital stock and resource supply, however, is relevant for the strength of the equilibrium price reaction. If the future capital stock negatively depends on future resource supply ($\frac{dK_2}{dR_2} < 0$) as in Moussavian and Samuelson (1984), the negative own-price effect taken into account by the non-naive sheikh will be even larger than in the standard case, and vice versa. This is reflected by the effective price elasticity of resource demand defined as

$$e_{R_2,p_2} = -\frac{1}{\frac{dp_2}{dR_2}\frac{R_2}{p_2}} = \frac{\sigma}{1-\theta_{2R}-\theta_{2K}\frac{dK_2}{dR_2}} \gtrless \frac{\sigma}{1-\theta_{2R}} = -\frac{1}{\frac{\partial p_2}{\partial R_2}\frac{R_2}{p_2}} = \epsilon_{R_2,p_2} \quad \text{for} \quad \frac{dK_2}{dR_2} \gtrless 0 \tag{5.16}$$

which includes the feedback effect from the capital dynamics. Since future resource demand becomes less price-elastic, accounting for the stronger resource price reaction clearly leads the sheikh to shift resources to the first period in order to boost production and savings and thereby to take advantage of the increased resource demand in the next period. The indirect feedback via the endogeneity of capital accumulation enables the sheikh not only to exploit but even to manipulate the dependency or “addiction” of the resource importing countries on fossil resources, and therefore introduces what we may call an “addiction motive” in this case. In contrast, if the capital stock increased with a postponement of extraction ($\frac{dK_2}{dR_2} > 0$), the induced upward shift in resource demand would attenuate the negative own-price effect. Thus, in this case, the sheikh obviously has an incentive to supply more conservatively than her naive counterpart.

The effective price elasticity of resource demand in (5.16) also directly implies that the sheikh does not follow the competitive extraction path anymore for iso-elastic resource demand, or $\sigma = 1$, but depletes the resource stock less (more) conservatively if future resource demand is less (more) price-elastic than first period resource demand, i.e. if $\frac{dK_2}{dR_2} < 0$ ($\frac{dK_2}{dR_2} > 0$). The non-naive sheikh's supply policy will only coincide with the competitive extraction path if by chance we have for the elasticity of the second period capital stock with respect to future resource supply[12]

$$\frac{dK_2}{dR_2}\frac{R_2}{K_2} = \epsilon_{R_2,i_2}\frac{\epsilon_{R_1,p_1} - \epsilon_{R_2,p_2}}{\epsilon_{R_2,p_2}\epsilon_{R_1,p_1}} = \frac{\theta_{1R} - \theta_{2R}}{\theta_{2K}}$$

where we denote by

$$\epsilon_{R_t,i_t} = \frac{1}{\frac{\partial p_t}{\partial K_t}\frac{K_t}{p_t}} = \frac{\sigma}{\theta_{tK}} \tag{5.17}$$

the cross price elasticity of resource demand. Along an over time decreasing competitive supply path, the right side in the above equality condition will be negative (positive) if the price elasticity of resource demand is falling (increasing) in resource consumption or, equivalently according to (5.6), if $\sigma < 1$ ($\sigma > 1$). In this case, the naive sheikh extracts more (less) conservatively than the competitive market. If the capital stock negatively (positively) depends on second period resource supply, the internalization of the endogeneity of the capital stock counteracts the monopolistic extraction bias so that the non-naive sheikh is induced to more closely follow the competitive extraction path. To which extent the standard monopolistic extraction bias is counteracted depends on the strength of the additional feedback effect from the capital dynamics taken into account by the non-naive sheikh, which is measured by the elasticity of the capital stock with respect to postponements of resource supply on the left side of the condition.

In contrast to the asset motive, the effect of the endogeneity of capital accumulation is neutral with respect to a redistribution of capital endowments. Again, this is due to the assumption of symmetric homothetic preferences, which ensures that aggregate savings and the equilibrium market prices do not depend on the distribution of wealth between both countries.

Moreover, in contrast to Moussavian and Samuelson (1984), we find depending on the sign in (4.28) unambiguous extraction incentives from internalizing the endogeneity of the future capital stock. This difference is due to infinite time horizon in Moussavian and Samuelson (1984). With an infinite time horizon, a shift in the resource extraction path does not only induce a reduction of the capital stock in the next period but also a change of the complete capital accumulation path over all future periods.

[12] The equality condition follows from setting $1 - \frac{1}{\epsilon_{R_2,p_2}} = 1 - \frac{1}{\epsilon_{R_1,p_1}}$ which implies by the Hotelling conditions (2.3) and (5.15) that the sheikh will follow the competitive extraction path.

Moreover, since the marginal productivity of the resource, equaling the resource market price just as in our setting, increases over time, postponing resource extraction to a future period with a given savings ratio yields a different, namely higher, contribution to the capital stock. At the same time, however, the value of additional capital decreases over time as additional capital in later periods is effective only over a shorter period of time. Trading-off these counteracting effects may lead the monopolist to slow down extraction compared to the naive monopolist and thereby to reverse the addiction motive if the increase in the resource productivity overcompensates the decrease in the value of increments to the capital stock. In this case, the marginal value of the resource in terms of increments to the capital stock[13] increases over time. Otherwise, the monopolist will choose a less conservative extraction path.

The Endogeneity of the Future Capital Stock and the Asset Motive

If the sheikh is already aware of the complementarity driven influence on the interest rate, or the return on capital investments, and pursues the asset motive, internalizing the dependency of the future capital stock on the resource supply path will affect the sensitivity of the future return on capital investments to changes in resource supply. Again, since the marginal resource value in the first period is not affected by the endogeneity of the capital accumulation qualitatively, we can derive our conclusions only by considering the second period.

According to (4.31), the sheikh will take into account that the overall influence on the interest rate is given by

$$\frac{di_2}{dR_2} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2} > 0$$

As we already know, the positive sign holds irrespective of the relationship between resource supply and the capital stock for symmetric homothetic consumption preferences. This implies that our previous conclusions about the asset motive qualitatively do not depend on the feedback effect from the endogeneity of the future period capital stock. However, due to the diminishing returns to capital ($F_{tKK} < 0$) this feedback effect implies a stronger positive reaction of the interest rate i_2 to increases in the future resource supply, if a postponement of resource extraction comes along with a

13 This is given by the term syp in Moussavian and Samuelson (1984) where s denotes the constant savings ratio, y represents the present value of marginal additions to the capital stock, and p denotes the resource price, or in market equilibrium equivalently the marginal productivity of the resource.

decrease in the capital stock (i.e. $\frac{dK_2}{dR_2} < 0$). In this case, the asset motive in the future period is strengthened compared to the first period asset motive as soon as the sheikh internalizes the endogeneity of the capital stock, and an incentive to postpone extraction is established. In contrast, if the capital stock positively depends on the future resource supply (i.e. $\frac{dK_2}{dR_2} > 0$), the sheikh takes into account that she indirectly induces a negative own-price effect in the capital market by postponing extraction, which partly offsets the positive complementarity driven reaction of the interest rate. Since the future period asset motive is thereby attenuated, realizing and internalizing the feedback effect from the endogeneity of capital accumulation then leads the sheikh to accelerate extraction.

The Extraction Path of the Omniscient Sheikh

In the extraction decision of the truly omniscient sheikh characterized by (5.2) both indirect effects from the capital dynamics are present. Irrespective of the relationship between the capital stock and resource supply in the future period, these indirect effects create unambiguous but counteracting extraction incentives. For example, for $\frac{dK_2}{dR_2} < 0$, the addiction motive is clearly counteracted by the simultaneous strengthening of the future period's asset motive. We may capture and summarize these indirect effects by defining

$$\Psi = (1-\tau)\frac{\partial p_2}{\partial K_2}R_2 + \frac{\partial i_2}{\partial K_2}s_{1E} \gtrless 0 \tag{5.18}$$

which will be positive if internalizing the endogeneity of the capital stock has a stronger effect on the resource income component than on the capital income component of the overall marginal resource value in the future period (see 5.2.2), and negative otherwise.

Given that the asset motive introduces a generally ambiguous extraction incentive as well, it does not come as a surprise that there are no unambiguous and clear conclusions about the extraction policy of the omniscient sheikh to draw. Still, we may characterize the supply path along the by now familiar comparisons to the naive sheikh and the competitive outcome. This will also illustrate the interaction of the additional considerations which are taken into account by the omniscient sheikh in general equilibrium.

First, to draw the comparison with the naive monopolist, we derive analogue to (5.12) the neutrality condition

$$\frac{s_{1E} + \frac{\Psi}{F_{2KR}} \frac{dK_2}{dR_2}}{s_{0E}} = \Phi(R_1^n, R_2^n) \tag{5.19}$$

The threshold Φ is defined as before, whereas the left side is obviously extended by the indirect effects from the capital dynamics, which the omniscient monopolist additionally takes into account and are captured in Ψ from (5.18). Completely analogue to our previous discussion of the asset motive, the omniscient sheikh will choose a more (less) conservative extraction path than the completely naive monopolist if along the naive sheikh's extraction path (R_1^n, R_2^n) the left side is greater (lower) than the threshold Φ. To get further insights, consider again the case $\frac{dK_2}{dR_2} < 0$. If the strengthening of the asset motive dominates the addiction motive and we have $\Psi < 0$, the omniscient sheikh overall has a stronger incentive to supply resources in the second period than the sheikh just pursuing the asset motive without internalizing the capital dynamics (sheikh "na" from section 5.2.2.2). Correspondingly, the asset holdings do not need to increase over time as much as before in order to induce the omniscient sheikh to follow the standard naive monopolist's extraction path characterized by Hotelling condition (5.4). If the addiction motive dominates the strengthening of the asset motive so that $\Psi > 0$, the internalization of the capital dynamics will lead the omniscient sheikh to accelerate extraction so that the increase in the asset holdings must compensate for this incentive to keep the omniscient sheikh at the supply policy of her naive counterpart. Of course, for $\frac{dK_2}{dR_2} > 0$, these conclusions are exactly reversed.

Redistributing capital endowments to country E unambiguously creates an incentive to accelerate extraction for the sheikh who only pursues the asset motive. For the omniscient sheikh, however, this does not necessarily hold true. Rewriting the left side of condition (5.19), its derivative with respect to capital endowment s_{0E} is given by

$$\left.\frac{\partial \left(\frac{s_{1E}}{s_{0E}}\right)}{\partial s_{0E}}\right|_{K_1} \frac{\frac{di_2}{dR_2}}{F_{2KR}} - \frac{R_2}{(s_{0E})^2} \frac{dK_2}{dR_2} \gtrless 0$$

By (5.13), we know that the first term is negative. Thus, the left hand side of condition (5.19) unambiguously falls with a redistribution of capital endowment to country E if $\frac{dK_2}{dR_2} > 0$ and the omniscient sheikh will speed up extraction just as the sheikh who only pursues the asset motive. However, if $\frac{dK_2}{dR_2} < 0$, the first and the second term are counteracting and it is generally not excluded that the left hand side increases with a redistribution of capital endowment, which induces the omniscient sheikh to postpone extraction compared to the completely naive monopolist. In the end, the reason for this ambiguity is that the capital endowment redistribution raises savings s_{1E}. For $\frac{dK_2}{dR_2} < 0$, this implies that the strengthening of the future period's asset motive from the internalization of the capital dynamics is more likely to dominate so that Ψ from (5.18) is more likely to become negative. Hence, the redistribution of capital endowments to country E reduces the ratio of future to present asset holdings as before, but at the same time implies that the extraction incentive introduced by the internalization of the general equilibrium feedback effects from the capital dynamics becomes more conservative.[14]

Second, to assess the effect of resource market power we again contrast the omniscient sheikh's extraction decision with the competitive outcome. From equating Hotelling conditions (2.3) and (5.2), we observe that the omniscient sheikh will exactly follow the competitive extraction path if

$$\begin{aligned}(1-\tau)p_2\left(\frac{1}{\epsilon_{R_2,p_2}}-\frac{1}{\epsilon_{R_1,p_1}}\right) &= \\ F_{1KR}s_{0E}\left[\frac{F_{2KR}s_{1E}}{F_{1KR}s_{0E}}-(1+i_2)+\frac{\Psi}{F_{1KR}s_{0E}}\frac{dK_2}{dR_2}\right]\end{aligned} \tag{5.20}$$

holds with equality. This condition separates the effect of resource market power in the standard naive monopoly case on the left side from the additional strategic considerations of an omniscient resource monopolist in general equilibrium on the right side. In contrast to (5.14), which gives the corresponding condition for the asset motive pursuing sheikk ("na"), it also includes the extraction incentives arising from the internalization of the capital dynamics on the right side.

Recall that along a falling competitive supply path the left side will be negative (positive) if the price elasticity of resource demand is decreasing (increasing) in resource supply, or $\sigma < 1$ ($\sigma > 1$). For iso-elastic resource demand, or $\sigma = 1$ in our framework, the left side is zero whereas the right side generally is not. This implies again that iso-elastic resource demand no longer is sufficient for monopolistic and competitive resource extraction to coincide when resource extraction comes at no costs. Assume that the naive sheikh extracts more conservatively than the competitive market so that the left side is negative, and that $\frac{dK_2}{dR_2} < 0$. In this case, the omniscient sheikh will neutralize the conservationist's bias if the internalization of all the additional cross market effects leads him to accelerating extraction so that the right side is negative, too. Note that this may be due to the pure complementarity driven asset

[14] We also illustrate the effect of the capital endowment redistribution for the omniscient monopolist by use of an exemplary numerical simulation at the end of appendix 9.1.3.1.

motive, which introduces such an incentive for acceleration if the sum of the first two terms is negative, and/or due to the addiction motive dominating the strengthening of the future asset motive so that $\Psi > 0$. However, the omniscient sheihk may very well also choose an even more conservative extraction policy and thereby exacerbating the effect of resource market power represented by the bias in the timing of extraction in comparison to the competitive outcome. Given that the addiction motive establishes an unambiguous incentive to accelerate extraction for $\frac{dK_2}{dR_2} < 0$, we can conclude that such a case can only arise from the asset motive, either due to just the complementarity driven part or in combination with the strengthened second period asset motive from the internalization of the capital dynamics. In condition (5.20), such an increase in the conservationist's bias will be reflected by the right side being greater than the left for the competitive extraction path (R_1^c, R_2^c).

Finally, the ambiguity also carries over to the question whether the omniscient monopolist will choose a higher aggregate resource extraction if the naive monopolist leaves some resources underground. Whereas in the first period the marginal resource value to the omniscient sheikh is unambiguously higher due to the asset motive, in the second period it may even be lower if the feedback effects from the capital dynamics are negative, i.e. $\Psi \frac{dK_2}{dR_2} < 0$, and overcompensate the positive contribution from the capital asset motive.

5.2.2.4 Numerical Simulations and Limitations of Arbitrage Considerations

The analysis and interpretation of the omniscient sheikh's extraction decision hinge on the familiar Hotelling type arbitrage considerations. We argued that the sheikh's incentives to adjust the resource extraction path can directly be derived from the comparison of the marginal resource value (in present value terms) in both periods, and therefore that, for example, a higher marginal resource value in the future period always creates an incentive to postpone extraction. In particular, we followed the same reasoning when comparing the extraction decision of the naive monopolist, the asset motive pursuing sheikh, and the omniscient sheikh. We thereby took the naive monopolist's extraction decision as reference, investigated whether for the asset motive pursuing or the omniscient sheikh the first period marginal resource value exceeds the second period marginal resource value or not, and finally concluded from this comparison whether the modifications to the extraction decision entail a more conservative extraction path or not.

This approach implicitly assumes that shifting resources to the period where the marginal resource value is higher actually leads the sheikh to the optimal or equilibrium extraction decision characterized by the respective modified Hotelling condition. This is ensured if the marginal resource value is falling in the resource consumption of the respective period as it is typically the case in partial equilibrium, which is, for example, graphically illustrated in figure 2.1. In this case, if the sheikh, for whatever reason, deviates from the optimal extraction policy, the extraction incentives arising from the difference in the present value of resource supply in both periods will induce the monopolist to revert to the equilibrium outcome.

In our general equilibrium framework, however, we discuss in detail in appendix 9.1.3.1 that only the marginal resource revenue (MR_t^n) is unambiguously falling in resource supply in both periods whereas the second period marginal resource value may, at least for some interval, increase in resource supply if the sheikh is no longer naive with respect to the complementarity effect on the interest rate or even truly omniscient (i.e. MR_2^{na} or MR_2^o). For an exemplary numerical simulation this is illustrated by figure 5.1, at least for MR_2^o. The figure includes the Hotelling conditions for the pure naive, the asset motive pursuing, and the omniscient monopoly by showing the left and the right side of the respective condition as a function of the resource supply path.[15] Obviously, the monopolistic equilibrium is characterized by the respective point of intersection. For this exemplary specification, the asset motive introduces an incentive to accelerate extraction compared to the naive monopolist and thereby to at least attenuate the conservationist's bias. The internalization of the general equilibrium feedback effects leads the omniscient sheikh to accelerating extraction even further – since we have $\frac{dK_2}{dR_2} < 0$ due to condition (4.29) in our simulations, this implies $\Psi > 0$.

Figure 5.1 does not show that MR_2^{na} may not monotonously fall with postponing resource extraction to the second period, too, which, however, follows from the discussion in appendix 9.1.3.1. Basically, our conclusion there is that if MR_2^{na} is upward sloping this must be due to the asset motive. The reason is that the asset motive is strengthened by an increase in the cross derivative F_{2KR}, which follows from the fall in the capital stock K_2 as for very conservative extraction paths $R_2 \to \bar{R}$ first period production almost entirely breaks down (for $\sigma \leq 1$). This increase in the complementarity relationship F_{2KR} may even overcompensates the reduction in asset holdings

[15] Note that along these curves the capital stock K_2 as well as the interest rates i_1 and i_2 adjust in contrast to a partial equilibrium setting.

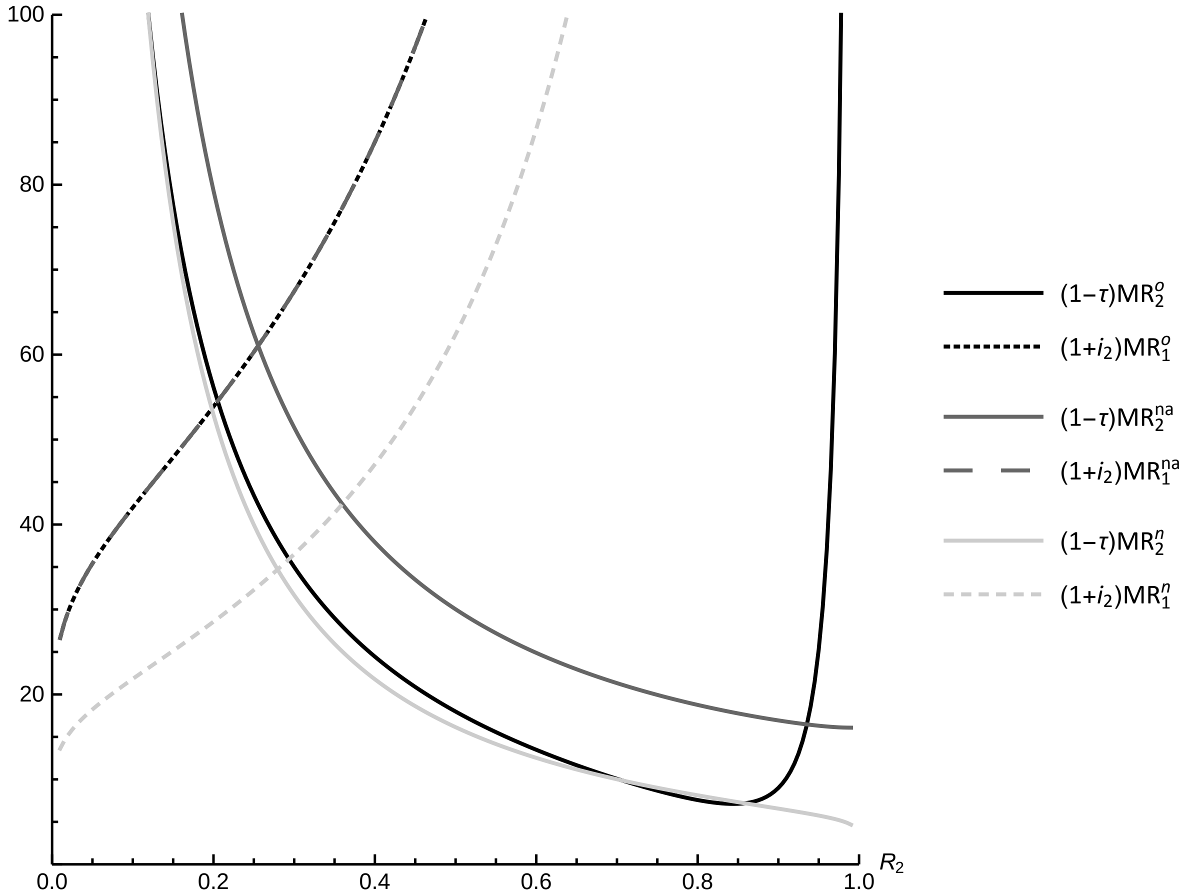

Figure 5.1: Comparison of the extraction decision of the omniscient, the naive, and the asset motive pursuing sheikh;
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, $\tau = 0$, total factor productivity $A = 300$

s_{1E} (see figure 9.3) which is illustrated in figure 9.2 in the appendix. That MR_2^{na} overall can be upward sloping is numerically verified for a larger resource stock $\bar{R} = 10$ (see figure 9.4). For $\bar{R} = 1$, the comparison between the omniscient sheikh's marginal resource value MR_2^o and MR_2^{na} demonstrates that the upward sloping of MR_2^o in this specification arises only from the feedback effects from the capital dynamics on the asset motive and the own-price effect of resource supply, which is captured by $\Psi \frac{dK_2}{dR_2}$ and graphically illustrated in figure 9.5 in the appendix.

Why is the observation that the right side of Hotelling condition (5.2) may not monotonously fall but, at least piecewise, increase with future resource supply relevant for our previous analysis of the sheikh's extraction decision? First, we generally can no longer exclude that there are multiple points of intersection between the left and the right hand side, and therefore that there may be multiple extraction policies for which Hotelling condition (5.2), in principle, holds. Second, there might be special constellations for which our approach to interpret the extraction decision of the omniscient sheikh may fail. We will discuss these issues in a little more detail in the following, even though we have not observed neither of them in the numerical simulations of the model for a broad variation of parameter specifications.

Even though we generally cannot exclude that there are multiple points of intersection, not all of them actually constitute an equilibrium outcome. The reason is that an extraction policy can only represent an equilibrium if it actually maximizes the sheikh's objective function (5.1) so that there is no incentive to deviate. Thus, since the Hotelling condition only represents the first-order condition of the sheikh's decision problem, we can reduce the number of possible equilibrium outcomes by additionally considering the second-order condition for a utility maximum.

Since we can show (see appendix 9.1.3.1) that for symmetric homothetic preferences the marginal resource revenue in both periods is falling in resource supply of the respective period, we must have

$$(1 + i_2)\frac{dMR_1^n}{dR_1} + \frac{dMR_2^n}{dR_2} - MR_1^n \frac{di_2}{dR_2} < 0 \tag{5.21}$$

for the equilibrium extraction path (R_1^n, R_2^n) of the naive monopolist from section 5.2.2.1.[16] As demonstrated in appendix 9.1.3.2, the negative sign is also ensured by

[16] Recall that by (4.31) we have $\frac{di_2}{dR_2} > 0$ for symmetric preferences.

the second-order condition of the naive sheikh's optimization problem. Condition (5.21) can easily be recognized to state that

$$\frac{d[(1+i_2)MR_1^n]}{dR_2} > \frac{dMR_2^n}{dR_2}$$

or, graphically, that at the equilibrium extraction policy the left hand side of Hotelling condition (5.4) has to increase more strongly in second period resource supply than the right hand side. Obviously, since we can show that the left hand side increases in second period resource supply whereas the right side falls monotonously, this always holds true for the naive monopolist.

With the right hand side of the Hotelling condition increasing in future resource supply, this generally may no longer be the case for the omniscient, or just the asset motive pursuing sheikh. However, we show in appendix 9.1.3.2 that we must have by the respective second-order condition

$$(1+i_2)\frac{\partial MR_1^o}{\partial R_1} + \frac{dMR_2^o}{dR_2} - MR_1^o \frac{di_2}{dR_2} < 0 \tag{5.22}$$

along the optimal extraction policy (R_1^o, R_2^o) of the omniscient sheikh, and completely analogously for the optimal extraction policy (R_1^{na}, R_2^{na}) of the asset motive pursuing sheikh

$$(1+i_2)\frac{dMR_1^{na}}{dR_1} + \frac{dMR_2^{na}}{dR_2} - MR_1^{na} \frac{di_2}{dR_2} < 0 \tag{5.23}$$

Thus, the second-order condition in either case ensures that for the optimal extraction policy the left side of the respective Hotelling condition indeed more strongly increases in second period resource supply R_2 than the right side, even though the additional components of the supply decision in combination with endogenous capital accumulation may cause the right side of the respective Hotelling condition to at least piecewise increase in resource supply.

The second-order condition does not exclude equilibrium outcomes in the upward sloping part of the second period marginal resource value, in general, but only such points of intersection as equilibrium outcomes where the left side of the Hotelling condition increases more strongly than the left. More intuitively, this restriction ensures that if the omniscient sheikh or the just the asset motive pursuing sheikh, for whatever reason, slightly deviates from her respective equilibrium solution, the comparison of the (present value) marginal resource value in either period will always establish an incentive to reallocate resource extraction towards the equilibrium extraction policy. Thus, the second-order condition in the end ensures that the familiar

Hotelling arbitrage considerations hold, at least locally, around the equilibrium outcome.

The second concern arising from the potential upward sloping of the second period marginal resource value is that our approach in the previous sections to intuitively interpret the components and the overall extraction decision of the omniscient sheikh might fail. The reason is that to infer the differences in the extraction policies, which arise from different degrees of information, we resorted to the familiar Hotellling arbitrage considerations, even though these strictly speaking only hold true locally by the second-order conditions, as argued before. In general, this approach is valid as long as postponing resource extraction monotonously increases the marginal resource value in the first period and decreases the marginal resource value in the second period, in particular since we are only interested in which direction the extraction decision deviates and not in the quantitative difference between the equilibrium outcomes. Moreover, in this case, the comparison between the present and the future marginal resource value even directs, for example, the omniscient sheikh constantly to the equilibrium outcome when starting at the naive sheikh's supply policy. Even with an upward sloping part of the second period marginal resource value, this is not necessarily excluded as can be observed, for example, from figure 5.1. At the naive sheikh's extraction path we clearly have $(1 + i_2)MR_1^o(R_1^n, R_2^n) > MR_2^o(R_1^n, R_2^n)$, which represents an incentive to shift resources to the first period and thereby towards the equilibrium solution of the omniscient sheikh.

But since the second period marginal resource value may be increasing in resource supply R_2, we generally cannot rule out that a constellation as illustrated in figure 5.2 arises for which our approach to compare equilibrium outcomes for different degrees of economic information fails. In fact, the comparison of the (present value of the) first and the second period marginal resource value at the naive sheikh's extraction path in this case obviously induces the sheikh to postpone extraction, although the only equilibrium outcome requires an acceleration of extraction. In contrast, the second point of intersection can clearly be ruled out as an equilibrium outcome by the second-order condition for an utility maximum (5.22).

Similar to the multiple equilibrium outcomes, we have not observed such a constellation in the numerical simulation of the model for a broad range of different parameter assumptions. Our objective in this section was to just point out that the analytical approach which we have taken in the previous sections primarily for intuitive reasons might not always be valid.

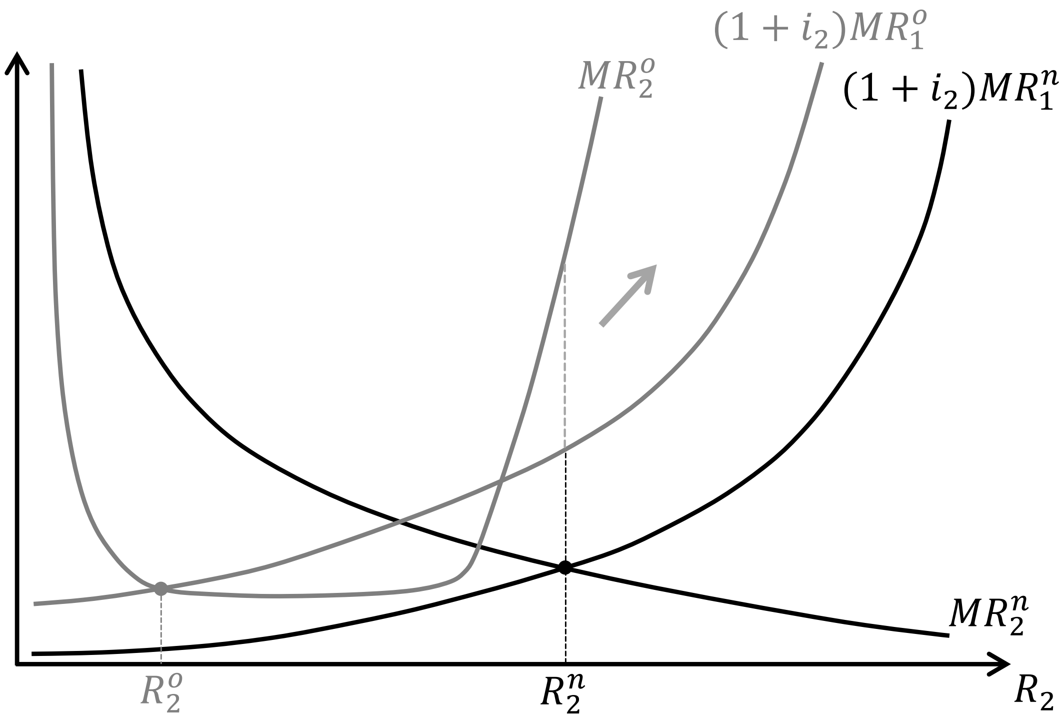

Figure 5.2: A special case with increasing second period marginal resource value MR_2^o

5.3 Discussion and Conclusion: Resource Market Power in General Equilibrium

In the previous sections, we provided a systematic discussion of what exerting resource market power may imply in a general equilibrium model of the interaction between the resource and the capital market which is basically established by the complementarity of both production factors and the endogeneity of savings. Our objective was to point out that neglecting the cross market effects in a general equilibrium framework and just transferring the familiar monopolistic extraction behavior from standard partial equilibrium approaches to such a general equilibrium setting may be misleading,[17] whereas the additional interactions in general equilibrium do not have any qualitative implications for the supply behavior of competitive resource owners with rational expectations.

[17] This conclusion is also supported by the observation that the effect of carbon taxation may exactly be reversed compared to the naive monopolist and the competitive market due to the asset motive, which we find later on in section 6.4.

We argued, following the familiar reasoning from partial equilibrium (see chapter 2), that a resource monopolist is, in principle, aware of the market influence of her supply decision. However, given the additional interaction of markets in a general equilibrium setting, there actually is a much more widespread influence of resource supply than the own-price effect in the resource market, which is well-known from Cournot monopoly settings. In fact, our analysis demonstrates that there is, in principle, a range of different "types" of monopolists. The choice of the most plausible one in the end depends on the inherently subjective assessment which of the various transmission channels a resource owner with market power is most plausibly able to recognize and thereby to internalize into its supply decision. This illustrates the role of information about the economic relationships in a general equilibrium setting. While this generally holds true for any setting of imperfect competition in general equilibrium, we believe that this reasoning is particularly relevant in case of fossil resources, and especially oil, due to the close and manifold interrelationship between the resource and the capital market, which we discussed in section 3.1.

The exemplary numerical simulations summarized in figure 5.1 demonstrate that the various extensions to the supply decision of the rather familiar naive monopolist do not only introduce qualitative differences in the extraction decisions but also can be quantitatively important. For example, internalizing all the additional supply effects in general equilibrium induces the omniscient sheikh to shift about 10% of the overall available resource stock to the present period.

What implications do the extensions of the supply decisions have for the role of market power in resource markets, or to refer to Stiglitz (1976), do they extend the scope for exerting market power compared to its rather minor role in partial equilibrium discussed in section 2.1.2? One might argue from a more general point of view at first that the additional cross market effects in general equilibrium should enlarge the influence of the resource monopolist and thereby the possibilities to exert market power if the monopolist is able to recognize and use them to her advantage. However, the resource importing countries, or the industrialized world, are not simply at the monopolist's mercy. In fact, in particular the omniscient sheikh's interest in the prosperity of the resource importers is at least twofold. On the one hand, there clearly is an incentive to sustain and even increase the resource importing countries' addiction to the resource for the future. On the other hand, the sheikh does not want to jeopardize the capital income which her constituency derives from capital investments in the resource importing economies. From this perspective, the often discussed dependency of the western oil importing countries on the “good-will” of resource exporting countries, for example in the Middle East, is in fact mutual.

Closely related to this line of reasoning, we found that internalizing the additional supply effects creates mostly ambiguous extraction incentives and overall does not allow for unambiguous conclusions about its implications for the scope for exerting market power. First, as long as the resource stock underground is actually scarce and binding, resource market power is only reflected in the timing of extraction as pointed out by Stiglitz (1976). A seminal result from the literature is that the monopolist is often induced to deplete the resource stock more conservatively than the competitive market (see also our discussion in section 2.1.2), which also holds true for the naive sheikh in our general equilibrium setting for rather general assumptions. The additional supply motives, however, in general may accelerate or slow down resource extraction compared to the naive monopolist, and even compared to the competitive outcome. Thus, in contrast to comparable partial equilibrium settings of costless resource extraction, the conservationist’s bias may no longer arise even with an over time increasing price elasticity of resource demand. Similarly, while the naive monopolist, just as in partial equilibrium, follows the competitive supply path for iso-elastic resource demand, this holds true only for extremely specific constellations when the sheikh pursues the asset motive or even is completely omniscient.

Second, we also pointed out in section 2.1.2 by referring to the Tullock (1979) note on Stiglitz (1976) that with a finite time horizon the monopolist may not necessarily choose to completely exhaust the given resource stock but prefer to reduce aggregate resource market supply compared to the competitive market. In this case, the scope for exerting market power is not only reflected in the timing of extraction but also in the reduction of aggregate resource supply. We found that the asset motive pursuing sheikh, albeit using more information about her market influence to her advantage, clearly has an incentive to increase depletion compared to her naive counterpart and thereby to reduce the bias in aggregate extraction from market power. The omniscient sheikh, in contrast, is confronted with a trade-off between the asset and the addiction motive, which, in general, may or may not lead to a reduction in aggregate market supply.

Finally, to assess the role of the additional supply motives for the implications of resource market power, we might also consider the welfare of country E and I for the naive, the asset or addiction motive pursuing sheikh, or the omniscient sheikh. Obviously, the omniscient benevolent sheikh corresponds to a social planner for country E so that her extraction decision clearly represents the social optimum for country E, but not necessarily for country I. In fact, without any externalities in our setting, the most efficient use of the fossil resource stock, i.e. the social optimum for the world economy as a whole, would be given by the competitive market solution. However, since the welfare positions of countries are again directly related to the extraction path in our setting, the ambiguity of our previous conclusions can also not be resolved by resorting to such a welfare analysis. The welfare analysis, however, illustrates that increasing the level of information about the economic effects of resource supply, which the sheikh can use when planning extraction, is not always to the sheikh's advantage. This may be contrary to what one would have expected at first but again follows from the ambiguity of the extraction incentives, which are established by the additional supply effects in general equilibrium. In fact, becoming aware of the complementarity between resources and capital and pursuing the asset motive may lead the otherwise naive benevolent sheikh to even more strongly deviate from the planner's extraction policy for country E. In contrast, raising the level of information further so that the sheikh becomes truly omniscient never reduces the welfare in country E. Similarly, and already pointed out by Moussavian and Samuelson (1984), the naive monopolist, by not recognizing the relationship between resource extraction and capital accumulation in their setting, may actually be worse off compared to the competitive outcome. Thus, exerting market power at all can be detrimental to country E's welfare. In the end, however, since the potential to exert market power in the familiar Cournot settings is closely linked to the monopolist's ability to recognize at least the own-price effect, this conclusion is more or less equivalent to our previous observation that additional information is not necessarily to the monopolist's advantage as long as her information is still incomplete.

One of the most striking results from this systematic analysis of resource market power in our a general equilibrium framework is certainly the asset motive, which provides a completely new perspective on the role of the foreign capital asset holdings for the extraction decision of resource-rich countries. In the traditional Hotelling framework, the capital investments of resource owners are only implicitly relevant at the margin as the market return on these investments represents the opportunity costs of leaving resources underground. However, the volume or the development of these asset holdings do not have any implication for the supply decision. However, by recognizing the prominent role of fossil resources for the real economy and economic growth, resource owners with at least some influence on the aggregate market resource supply become increasingly reluctant to put economic development and growth in resource importing countries at risk the more capital assets they hold in these economies and the stronger the return of their capital savings is dependent on the supply of resources.

It is important to note that the asset motive does not require the resource-rich country to have market power in the capital market, which fundamentally separates our approach, for example, from the setting in Hillman and Long (1985). Instead, the asset motive crucially depends on the cross market influence of fossil resources on capital returns and the ability of resource owners to recognize and internalize this effect. To us this seems to be more plausible than capital market power even though resource-rich countries have accumulated large capital wealth over the past decades, which is held in sovereign wealth funds and other, mostly not officially reported deposits and investments (see section 3.1.2). Our analysis of the asset motive demonstrates that it is not the absolute value of assets under management but the development of these asset holdings over time which crucially influences the extraction decision of the non-naive resource owner with market power. Intuitively, with accumulating more and more capital assets the pure resource revenues become secondary compared to the value of the fossil resource as a means to manipulate the capital market return to the resource owner's advantage. This kind of a metamorphosis of the resource owner from a pure resource supplier to a capital investor over time may, for example, also be illustrated by the very recent announcements of Saudi Arabia to divest from resource extraction and increasingly rely on the financial returns of sovereign wealth funds to finance the state budget (see, e.g., Economist 2016). Moreover, this observation also implies that the role of the asset motive for the supply decision might change over time. Thinking of resource-rich OPEC member states with a dominant position in the global oil market like Saudi Arabia, these countries have experienced a substantial increase in their capital assets from the recycling of petro-dollars, but it may very well be that the growth in the capital asset holdings may be slower in the future periods, just because they accumulated stock is already that large. Thus, whereas the asset motive may have induced Saudi Arabia over the past decades to extract its oil resources rather conservatively, the opposite might be true for the future. Such long-term conclusions, however, obviously require that the macroeconomic complementarity between fossil resources and capital is rather stable over time. In fact, if the complementarity relationship is resolved or attenuated, for example by the arrival of competitive substitutes to fossil resources or substantial increases in the substitutability of production factors, i.e. the elasticity of substitution, the asset motive may be attenuated or may even completely disappear over time.

We also have noted that the asset motive influences the overall valuation of the resource by its owner. For example, by increasing the economic value of the resource, the asset motive induces the sheikh to increase aggregate extraction if the naive sheikh chooses to leave some resources underground. In this case, the sheikh pursues an intertemporal, or dynamic, resource supply policy even though the marginal resource revenue is negative. However, this does not only have implications for the scarcity of the given resource stock underground with a finite time horizon and given resource demand. Since a negative marginal resource revenue can also be due to price-inelastic resource demand, the asset motive can also be seen as an approach to reconcile inelastic resource demand schedules, which are typically found empirically, with resource market power, similar to limit pricing regimes as suggested by Andrade de Sà and Daubanes (2016) (see also the corresponding discussion in section Economist 2016).

The capital asset holdings of resource-rich countries may also be related to more strategic considerations, which we leave, however, for future research. First, the more recent decline of oil prices since 2014 is often explained by the fight for market shares of resource-rich countries within OPEC, and in particular Saudi Arabia, against the producers of unconventional oil in the United States (see, for example, The Economist 2015). However, it has also been pointed out that not the least the large capital holdings accumulated throughout the phase of surging oil price before have enabled Saudi Arabia to pursue and sustain such a strategy of flooding the oil market to push out unconventional producers so far. Thus, capital holdings, by reducing the dependence of the state budget on oil revenues, can establish or enlarge the scope for strategic extraction behavior, which may also be relevant with respect to the development of carbon free substitutive technologies. Second, we so far have not specified where the resource exporting country invests its capital. In fact, this is not necessary as long as we stick to our assumption of a perfect and competitive international capital market. Putting more emphasize on the volume of capital investments from resource-rich countries, however, may raise the question whether these countries strategically invest in sectors or technologies which are more complementary to their resources underground and thereby influence the development of resource demand over time. Of course, following this line of reasoning would bring us closer to the setting of Hillman and Long (1985), which then at least would have to include differentiated capital stocks, for example, for more and less complementary technologies.

6 Revisiting the Green Paradox in General Equilibrium

In this chapter, which builds upon and extends the contribution in Marz and Pfeiffer (2015a), we will revisit the effects of climate policies on the resource extraction path in general equilibrium. We focus thereby on the interaction of the capital and the resource market as captured in our general equilibrium framework and investigate its implications for the supply reactions to future carbon taxation.

Following the line of reasoning in sections 3.1 and 3.2, it proofs useful to distinguish between general equilibrium effects of climate policies on the resource extraction decision, which arise from the influence of climate policies on the capital market, and pure feedback effects from the induced adjustments in the resource extraction path, which are, in principle, evident from the comparative statics analysis of the conditional market equilibrium with respect to the resource supply path in section 4.2.2. General equilibrium effects of carbon taxation in our setting primarily arise from the redistribution of resource rents which comes along with such a climate policy. We investigate these in detail by studying the influence of a carbon tax in the conditional market equilibrium. Combining our results with the comparative statics analysis of the conditional market equilibrium, we then are able to derive the resource supply reaction for different assumptions about the structure of the supply side in the resource market.

Assuming a competitive resource market, we, in principle, adapt and reconstruct the analysis of van der Meijden et al. (2015b), which is most closely related to our study. However, we will go one step further and consider for the first time in the literature on the green paradox in general equilibrium the case of resource market power. We thereby build upon our discussion of the supply behavior under imperfect competition in section 5.2 and illustrate the role of market power, and especially that of the asset motive, for the effect of future carbon taxes. Our main conclusion from this analysis will be that resource market power in contrast to a partial equilibrium setting can be crucial for the effect of future carbon taxes. In fact, we will show that if the monopolist is not naive and at least partially internalizes her influence on capital returns and income and, therfore pursues the asset motive the green paradox may be reversed even for symmetric preferences, whereas in this case such a reversal is excluded with competitive resource supply. To contrast and relate our results to the literature, we will start in the following with reviewing the so far rather small strand of literature on the effect of climate policies and the green paradox in general equilibrium settings.

6.1 General Equilibrium Effects of Climate Policies and Technological Change

General equilibrium effects of climate policies (and technological change) on the use of fossil resources have already been studied in the literature but to the best of our knowledge so far only to a very limited extend and only under the assumption of perfect competition in the resource market. Most closely related to our contribution are certainly van der Meijden et al. (2015b) and van der Ploeg (2015), who consider the effect of a carbon tax increase in virtually the same framework as we use, but they assume a competitive resource market and, in particular, focus on the implications of the distributive effect of climate policies, which we already pointed out in section 3.2.3, in general equilibrium. We will discuss the main results of their analysis separately and in more detail when we analyze the competitive case in our setting.

Overall, the basic line of reasoning in the literature mostly is that climate policies (or technological change) lead to imbalances in the intertemporal consumption equilibrium, which typically is represented by some intertemporal arbitrage condition like the Euler equation in (4.11) in our setting. These imbalances then require adjustments in the interest rate and/or capital accumulation and thereby induce changes in the resource extraction path, which do not arise in partial equilibrium. In the following, we will give an overview over the different rationales for such intertemporal imbalances and the different implications which so far have been identified in the literature.

Smulders et al. (2012) as well as Long and Stähler (2014a) and Long and Stähler (2014b) demonstrate that in contrast to the partial equilibrium settings the use of fossil resources and, therfore carbon emissions in the short run can increase due to the adjustments which are necessary to restore the intertemporal consumption equilibrium even without resource scarcity. Smulders et al. (2012) highlight the role of future mitigation costs for the capital market as they take on our general discussion in section 3.2.1 by arguing that the credible announcement of future climate policies is likely to affect the current savings behavior and thereby the formation of the capital stock over time. The reason in their setting is that a strict(er) future climate policy, which increases the resource price and thereby reduces the use of fossil resources, brings about a loss in aggregate production and income if the production technology does not change over time and if there is a limited substitutability of fossil resources in output production. Hence, with households having perfect foresight or rational expectations, the credible announcement of such a future climate policy will induce an increase in savings in the short term as households want to insure against the impending losses in future income. This increase in savings directly follows from the familiar consumption smoothing motives, which in our setting, for example, are reflected in the savings reactions given in (4.13), but may also be interpreted as a precautionary savings reaction to the higher uncertainty about future income and economic growth which arises from a strict regulation of carbon emissions and the still prominent role of fossil resources for economic growth and development (see also our discussion in section 3.2.1). With complementary production factors, the savings increase and the accompanying increase in the capital stock in the short run in Smulders et al. (2012) raise resource demand. This in the end gives rise to a green paradox like increase in resource consumption and carbon emissions in the short run, which they call the "early announcement paradox". First, the precautionary savings reactions of households and the accompanying increase in the capital stock (accumulation path) are very likely to affect the interest rate in the short run, too. However, without scarcity, resource supply does not derive from intertemporal (dynamic) optimization and, therfore in a simplified framework without extraction or exploration costs does not depend on the market rate of interest at all. Second, note that we cannot directly observe this transmission channel in our framework. The reason is that Smulders et al. (2012) consider a continuous infinite horizon growth model where apart from the initial period the capital stock in the short and the long run is endogenously determined by the savings decisions of households. In contrast, in our two period discrete time setting, the short run, or first period, capital stock is exogenously given by capital endowments and the endogenous saving decisions only determine the future period, or long run, capital stock. Thus, increases in the present period's capital stock due to future income losses, and thereby changes in short run resource demand, are excluded by construction in our framework.

Somewhat similarly, Long and Stähler (2014a) and Long and Stähler (2014b) point out that technological change reducing the costs of a potential green energy substitute to fossil resources comes along with income effects which require adjustments in the interest rate as to restore the intertemporal consumption equilibrium. They consider a two period setup with competitive consumption goods production by use of energy, which is simultaneously supplied from the substitutive technology and fossil resources. The energy market price in both periods is set by the energy generation costs of the competitive substitutive technology, which uses consumption goods, but there is residual demand for fossil resources. Their argument again does not rely on the (physical) scarcity of fossil resources. Still, since resource extraction is costly and second period extraction costs increase in first period extraction with the depletion of the resource stock, resource supply in both periods is a function of the interest rate, i.e. there is an intertemporal resource supply decision.[1] The market rate of interest rate is endogenously determined in the intertemporal consumption equilibrium by the Euler equation. In this setting, they study the effect of (exogenous) technological change, which reduces the energy generation costs of the substitutive technology in both periods. First, with a lower energy price in both periods, final goods producers use more energy in both periods so that in any case total output and income rise. Second, regarding the use of fossil resources, there are two counteracting effects. As expected, as the substitutive energy becomes cheaper, fossil resources get crowded out of the energy market. However, in addition to this direct effect there is also an indirect, or general equilibrium, effect of technological change from the adjustment in the interest rate. This is due to the fact that the crowding out of the resource is stronger in the first than in the second period because the decrease in first period extraction comes at the advantage of lower future extraction costs. Thus, while energy use will increase in both periods, it will increase by more in the second as compared to the first period and, correspondingly, there will be a larger increase in output production and income available for consumption in the second period than in the first. Technological change, therfore leads to an imbalance in the intertemporal consumption equilibrium.[2] Since second period production increases by more than first period production, the interest rate has to rise such as to give households an incentive to increase their relative future consumption, which can directly be observed from the Euler equation (see (4.11)) for concave period utility functions. But since with a higher interest the future extraction costs are discounted more heavily so that the overall costs of first period resource supply decrease, resource owners are induced to extract more in the first period and the crowding out of resource use

[1] Thus, in the end, there is no physical but economic scarcity of the resource for the given constant energy market price defined by the backstop technology.

[2] Note that there is no capital or financial market for consumption smoothing in the model so that the imbalance in the intertemporal consumption equilibrium can be directly observed from the Euler equation for the new first and second period consumption goods production for a given interest rate.

in the first period is at least partly offset. Long and Stähler (2014a) and Long and Stähler (2014b) demonstrate that dependent on the consumption preferences, which obviously determine the strength of the necessary increase in the interest rate, the indirect effect from the induced adjustment in the interest rate may even overcompensate the direct effect of technological change. Hence, a strong green paradox may arise in the sense that total resource use increases upon the reduction in the costs of a substitutive (clean) energy technology.

Finally, Eichner and Pethig (2011), and extending their analysis by endogenising aggregate resource extraction Ritter and Schopf (2014), also introduce a general equilibrium setting of trade in fossil resources but focus on geographical leakage and the role of the adjustments in the intertemporal consumption equilibrium for the strength of the leakage effect. In a two period, three country setting with a resource exporting country, and an abating and non-abating country they show that the leakage effect may reverse the familiar conclusions from standard partial equilibrium approaches, namely that a climate policy which becomes less strict over time may induce a green paradox whereas a climate policy with an increasingly strict regulation of emissions over time does not give rise to a green paradox, which both is in contrast to, for example, the conclusions in Sinn (2008b). Eichner and Pethig (2011) point out that it is again the necessary adjustment in the (intertemporal) commodity market equilibrium which may strengthen the leakage effect so much that the tightening of the first period's emission cap in the abating country may be overcompensated and a green paradox may arise even though in this case emissions are less regulated in the second period.[3] Although Eichner and Pethig (2011) do not explicitly consider a market interest rate, Long (2015) points out that an interest rate can actually be derived from the relative market price of consumption goods in both periods. In fact, the results in Eichner and Pethig (2011) may best understood by again considering the changes in the interest rate which are necessary to restore the equilibrium in the (intertemporal) consumption goods market. From this perspective, an unilateral climate policy induces a reallocation of production and emissions to the non-abating country. Since the production technology exhibits diminishing returns, this ceteris paribus leakage effect is below 100 %. World consumption goods production in the first period overall decreases but with complete exhaustion of the resource stock future production must

[3] The strength of the leakage effect thereby depends on the price elasticity of resource demand from the consumption goods producers in the non-abating country and on the intertemporal elasticity of substitution. The reason is that the interplay between the climate policy induced change in first period consumption good supply and demand in the end determines how strongly the climate policy affects the relative price of first to second period consumption.

increase. Hence, the unilateral emission cap induces an imbalance in the intertemporal consumption market equilibrium which requires an increase in the interest rate so that households are willing to increase their second period consumption. However, since the resource supply path follows the Hotelling condition, this increase in the interest rate in turn induces an acceleration of extraction and thereby exacerbates the leakage effect, in particular since emissions and thereby resource use in the first period are bound by the emission cap in the abating country. Intuitively, with a high price elasticity of resource demand, the ceteris paribus leakage effect is already rather strong as the producers in the non-abating country strongly react to the fall in the resource price which follows from the decrease in overall resource demand. The intertemporal elasticity of substitution determines how much the interest rate has to adjust. If it is rather low, second period consumption is only a bad substitute to first period consumption and the interest rate has to increase strongly as to give households an incentive to consume more in the second period. Hence, a high price elasticity of resource demand and a low intertemporal elasticity of substitution increase the leakage effect into the first period and, therfore work towards the arising of the green paradox.

Of course, our focus is on the interaction of the resource market and the market for physical capital and, therfore somewhat different to the geographical leakage which Eichner and Pethig (2011) and Ritter and Schopf (2014) study. However, recall from our note in section 3.2 that with regulating emissions by setting emission caps instead of carbon taxes as in Eichner and Pethig (2011), the presence of a third non-abating country is more or less necessary for the arising of the green paradox. In fact, in this case, emissions in the short run can only increase if there is either, at least in the present period or in the beginning, a non-abating region to which carbon emissions can be relocated, or if the emissions cap is only introduced in the future so that in the beginning emissions are completely unregulated.

6.2 The Influence of the Carbon Tax on the Conditional Market Equilibrium

Before we study the reaction of resource owners, we investigate in this section the influence of the resource, or in the context of climate change, of the carbon tax τ on the conditional market equilibrium of the world economy laid out in section 4. By construction of the conditional market equilibrium, we, therfore consider the equilibrium effect of carbon taxation for some given resource extraction path, which completely exhausts the resource stock $\bar{R}$. Thus, we focus on the general equilibrium transmission channel(s) of the carbon tax in our setting which are crucial for the discussion of the resource supply reaction to increases in the carbon tax later on.

To this end, we take on the comparative statics analysis of section 4.2.2. The total derivative of the second period capital stock is derived in appendix 9.1.2 (see (9.1)). From there we know that the equilibrium relationship between the second period capital stock K_2 and the carbon tax is given by

$$\frac{dK_2}{d\tau} = -\frac{ID_2 p_2 R_2}{1 - \frac{\partial i_2}{\partial K_2}\left(SE + ID_2 s_{1E}\right) - ID_2(1-\tau)\frac{\partial p_2}{\partial K_2} R_2} d\tau \tag{6.1}$$

which by construction represents the influence of the carbon tax for any given extraction path which exhausts the resource stock. Our accompanying discussion in section 4.2.2 revealed that the denominator must be of positive sign due to the second-order condition (9.2) in the (conditional) market equilibrium. Recall that this intuitively implies that the equilibrium feedback effect on the households' savings incentives from a change in the capital stock K_2, irrespective of the net savings effect of the simultaneous income redistribution between both countries (ID_2 from (4.20)), cannot reverse the savings incentives directly created by the resource tax.

The "direct" effect of the carbon tax on the capital market is captured by the numerator. Since capital demand does not directly depend on the tax rate according to (4.7), this influence of the resource tax on the equilibrium capital stock arises solely from capital supply (see also (4.17)). Our framework also exhibits a time constant and more or less limited substitutability of production factors measured by the elasticity of substitution σ, as in Smulders et al. (2012), but the equilibrium influence of the carbon tax on the capital market here does not arise from a precautionary savings reaction to impending future mitigation costs but from the asymmetric distribution of the resource endowment in our two country setting and the accompanying distributive effect of the climate policy (see also the discussion of the various potential effects of climate change mitigation on the capital market in section 3.2).

Aggregate (world) production and income in each period is, by the period budget constraints (4.9) and (4.10), given by $F_t + K_t$ and, therfore only dependent on the use of both variable production factors, capital and fossil resources, in our setting. Thus, as long as the resource extraction path does not adjust, climate policies do not affect aggregate income.[4] For a given resource extraction path and, therfore a given resource consumer price a higher carbon tax then at first just reduces the resource producer price, and thereby resource rents. However, since we assume an asymmetric distribution of resource endowments in contrast to Smulders et al. (2012), this implies that the carbon tax is of redistributive effect in our setting. By redistributing resource rents, the rising carbon tax brings about future income losses in the resource-rich country E whereas the resource-poor countries I are ceteris paribus able to capture a larger share of the resource rent at home, which in form of tax revenue is lump-sum distributed to the representative household in country I.

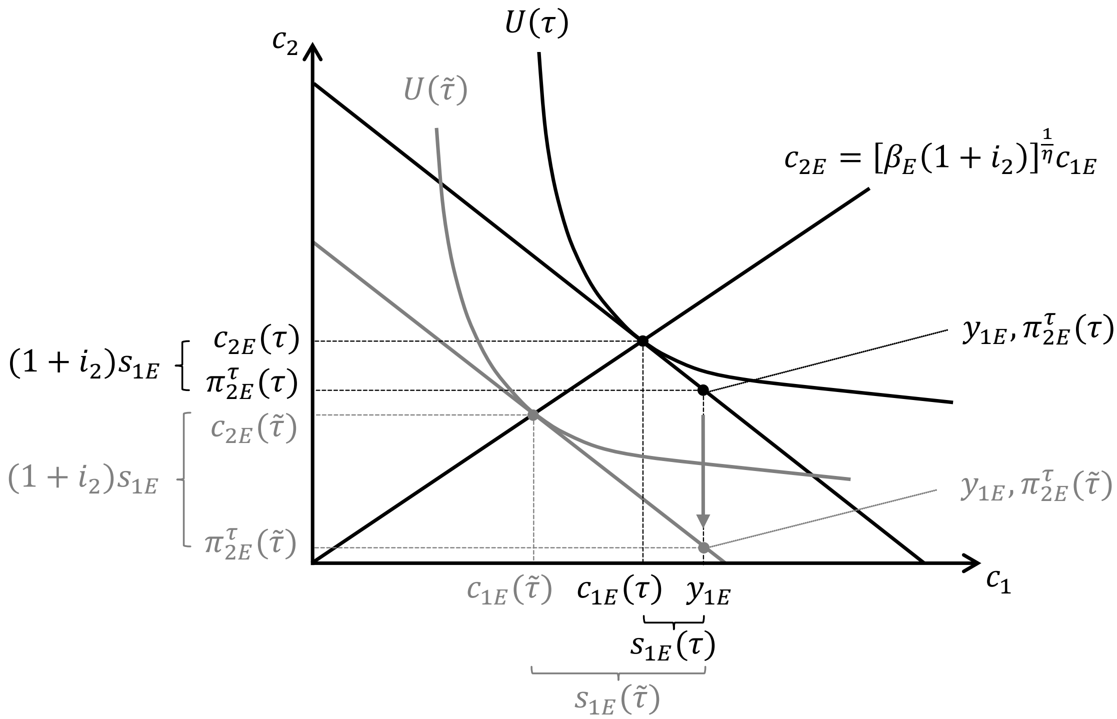

Figure 6.1: Savings reaction of the representative household in country E to an increase in the carbon tax in the second period from τ to $\tilde{\tau}$

With rational expectations the representative households in either country correctly foresees the respective change in its future period income whereas the first period income streams y_{1E} and y_{1I} are not affected by the resource tax. Since the households'

[4] Note that this is also the case in Smulders et al. (2012). There, the future income losses from a stricter regulation of emissions in the end also arise from an increase in the energy price and a reduction in the use of energy in production.

savings decisions are made as to smooth consumption over time for the given interest rate i_2, which is reflected in the marginal savings propensities $\frac{\partial s_{1m}}{\partial \pi^{\tau}_{2m}} < 0$ for country $m = E, I$ from (4.13), the representative household in country E reacts to the raising carbon tax and the induced future income loss by increasing its savings while the representative household in country I reduces its savings.

Note that the representative household in country E unambiguously increases its savings even though it suffers a loss in its life time income, or wealth, $w_E = y_{1E} + \frac{\pi^{\tau}_{2E}}{1+i_2}$ by the higher resource tax ceteris paribus. The reason is that for homothetic preferences the household in country E spends a specific share of the present value of life-time income w_E on first period consumption c_{1E}, which only depends on the interest rate i_2, the utility discount factor β_E and the intertemporal elasticity of substitution $\frac{1}{\eta}$ but not on its life-time income. To see this, first note that by the budget constraints (4.10) the present value of consumption must not exceed the life-time income, i.e.

$$c_{1E} + \frac{c_{2E}}{1+i_2} = w_E$$

Substituting c_{2E} from the Euler equation (4.11), we observe that

$$c_{1E} = \frac{1+i_2}{1+i_2+[\beta_E(1+i_2)]^{\frac{1}{\eta}}} w_E \qquad \text{and} \qquad c_{2E} = \frac{[\beta_E(1+i_2)]^{\frac{1}{\eta}}}{1+i_2+[\beta_E(1+i_2)]^{\frac{1}{\eta}}} w_E$$

This implies that the income expansion path is a straight line through the origin with slope $[\beta_E(1+i_2)]^{\frac{1}{\eta}}$ as it is depicted in figure 6.1.

The increase in the tax rate induces a downward shift in the income endowment point $(y_{1E}, \pi^{\tau}_{2E})$ and, therfore in the life-time wealth for a constant interest rate i_2, which graphically is reflected in the downward shift in the budget line as the point of intersection between the c_1-axis and the budget line indicates the life time wealth w_E. The optimal consumption point after the tax increase is graphically determined by the new point of intersection between the adjusted budget line and the income expansion path. But since savings correspond to the difference between first period income y_{1E} and consumption c_{1E} on the c_1-axis, or analytically

$$s_{1E} = y_{1E} - c_{1E} = y_{1E} - \frac{1+i_2}{1+i_2+[\beta_E(1+i_2)]^{\frac{1}{\eta}}} w_E$$

we can conclude that the household in country E unambiguously raises its savings upon an increase in the tax rate ceteris paribus, i.e. for a given first period income y_{1E} and a given interest rate i_2. The unambiguous decrease in the savings of the representative household in country I can be shown by the analogue reasoning for an

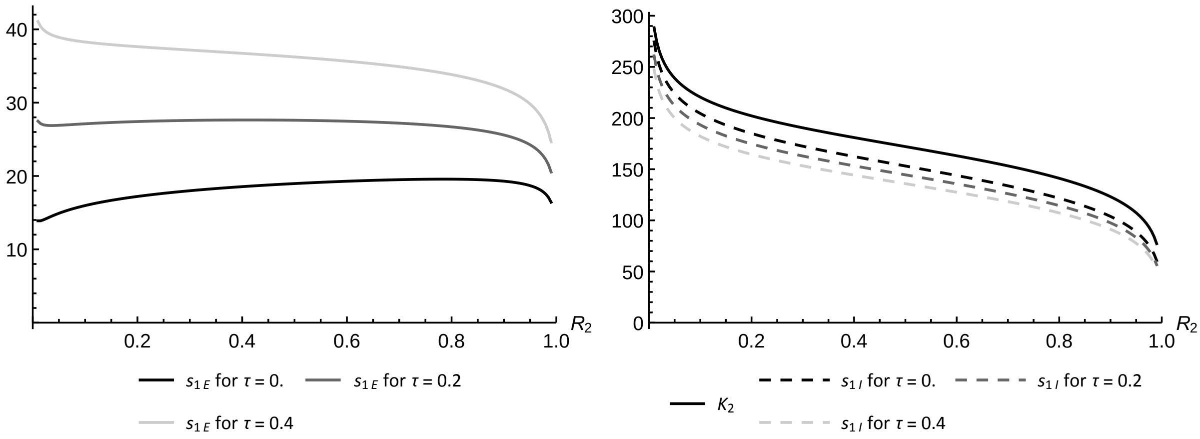

Figure 6.2: The effect of the carbon tax on the aggregate capital stock K_2 and savings of both countries;
Parameter assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, total productivity factor $A = 300$, $L = 1$

increase in second period income and life-time wealth by the lump-sum distribution of the higher tax revenue.

As we already know from our discussion in section 4.2, if both countries have symmetric consumption preferences and, therfore $ID_2 = 0$ from (4.20), these adjustment in the savings of both countries induced by the redistribution of income exactly offset each other and the carbon tax is completely neutral with respect to the capital stock K_2. The symmetric country case is graphically illustrated by figure 6.2 for the exemplary numerical simulation, which is already familiar from section 5.2.2.4. The figure displays the aggregate capital stock and the savings of country E and country I as a function of the resource extraction path for different carbon tax rates τ and clearly demonstrates the adjustments in the savings of the respective country whereas the overall capital stock does not change.

For asymmetric preferences, the influence of the carbon tax on the capital stock depends on the net effect of the savings reactions. If, for example, the resource importing countries are less patient than the resource exporting country E so that $ID_2 > 0$ according to (4.20), the representative household in country I will reduce its savings upon the higher tax revenue payments in the second period by more than the representative household in country E increases its savings due to the loss second period resource income. Thus, net savings and the equilibrium capital stock will decrease with a higher resource tax in this case while the opposite holds true for $ID_2 < 0$.

In the asymmetric country case, the future marginal productivity of resources and capital and, therfore the factor market prices in market equilibrium then also depend on the resource tax via the capital stock. Since the resource tax has an influence on capital supply and thereby on the equilibrium capital stock but not on the marginal productivity of the production factors, we have analogue to the decompositions in (4.30) and (4.31)

$$\begin{aligned}\frac{dp_2}{d\tau} &= \frac{\partial p_2}{\partial K_2}\frac{dK_2}{d\tau} \\ &= -\frac{ID_2F_{2KR}p_2R_2}{1 - F_{2KK}\left(SE + ID_2s_{1E}\right) - ID_2(1-\tau)F_{2KR}R_2}\end{aligned} \tag{6.2}$$

for the resource price p_2 and

$$\begin{aligned}\frac{di_2}{d\tau} &= \frac{\partial i_2}{\partial K_2}\frac{dK_2}{d\tau} \\ &= -\frac{F_{2KK}ID_2p_2R_2}{1 - F_{2KK}\left(SE + ID_2s_{1E}\right) - ID_2F_{2KR}(1-\tau)R_2}\end{aligned} \tag{6.3}$$

for the interest rate i_2. For example, if the capital stock decreases due to the carbon tax induced transfer of resource income to country I ($\beta_E > \beta_I$), the equilibrium interest rate will increase as a reduction in the capital stock raises the marginal productivity of capital by the concavity of the final goods production technology. In contrast, the resource market price will fall due to the complementarity of physical capital and fossil resources in production. For symmetric countries, since purely redistributive effects are completely neutral with respect to aggregate savings, the resource tax does not affect the equilibrium capital stock and, therfore also does not affect the equilibrium factor prices.

6.3 The Competitive Case

We now build on our analysis of the carbon tax influence on the conditional market equilibrium and derive and discuss the equilibrium reactions of the resource owners to an (marginal) increase in the carbon tax if there is a competitive resource market. In this case, the overall market equilibrium of the world economy is characterized by Hotelling condition (2.3) and the conditional market equilibrium defined in section 4.2. As pointed out before, the competitive case has already been studied in van der Meijden et al. (2015b), or using duality in van der Ploeg (2015). By deriving and interpreting the comparative static effect of the increase in the carbon tax based upon our analysis of the conditional market equilibrium we follow a slightly different approach of analysis, which nevertheless allows us to reproduce the main insights from these contributions.

Following van der Meijden et al. (2015b), our focus in the following will be on the one hand on the feedback effects which additionally arise in general equilibrium from any adjustment in the resource extraction path and which may be seen as a consequence of the still prominent role of fossil resources for economic development and growth (see sections 3.1.1 and 3.2.1). On the other hand, as already suggested by the previous section on the equilibrium influence of the carbon tax, we will in particular point out the implications of the redistributive effect of climate policies in such a general equilibrium setting for the supply reaction of resource owners (see section 3.2.3). Note that we do not consider the optimal carbon tax here and, therfore, also do not introduce a dynamic game between the resource importing countries choosing the tax rate and the resource exporting countries planning resource extraction as, for example, in Liski and Tahvonen (2004).

6.3.1 Symmetric Consumption Preferences: Implications of General Equilibrium Feedback Effects

To study the equilibrium effect of the climate policy on the resource extraction path in the competitive resource market, we totally differentiate Hotelling rule (2.3) with respect to the resource tax τ and resource supply R_2. Recall that the latter represents a shift of resources from the first to second period due to the binding resource constraint in market equilibrium. For symmetric countries and, therfore, $ID_t = 0$, we already know from our analysis in the previous section that the carbon tax does not directly, or separately, influence the capital market equilibrium since it is only of redistributive effect. By (4.26), (4.30), (6.2), (4.31), and (6.3) we, therfore, get for the comparative statics

$$\frac{dR_2^c}{d\tau} = \frac{-p_2}{\frac{di_2}{dR_2}p_1 - (1+i_2)\frac{\partial p_1}{\partial R_1} - (1-\tau)\frac{dp_2}{dR_2}} < 0 \tag{6.4}$$

The negative sign holds true as the denominator is unambiguously positive for symmetric countries. It implies that the resource extracting firms will speed up overall extraction if the resource tax, or equivalently the carbon tax, in the future period is marginally increased. The intuition behind this green paradox result is, in principle, completely analogue to the partial equilibrium analysis in section 2.2. By the increase in the (value added) resource tax, the producer price of the resource, and thereby the resource rent, is ceteris paribus reduced in the future period, which for a given interest rate i_2 induces the resource owners to shift resource supply from the second to the first period. This is captured by the numerator.

The denominator measures how (the future value of) the resource rent, which can be earned in the first and the second period, and, therfore, the incentives to supply in either period, change as soon as the aggregate market supply path starts to adjust, just as in the partial equilibrium setting of section 2.2. Correspondingly, if the resource owners are induced to shift resources to the first period, the first period resource rent will decrease (see (4.26)) whereas the second period resource producer price will increase (see (4.30)) so that the incentives to speed up extraction diminish throughout the adjustment process and Hotelling condition (2.3) will eventually be met again for the higher carbon tax. In contrast to the partial equilibrium setting, however, these "feedback" effects on the extraction incentives of resource firms are extended in general equilibrium. We know from our discussion of the conditional market equilibrium that the capital market equilibrium represented by the second period capital stock K_2 and the interest rate i_2 change according to (4.28) and (4.31) as soon as the adjustment of the resource extraction path starts. Both, the change in the capital stock as well as the change in the interest rate, have direct implications for the resource supply decision of resource extracting firms. Any adjustment in the capital stock shifts future resource demand due to the complementarity of production factors, whereas the interest rate i_2 represents the opportunity costs of leaving resources underground to the resource owners as pointed out in section 2.1.

To focus on the effect of the endogenous interest rate first, assume that the second period capital stock is exogenous with respect to the extraction path so that $\frac{dK_2}{dR_2} = 0$. By the complementarity of production factors the interest rate positively depends on future resource supply and, therfore, falls as soon as the resource owners start to accelerate resource extraction. With this simultaneous fall in the opportunity costs of leaving resources underground, the overall incentive for an acceleration of extraction is lower so that the green paradox effect of the carbon tax increase is attenuated compared to the standard partial equilibrium setting. A similar conclusion can be drawn for the scenario without physical capital, which van der Meijden et al. (2015b) study, too. However, there the influence of the resource extraction path on the interest rate arises not by the complementarity of the production factors but by the fact that a shift of resource extraction from the second to the first period necessarily comes along with a shift of aggregate production and income from the second to the first period. Given the consumption smoothing motives of households, this intertemporal reallocation of income then requires an adjustment in the interest rate so that households in both countries are willing to consume more in the first period and to consume less in the second period.

If the second period capital stock is endogenous and we have $\frac{dK_2}{dR_2} < 0$, the second period capital stock will increase with an acceleration of resource extraction. In this case, the savings disincentives from the negative substitution effect, which arises as the interest i_2 falls with lower R_2 (see (4.31)), are dominated by the positive savings incentive from the shift of income from the second to the first period (see our discussion of (4.28)). This increase in the second period capital stock shifts future resource demand upward due to the complementarity of production factors. This implies that the second period resource rent will rise more strongly than in partial equilibrium where there is just the increase in the marginal resource productivity from the concavity of the production technology. At the same time, we know from (4.31) that the interest rate will decrease by more than without an endogenous future capital stock. We already have discussed that such a development generally counteracts the incentives to speed up extraction as the opportunity costs of conserving resources underground for second period supply fall. Thus, overall the additional feedback effects on the extraction incentives in general equilibrium both tend to counteract the resource owners' incentive to evade the higher resource tax by shifting resources to the first period for $\frac{dK_2}{dR_2} < 0$. The green paradox, therefore, is attenuated compared with the tax effect in the standard partial equilibrium setting (see (2.8)) but nevertheless necessarily arises for symmetric preferences.

If the aggregate substitution effect dominates the effect of the intertemporal income shift and the capital stock decreases with a shift of resources to the first period, i.e. if we have $\frac{dK_2}{dR_2} > 0$, accelerating extraction will come along with a downward shift in future resource demand, again due to the complementarity of production factors.[5] This creates an additional incentive to shift resources to the first period. At the same time, however, the interest rate i_2 still decreases as before since the interest rate less

[5] An intertemporal elasticity of substitution $\frac{1}{\eta} \geq 1$ is sufficient for the substitution effect dominating the income effect induced by a change in the interest rate in the individual household's savings decision by (4.14)). However, since a shift in the extraction path does not only entail a change in the interest rate i_2 but also an intertemporal transfer of income between both periods we must have

$$\frac{dK_2}{dR_2} > 0 \qquad \text{for} \qquad \frac{1}{\sigma\eta} > \frac{1 + i_2 + (1-\tau)\left[\beta_E(1+i_2)\right]^{\frac{1}{\eta}}}{i_2 + \theta_{2K}} > 1$$

strongly but still positively depends on second period resource supply according to (4.31) for symmetric countries. Thus, the additional feedback effects from the endogeneity of the capital market equilibrium are counteracting in this case. The green paradox is attenuated compared to the partial equilibrium setting if the decrease in the interest rate dominates. However, we cannot exclude that the downward shift in future resource demand has a stronger effect on the extraction incentives of the competitive resource owners than the decrease in the opportunity costs of leaving resources underground. The additional feedback effects in general equilibrium by the shift in second period resource demand and the endogeneity of the interest rate then strengthen the incentive to accelerate resource extraction. By the decompositions in (4.30) and (4.31) such an amplification of the green paradox compared to the partial equilibrium outcome will arise if

$$(1-\tau)\frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} - p_1\frac{di_2}{dR_2} > 0 \qquad \text{or} \qquad \frac{dK_2}{dR_2} > \frac{\theta_{2K}}{\theta_{2K}+i_2}p_2$$

Thus, for an amplification of the green paradox the positive dependency of the second period capital stock on future resource supply must be sufficiently large. This is intuitively plausible because the larger the decrease in the capital stock from an acceleration of extraction the larger is the downward shift in future resource demand, but at the same time the lower is the counteracting overall reaction of the interest rate according to (4.31).

6.3.2 Asymmetric Consumption Preferences: Resource Rent Redistribution

If we give up the restrictive assumption of symmetric consumption preferences, the comparative statics capturing the equilibrium shift in the resource extraction path upon a marginal increase in the carbon tax rate will read

$$\frac{dR_2^c}{d\tau} = \frac{-p_2 + (1-\tau)\frac{dp_2}{d\tau} - \frac{di_2}{d\tau}p_1}{\frac{di_2}{dR_2}p_1 - (1+i_2)\frac{\partial p_1}{\partial R_1} - (1-\tau)\frac{dp_2}{dR_2}} \tag{6.5}$$

where the additional terms in the numerator are given in (6.2) and (6.3). First, the interpretation of the denominator is completely analogue to the symmetric country case. Even though (4.30) and (4.31) are generally of ambiguous sign for the asymmetric country case, we can refer to the second-order condition for a profit maximizing competitive extraction path to argue analogue to section 5.2.2.4 that the denominator must be of positive sign for any change in the tax rate, given some profit maximizing competitive equilibrium extraction path (R_1^c, R_2^c). In fact, the second-order condition for the representative firm's profit maximization problem (2.2) states that

$$-\frac{dp_1}{dR_1}\frac{dR_{1j}}{dR_{2j}} + \frac{(1-\tau)\frac{dp_2}{dR_2}}{1+i_2} - \frac{(1-\tau)p_2}{(1+i_2)^2}\frac{di_2}{dR_2} = \frac{1}{1+i_2}\left[(1+i_2)\frac{\partial p_1}{\partial R_1} + (1-\tau)\frac{dp_2}{dR_2} - p_1\frac{di_2}{dR_2}\right] < 0 \tag{6.6}$$

which can be derived from the first-order condition since $\frac{(1-\tau)p_2}{1+i_2} = p_1$ holds along the optimal extraction path according to Hotelling condition (2.5).

Second, in the two country general equilibrium setting, the ceteris paribus reduction in the resource producer price, or the resource rent, which drives the green paradox outcome in the standard partial equilibrium setting, entails a redistribution of resource income from country E to country I as already pointed out in the previous section 6.2. The resource importing country I is able to retain a larger share of the resource rent ceteris paribus, i.e. for a given resource extraction path. Whereas this redistributive effect of climate policy was completely neutral for symmetric homothetic preferences, it influences aggregate savings and thereby the capital market equilibrium for asymmetric homothetic preferences. Since the resource supply path directly depends on the capital market equilibrium by the complementarity of production factors and by the interest rate representing the opportunity costs of leaving resources underground, additional transmission channels of the carbon tax change arise via the capital market which are captured in the numerator by the separate, or direct, effects of resource taxation on the resource market price and the interest rate.

Using the definitions in (6.2) and (6.3) allows us to rewrite the numerator to

$$-p_2 + (1-\tau)\frac{dp_2}{d\tau} - \frac{di_2}{d\tau}p_1 = -p_2 + \frac{dK_2}{d\tau}\left[(1-\tau)\frac{\partial p_2}{\partial K_2} - \frac{\partial i_2}{\partial K_2}p_1\right]$$

The term in curly brackets is positive due to the concavity of the production technology and the complementarity of production factors. As we already know, the net effect of this second period income redistribution on aggregate savings depends on the strength of the respective savings reaction and, therfore, on whether country E is more willing to save for second period consumption than country I or not.

If we have $\beta_E > \beta_I$, country E will be more patient than country I and, therfore, will not adjust its savings as much as country I. Thus, raising the carbon tax will decrease the second period capital stock in this case (see also (6.1)). But this implies that in contrast to partial equilibrium the resource tax does not only reduce the resource producer price for given resource demand but also shifts resource demand downwards. At the same time, due to the concavity of the production technology, the interest rate increases, and, therfore, the opportunity costs of conserving resources underground, as indicated by the last term in the numerator. Since these additional effects of the carbon tax all create incentives to accelerate extraction, the green paradox necessarily arises in this case. However, even though the numerator is greater due to the additional tax effects in general equilibrium, the green paradox may be amplified or attenuated as the denominator may generally be greater or lower than in partial equilibrium (again depending on the relationship between resource supply and the capitals stock from (4.28)).

If we have $\beta_E < \beta_I$ and the savings reaction of country E to the income redistribution by the climate policy dominates, the capital stock will rise with a tightening of the climate policy. In this case, the additional effects of carbon taxation in general equilibrium will counteract the familiar reduction in the producer price, and we may even observe a reversal of the green paradox in the sense that the second period resource supply increases upon raising the carbon tax. This is completely excluded in partial equilibrium in such a standard setting without extraction costs or substitutive technologies. The intuition for such a reversal is as follows. By increasing the second period capital stock, the higher carbon tax shifts resource demand upwards which, at least partly, compensates for the larger share country I captures from the resource rent. At the same time, the increase in the capital stock reduces the interest rate due to the diminishing returns. This generally creates an incentive for a more conservative extraction path as the return on the alternative investment option for resource owners is lower. If these effects are strong enough, they will overcompensate the larger share which country I is able to capture from the resource rent for a higher carbon tax and thereby create an incentive to postpone extraction.

To further investigate when the green paradox is reversed, we use (6.1), (6.2), and (6.3) as well as (4.18) and (2.3) along the competitive equilibrium extraction path to further rearrange the numerator of (6.5). As shown in appendix 9.1.4, this confirms the observation from van der Meijden et al. (2015b) that the green paradox will only be reversed for a rather low intertemporal elasticity of substitution, or if

$$\frac{1}{\eta} < \frac{ID_2 c_{2E}}{\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} c_{2E} + \frac{\partial s_{1I}}{\partial \pi^{\tau}_{2I}} c_{2I}} = \frac{ID_2 c_{2E}}{ID_2 c_{2E} + \frac{\partial s_{1I}}{\partial \pi^{\tau}_{2I}} \left(c_{2E} + c_{2I}\right)} < 1$$

The right side is positive but lower than unity for $ID_2 < 0$ which we already have identified as a necessary condition for the reversal of the green paradox in the competitive case. A similar observation has been made by Eichner and Pethig (2011) who concluded that a low intertemporal elasticity of substitution is crucial for the geographical leakage rate to exceed 100 % (see section 6.1 above). With a low intertemporal elasticity of substitution first and second period consumption are rather complementary which is reflected in a low substitution effect SE from (4.18) – recall that for $\frac{1}{\eta} < 1$ the substitution effect induced from an increase in the interest rate is always dominated by the income effect in the individual household's savings decision (cf. (4.14)). Thus, if the redistribution of resource rents has a positive net effect on aggregate savings, the capital stock K_2 increases, which by the concavity of the production technology tends to reduce the market interest rate i_2. The fall in the interest rate creates an incentive to reduce savings again as the costs of present consumption in terms of future consumption decrease. However, if the intertemporal elasticity of substitution is rather low, this counteracting effect on savings is weak and there is a stronger overall increase in the capital stock from the redistribution of resource rents (see also (6.1) where the substitution effect is explicitly included in the denominator). Hence, the transmission channel which leads to the reversal of the green paradox is stronger with a lower intertemporal elasticity of substitution.

6.3.3 Endogenizing Aggregate Extraction

Throughout the analysis we abstracted from the costs of extraction or exploration for simplification. However, not the least the literature overview in section 2.2 illustrates that the endogeneity of aggregate resource extraction often is of crucial importance for the assessment of the supply reactions of resource owners and the implications of the green paradox. In fact, even if (future) climate policies lead to an acceleration of extraction, climate damages can often decrease when aggregate emissions fall sufficiently.

van der Meijden et al. (2015b) take on this line of reasoning and additionally endogenize aggregate extraction by considering convex exploration costs. They show that the trade-off between the timing and the volume of extraction also arises in general equilibrium, and that the general equilibrium structure, and the endogeneity of the capital market equilibrium in particular, does not introduce a qualitative difference to the conclusions from partial equilibrium. The reason is that in their setting the exploration investment decision to be made upfront does not depend on the capital market at all but only on the present value of fossil resources, which represents the marginal value of exploration investments in equilibrium. If there is an acceleration of extraction, the present value of resources given by the first period resource price necessarily falls, but it will fall by less if there is attenuation compared to partial equilibrium. This in turn implies that there will be more exploration activity and, therfore, a larger resource stock than in partial equilibrium. Put differently, and to follow our by now familiar line of reasoning, as long as the additional effects from the endogeneity of the capital market equilibrium do not have a separate influence on the exploration decision, the general equilibrium structure will not qualitatively change the implications of the endogeneity of aggregate extraction. If we assumed, for example, capital intensive exploration technologies instead, this might change as the carbon tax would affect exploration also directly via its influence on the capital market in the asymmetric country case.

6.4 Resource Monopolist

We now take on our analysis of resource market power in general equilibrium and consider the effect of climate policies on the extraction decision of the omniscient (benevolent) sheikh from section 5.2.2. The existing literature on general equilibrium aspects of resource supply and climate policies so far has always assumed competitive resource extraction. The following exposition can be seen as the monopoly case to the contribution of van der Meijden et al. (2015b).

We will demonstrate (again) that just transferring the familiar monopolistic supply decision from partial to general equilibrium can completely misleading – a conclusion which we already have drawn in section 5.2 for the resource extraction path but may hold true even more with respect to the effect of climate policies and potential supply reactions. Our focus will be on whether and how the additional considerations/motives, which may arise in general equilibrium given the interrelationship between the capital and the resource market and the more widespread cross market effects of the resource supply decision, affect the omniscient monopolist's perception of future climate policies. Note that this is somewhat different to the competitive case where we primarily were interested in the implications of the general equilibrium feedback effects and of the redistributive effect of climate policies on the supply reaction of fossil resource owners, mainly because the characterization of the supply behavior of resource owners does not change when we go from a partial equilibrium to a general equilibrium setting. However, we will point out that under imperfect competition the redistributive effect of climate policies can be of crucial importance for the resource supply reaction even for symmetric (homothetic) consumption preferences, which we assume again as before in section 5.2 to focus on the implications of the additional supply motives and considerations in general equilibrium.

By use of a comparative statics analysis we first show in the following that whereas a marginal increase in the future carbon tax unambiguously gives rise to a green paradox for the naive monopolist, the green paradox may be reversed with an omniscient sheikh, mainly due to the asset motive. We next discuss the role of the endogeneity of the capital accumulation and its internalization into the supply decision of the omniscient sheikh. Furthermore, we show that the effect of the carbon tax is monotonous and, therfore, independent of the tax rate. This implies that we can infer the effect of discrete carbon tax changes from the effect of marginal tax changes given by the comparative statics. Moreover, the monotonicity also allows us to consider the role of the capital endowments distribution for the effect of climate policies, which plays a crucial role for the effect of the asset motive on the speed of extraction as we saw in section 5.2.2.2 before. We finally investigate the potential reversal of the green paradox in more detail by discussing the more fundamental drivers for the effect of the future carbon tax policy. In particular, we thereby illustrate and discuss the crucial role of the elasticity of substitution in final goods production, as well as the role of the structure of the production technology represented by the productivity (or share) parameters of the CES production technology, and of the consumption preferences of households within a numerical sensitivity analysis.

6.4.1 Comparative Statics: Naive vs. Omniscient Sheikh

Similar to the analysis of the extraction decision, it proofs useful to contrast the supply reaction of the omniscient sheikh to an increase in the future carbon tax $\tau_2 = \tau$ with the supply reaction of the more familiar, completely naive monopolist in general equilibrium. We, therfore, consider the naive monopolist first before we analyze the supply reaction of the omniscient sheikh in detail. Overall, we capture and discuss the supply reactions in this section by use of comparative statics analyses.

6.4.1.1 Naive Monopolist

For the naive monopolist, we totally differentiate Hotelling condition (5.4) with respect to the resource supply path and the carbon tax, which gives us the comparative statics

$$\frac{dR_2^n}{d\tau_2} = \frac{-\left(p_2 + \frac{\partial p_2}{\partial R_2} R_2\right)}{\frac{d[(1+i_2)MR_1^n]}{dR_2} - \frac{dMR_2^n}{dR_2}} \tag{6.7}$$

The denominator captures how the left and the right side of the Hotelling condition change with a marginal shift of resource extraction from the first to the second period. Since we are interested only in the effect of the tax increase along the equilibrium extraction path (R_1^c, R_2^c), we can refer to the second-order condition (5.21) and argue that the denominator must always be of positive sign.[6]

The numerator captures the ceteris paribus reduction in the marginal resource revenue MR_2^n from (5.5) as we are considering a value added carbon tax, just as in partial equilibrium (see (2.9)). If we had a unit resource tax, the marginal effect of an increase in the tax rate on the marginal resource revenue would be just given by -1. However, the effect of an increase in the unit tax rate qualitatively does not differ from a value added tax as long as the second period marginal resource revenue MR_2^n is positive. For the naive monopolist, the latter is ensured as long as resource demand is price-elastic and fossil resources are scarce.

Since we focus on the symmetric country case here, the redistributive effect of the carbon tax is completely neutral with respect to the capital market equilibrium. Thus, the interest rate i_2, and, therfore, the left side of Hotelling condition (5.4), does not change with a change of the carbon tax. This implies that the (future value of) the first period marginal resource revenue is independent of the carbon tax. Hence, the increase in the carbon tax ceteris paribus unambiguously reduces the resource rent, or the marginal resource value given by marginal resource revenue in this case, which induces the naive monopolist to speed up extraction, and thereby gives rise to the familiar green paradox outcome.

Similar to the competitive case for symmetric countries, the only difference to the effect of the carbon tax in partial equilibrium (see (2.9)) is introduced by the feed-

[6] Since we are considering the symmetric country case, this also can be shown just by (9.4) and (9.5) in appendix 9.1.3.1.

back effects arising from the endogeneity of the interest rate i_2 and the endogeneity of the capital stock K_2 with respect to the resource extraction path, which can be observed in the denominator of the comparative statics. Again, since the interest rate i_2 falls with the acceleration of resource extraction, i.e. $\frac{di_2}{dR_2} > 0$ by (4.31) for symmetric countries, this feedback effect in general equilibrium counteracts the tax induced incentive for shifting extraction to the first period and thereby tends to attenuate the green paradox outcome. If the second period capital stock increases upon a shift of resource extraction to the first period for $\frac{dK_2}{dR_2} < 0$, both feedback effects tend to attenuate the green paradox outcome because the rising capital stock increases the future marginal resource revenue via the complementarity of production factors according to (5.7). In contrast, as we already have discussed for the competitive case, if $\frac{dK_2}{dR_2} > 0$, the general equilibrium feedback effects from shifts in the resource extraction path are counteracting so that the green paradox might also be amplified.

Overall, we arrive at the conclusion that if the resource monopolist is completely naive with respect to the more widespread influence of her supply decision in the economy, assuming resource market power does not fundamentally modify or alter the assessment how raising the future carbon tax affects the extraction path compared to the competitive market. Just as in partial equilibrium, resource market power is then only of minor relevance for the impending supply-side reaction to climate policies.

6.4.1.2 Omniscient Sheikh

In this section, we consider the supply reaction of the omniscient sheikh and study in particular whether and why our conclusion from the previous section may change as soon as the monopolist is no longer naive but omniscient.

By totally differentiating (5.2) and thereby taking into account that (consumer) factor prices are functions of the resource supply path only according to (4.26), (4.27), (4.30), (4.31) for symmetric preferences, we derive the optimal resource supply response to a marginal increase in the future (value added) resource tax as

$$\frac{dR_2^o}{d\tau} = \frac{-\left(p_2 + \frac{dp_2}{dR_2}R_2\right) + \frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}^\tau}\frac{\partial \pi_{2E}^\tau}{\partial \tau_2}}{\frac{d[(1+i_2)MR_1^o]}{dR_2} - \frac{dMR_2^o}{dR_2}} \tag{6.8}$$

The denominator again measures the influence of a marginal shift in the resource extraction path to the second period on the left and the right side of Hotelling condition

(5.2). We know from section 5.2.2.4 that the denominator generally is of ambiguous sign but must be positive along the equilibrium extraction path (R_1^o, R_2^o) by the second-order condition (5.22).

The numerator captures the direct influence of a marginal increase in the second period's resource tax on Hotelling condition (5.2) for the initially, i.e. before the tax increase, optimal resource supply path. Again, since we assume symmetric countries, the carbon tax does not have any effect on the capital market equilibrium and, therfore, directly influences only the right side of Hotelling condition (5.2), i.e. the future marginal resource value from the omniscient sheikh's perspective MR_2^o defined in (5.3). However, as we already know, the latter consists of two components.

First, the carbon tax is generally of similar effect as in case of a naive monopolist or in partial equilibrium. The increase in the carbon tax devaluates future resource supply by reducing marginal resource revenue, or the resource income component of MR_2^o, which obviously creates an incentive to accelerate extraction. In contrast to the naive sheikh and partial equilibrium, the marginal resource revenue here does not only include the direct own-price effect but also the indirect price effect of resource supply via the endogeneity of the capital stock. Correspondingly, we have $\frac{dp_2}{dR_2}$ from (4.30) instead of $\frac{\partial p_2}{\partial R_2}$ in the numerator. If we considered a unit carbon tax, the marginal effect of an increase in the tax rate on the marginal resource revenue would be again given just by -1. However, since the marginal resource value is extended by the capital income component, or the asset motive, for the omniscient, we already have pointed out before that the scarcity of fossil resources does no longer ensure that the marginal resource revenue is positive. Thus, the carbon tax increase does not necessarily reduce the resource income component represented by the marginal resource revenue anymore. This is obviously in contrast to the more familiar case of the naive sheikh, and in contrast to partial equilibrium, and also implies that the carbon tax increase may be of different effect for a value added than for a unit resource tax. We will discuss this special case separately below and focus on the case where the marginal resource revenue is positive for the moment.

Second, the presence of the capital income component in MR_2^o may not only lead to the special case of a negative resource revenue but is also affected by the carbon tax increase itself. This is captured by the second term in the numerator of the comparative statics and arises for both, the value added and the unit resource tax. As we already have discussed in section 6.2, the carbon tax is, of course, neutral with respect to the overall capital market equilibrium. However, the redistribution of resource rents induced by a more ambitious climate policy ceteris paribus still leads to changes in the savings of both countries. In particular, we already have shown in section 6.2 that whereas country I will reduce its savings, country E will increase its savings unambiguously for reasons of consumption smoothing. But given the positive relationship between resource supply and capital return $\frac{di_2}{dR_2} > 0$ from (4.31), larger savings directly strengthen the asset motive in the second period and thereby create an incentive to postpone extraction because the marginal return on resource supply in the second period in terms of the capital income gain is larger than before. Thus, the carbon tax induced adjustment of the future asset holdings unambiguously works towards a reversal of the green paradox in the symmetric country case if, and only if, the sheikh pursues the asset motive.

Overall, in the standard case with a non-negative resource income component, we arrive at the interesting conclusion that there are two counteracting effects from the increase in the carbon tax. The marginal value of second period resource supply raises in terms of capital income whereas it is reduced in terms of resource income. If the strengthening of the asset motive via the endogenous savings reaction dominates the reduction in the marginal resource revenue in the resource market so that

$$-\left(p_2 + \frac{dp_2}{dR_2} R_2\right) + \frac{di_2}{dR_2} \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} \frac{\partial \pi_{2E}^{\tau}}{\partial \tau} > 0$$

the sheikh may even be induced to shift resources to exactly that period in which the resource is taxed more heavily, and the green paradox may be reversed. Of course, such a supply reaction is exactly opposite to the one in a comparable partial equilibrium framework, i.e. monopolistic resource extraction without extraction costs, or opposite to the naive monopolist. It crucially depends on the one hand on the asset motive in general, i.e. on the fact that the benevolent sheikh is able to internalize the positive influence of resource supply on capital income, and on the other hand additionally on the endogeneity of savings with respect to future resource income (π_{2E}^{τ}). In fact, if savings did not depend on second period income, for example by assuming that a constant share of first period income is saved as in Moussavian and Samuelson (1984), the second term in the numerator of (6.8) would disappear completely and a reversal of the green paradox would be excluded, at least in the standard case with a positive resource income component of MR_2^o.

To show that such a reversal of the green paradox is actually a possible outcome, we first rearrange the numerator by use of the properties of the CES production technology and the decompositions (4.30) and (4.31). This demonstrates that the green paradox will be reversed if the elasticity of factor substitution in final goods production σ is lower than the threshold

$$\sigma < 1 - \theta_{2R}\left(1 + i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\right) - \frac{dK_2}{dR_2}\frac{R_2}{K_2}\left(\theta_{2K} - (1-\theta_{2K}) i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\right) \quad (6.9)$$

The threshold on the right side is obviously not independent of the elasticity of substitution but nevertheless allows for further insights due to the definition of the savings reaction in (4.13) and of the factor remuneration shares ($\theta_{tf} < 1$).

In fact, the threshold level on the right side generally may be greater than unity only if $\frac{dK_2}{dR_2} < 0$ but can never be of negative sign. To see this note that the second term is lower than unity because the share of resource remuneration before taxes in total output $\theta_{2R} < 1$ by construction and $i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} < 1$ by definition in (4.14). The last term of the threshold captures the implications which the internalization of the feedback effects from the endogeneity of the capital stock K_2 has for the reversal or the arising of the green paradox. Since savings negatively depend on future income according to (4.14), the bracketed term is always positive. Thus, if the second period capital stock negatively depends on future resource supply ($\frac{dK_2}{dR_2} < 0$), the right side may be greater than unity, and a reversal of the green paradox is possible for a rather high elasticity of substitution $\sigma \geq 1$. Otherwise, for $\frac{dK_2}{dR_2} > 0$, a reversal of the green paradox will only be possible for $\sigma < 1$. Finally, by the definitions in (4.30) and (4.31) and their unambiguous signs for symmetric preferences follows[7] that the elasticity of the second period capital stock with respect to future resource supply must be bounded from above

$$\frac{dK_2}{dR_2}\frac{R_2}{K_2} < min\left\{\frac{1-\theta_{2R}}{\theta_{2K}}; \frac{\theta_{2R}}{1-\theta_{2K}}\right\} = \frac{\theta_{2R}}{1-\theta_{2K}} < 1 \quad (6.10)$$

[7] We have by (4.30)

$$\frac{dp_2}{dR_2}\frac{R_2}{p_2} = \left(F_{2RR} + F_{2RK}\frac{dK_2}{dR_2}\right)\frac{R_2}{p_2} = \frac{1}{\sigma}(\theta_{2R} - 1) + \frac{1}{\sigma}\theta_{2K}\frac{dK_2}{dR_2}\frac{R_2}{K_2} < 0$$
$$\rightarrow \quad \frac{dK_2}{dR_2}\frac{K_2}{R_2} < \frac{1-\theta_{2R}}{\theta_{2K}}$$

and by (4.31)

$$\frac{di_2}{dR_2}\frac{R_2}{i_2} = \left(F_{KR} + F_{2KK}\frac{dK_2}{dR_2}\right)\frac{R_2}{i_2} = \frac{1}{\sigma}\theta_{2R} + \frac{1}{\sigma}(\theta_{2K} - 1)\frac{dK_2}{dR_2}\frac{R_2}{K_2} > 0$$
$$\rightarrow \quad \frac{dK_2}{dR_2}\frac{K_2}{R_2} < \frac{\theta_{2R}}{1-\theta_{2K}}$$

This upper bound, which is lower than unity due to the Euler theorem ($\theta_{tR}+\theta_{tK}+\theta_L = 1$), ensures that the right side of the reversal condition (6.9) can never be negative even if $\frac{dK_2}{dR_2} > 0$.[8]

Second, we show that the reversal condition can hold for a positive marginal resource value MR_t^o. The reason is that we know from our discussion of the naive sheikh that resource demand may become price-inelastic for a low elasticity of substitution $\sigma < 1$, which implies that the marginal resource revenue MR_t^n becomes negative (see, for example, (5.5) and (5.6)). If the reversal condition (6.9) entailed a negative MR_t^o, we would get a contradiction to our underlying assumption of resource scarcity, and a reversal of the green paradox would be excluded a priori. Rearranging MR_2^o from (5.3) again by using the properties of the CES production function (4.4) and the decompositions (4.30) and (4.31), and separating the feedback effects from the endogeneity of the capital stock we find that

$$MR_2^o > 0 \quad \text{for}$$
$$\sigma > 1 - \theta_{2R} - \frac{\theta_{2K}\frac{s_{1E}}{K_2}}{1-\tau} - \frac{dK_2}{dR_2}\frac{R_2}{K_2}\left(\theta_{2K} + \frac{\theta_{2K}\frac{s_{1E}}{K_2}}{(1-\tau)\theta_{2R}}(\theta_{2K}-1)\right) \tag{6.11}$$

By comparison of both thresholds, we observe that both conditions can hold true simultaneously if

$$\frac{dK_2}{dR_2}\frac{R_2}{K_2} < \frac{\theta_{2R}}{1-\theta_{2K}} < 1$$

This, however, is ensured by (6.10). We, therfore, can conclude that the reversal of the green paradox is in general a feasible outcome for an equilibrium extraction path (R_1^o, R_2^o), irrespective of the sign of $\frac{dK_2}{dR_2}$.

6.4.1.3 The Role of the Capital Dynamics

To further investigate the role of the endogeneity of the capital stock captured in the term $\frac{dK_2}{dR_2}$, we briefly investigate the supply reaction of the sheikh who does not internalize the endogeneity of the second period capital stock and only pursues the asset motive as in section 5.2.2.2. This, in principle, also corresponds to a framework where there is an endogenous savings decision in country E, but the capital stock in the world economy does not react to the resource supply path at all so that $\frac{dK_2}{dR_2} = 0$.

[8] In fact, using this upper bound the reversal condition simplifies to $\sigma < \frac{1-\theta_{2R}-\theta_{2K}}{1-\theta_{2K}}$ which is positive again by the Euler theorem.

The comparative statics in this case read

$$\frac{dR_2^{na}}{d\tau} = \frac{-\left(p_2 + \frac{\partial p_2}{\partial R_2} R_2\right) + \frac{\partial i_2}{\partial R_2} \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} \frac{\partial \pi_{2E}^{\tau}}{\partial \tau}}{\frac{d[(1+i_2)MR_1^{na}]}{dR_2} - \frac{dMR_2^{na}}{dR_2}} \tag{6.12}$$

which we again derive by totally differentiating the corresponding Hotelling condition (5.9) with respect to the extraction path and the carbon tax. Completely analogue to (6.8), the denominator must be of positive sign along the optimal, i.e. utility maximizing, extraction path (R_1^{na}, R_2^{na}) by the second-order condition of the sheikh's utility maximization problem (see (5.23)).

The numerator of the comparative statics, in principle, comprises the same elements as in (6.8) for the omniscient sheikh. However, as already pointed out in section 5.2.2.3, for $\frac{dK_2}{dR_2} < 0$, the negative own-price effect of resource supply is stronger in case of the omniscient sheikh as $\frac{dp_2}{dR_2} < \frac{\partial p_2}{\partial R_2} < 0$ by (4.30). Intuitively, the resource market price reacts stronger as the omniscient sheikh takes into account that the resource market price falls not only due to the decreasing productivity of resources but also due to a fall in second period resource demand by the induced decrease in the capital stock K_2. But this implies that for any given extraction path the resource income component in the overall marginal resource value is lower for the omniscient monopolist, and therefore that the tax induced loss in the marginal resource value is lower so that the carbon tax creates a lower incentive to accelerate extraction. Obviously, for $\frac{dK_2}{dR_2} > 0$, the opposite holds true.

Internalizing the endogenous response of the future capital stock to shifts in resource supply at the same time strengthens (counteracts) the positive complementarity relationship between resource supply and the capital return. The reason is that for $\frac{dK_2}{dR_2} < 0$ ($\frac{dK_2}{dR_2} > 0$) we have $\frac{di_2}{dR_2} > \frac{\partial i_2}{\partial R_2}$ ($\frac{di_2}{dR_2} < \frac{\partial i_2}{\partial R_2}$) by (4.31). Hence, the asset motive and thereby also the tax induced precautionary savings reaction in the resource exporting country E have a higher weight in the overall marginal resource value for any given extraction path if the sheikh internalizes the capital dynamics and $\frac{dK_2}{dR_2} < 0$ ($\frac{dK_2}{dR_2} > 0$).[9] Overall, the feedback effects from the endogeneity of the capital stock tend

[9] In terms of elasticities, by internalizing a negatively (positively) dependent second period capital stock, resource demand becomes less (more) price-elastic from the omniscient sheikh's perspective, which also gives rise to the addiction motive previously discussed in section 5.2.2, if $\frac{dK_2}{dR_2} < 0$ ($\frac{dK_2}{dR_2} > 0$). This can be observed from

$$e_{R_2,p_2} = -\frac{1}{\frac{dp_2}{dR_2}\frac{R_2}{p_2}} = \frac{\sigma}{1-\theta_{2R}-\theta_{2K}\frac{dK_2}{dR_2}\frac{R_2}{K_2}} \lessgtr \frac{\sigma}{1-\theta_{2R}} = -\frac{1}{\frac{\partial p_2}{\partial R_2}\frac{R_2}{p_2}} = \epsilon_{R_2,p_2} \qquad \text{if } \frac{dK_2}{dR_2} \lessgtr 0$$

to support the mechanisms which work towards the reversal of the green paradox if we have $\frac{dK_2}{dR_2} < 0$, while the opposite holds true if we have $\frac{dK_2}{dR_2} > 0$. Thus, the reversal of the green paradox will be more (less) likely if the sheikh internalizes the feedback effects, i.e. is omniscient, and if there is a negative (positive) relationship between the future capital stock and future resource supply. This conclusion is reflected in the reversal condition (6.9). For the sheikh who only pursues the asset motive but does not internalize the capital dynamics the last terms on the right side vanish.[10] By the Euler theorem, a reversal of the green paradox then is only possible for $\sigma < 1$. In contrast, for the omniscient sheikh and $\frac{dK_2}{dR_2} < 0$, we already have pointed out that the reversal may also be possible for $\sigma > 1$.

6.4.1.4 Special Case: Negative Resource Income Component

We already have briefly pointed out that the asset motive may give rise to a special case in which the resource income component of the overall marginal resource value for the omniscient sheikh MR_2^o – or even for the otherwise naive sheikh who only pursues the "partial" asset motive MR_2^{na} – is negative.[11] Intuitively, the fossil resource must be so valuable in terms of capital market income that the omniscient sheikh is willing to accept a suboptimal low resource revenue.

If the resource income component is negative, an increase in the value added resource tax actually decreases the negative contribution of this component and thus no longer reduces but raises the resource income component. The reason is that

Similarly, the cross price elasticity of capital demand is reduced (increased) from the omniscient sheikh's perspective as

$$e_{K_2,p_2} = \frac{1}{\frac{di_2}{dR_2}\frac{R_2}{i_2}} = \frac{\sigma}{\theta_{2R} + (\theta_{2K} - 1)\frac{dK_2}{dR_2}\frac{R_2}{K_2}} \lesseqgtr \frac{\sigma}{\theta_{2R}} = \frac{1}{\frac{\partial i_2}{\partial R_2}\frac{R_2}{i_2}} = \epsilon_{K_2,p_2} \qquad \text{if } \frac{dK_2}{dR_2} \lesseqgtr 0$$

[10] Reversal condition (6.9) in this case is simplified to

$$\sigma < 1 - \theta_{2R}\left(1 + i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\right)$$

[11] A negative marginal resource revenue, or resource income component, may also be due to price-inelastic resource demand which is compatible with resource market power in our setting as long as the sheikh pursues the asset motive in both periods (see also the corresponding discussion in Andrade de Sà and Daubanes 2016 and section 5.3).

a higher value added resource tax lowers the negative own-price effect of resource supply on the infra-marginal resource quantities sold so that the (negative) marginal resource revenue increases.[12] First, since this positive effect of the carbon tax comes in addition to the stronger future asset motive from the adjustment in the asset holdings, the overall marginal resource value MR_2^o necessarily increases. Thus, a negative marginal resource revenue is a sufficient condition for the reversal of the green paradox. Second, this also implies that in contrast to the unit tax case an endogenous savings reaction to the carbon tax is no longer necessary for a reversal of the green paradox. In fact, the reversal of the green paradox then only requires that the sheikh is able to internalize a positive influence of resource supply on the capital return and , therfore, to pursue the asset motive, which renders a negative resource income component compatible with resource scarcity. Finally, also note that this special case may only arise for a value added resource tax because for a unit resource tax the first element in the numerator of the comparative statics (6.8) (and also (6.12)) reduces to -1. The effect of a value added and a unit carbon tax , therfore, may fall apart if the sheikh is not naive but omniscient.

6.4.1.5 Monotonicity of the Carbon Tax Effect: Neutral Tax Policies and Capital Endowments Distribution

The findings in the previous sections directly derive from the comparative statics analysis, which strictly speaking only holds true for local, or marginal, changes in the carbon tax. Naturally, this restriction raises the question whether discrete changes in the carbon tax rate such as the introduction of a carbon tax lead to different outcomes or not. However, drawing conclusions about the effect of discrete changes in the carbon tax from the sign of the comparative statics is only possible if the sign of the marginal tax effect at least prevails when going from the low or not tax equilibrium outcome to the (high) tax equilibrium outcome. This general qualification is closely related to the discussion in section 5.2.2.4 where we pointed out that our conclusions from the local arbitrage considerations need not necessarily hold true for the

[12] Resource demand after taxes becomes more price-elastic from the sheikh's perspective, which increases the marginal resource revenue, i.e. inverse resource demand pivots inwards around the point of intersection with the horizontal (R_t-) axis in a $p_2 - R_2$-diagram. Note also that in case of a value added resource tax, increasing resource supply at the margin lowers not only the price on infra-marginal resource quantities sold but also the absolute tax revenue collected from these quantities.

comparison and qualitative interpretation of the different extraction policies. In the following, we will, however, show that the marginal tax effect given in the comparative statics is of the same sign – but not necessarily of the same absolute value which would imply linearity – irrespective of the initially given tax rate and irrespective of the magnitude of the tax increase. Thus, the sign of the marginal tax effect given in the comparative statics does not only prevail for discrete changes in the tax rate but is even monotonous for symmetric homothetic consumption preferences.

We at first show that the sign of the comparative statics (6.8) does not change with the tax rate. Since we assess the effect of the carbon tax along equilibrium extraction paths, the denominator must always be of positive sign and we can restrict this proof to the sign of the numerator. The numerator depends on the tax rate not directly (or explicitly) but only indirectly via the resource supply path because for symmetric preferences the second period capital stock K_2 and the factor market prices p_2 and i_2 are all functions of the resource supply path only according to (4.28), (4.30), and (4.31). This implies that even for different carbon taxes the numerator must be of the same sign if the sheikh eventually chooses the same extraction policy.

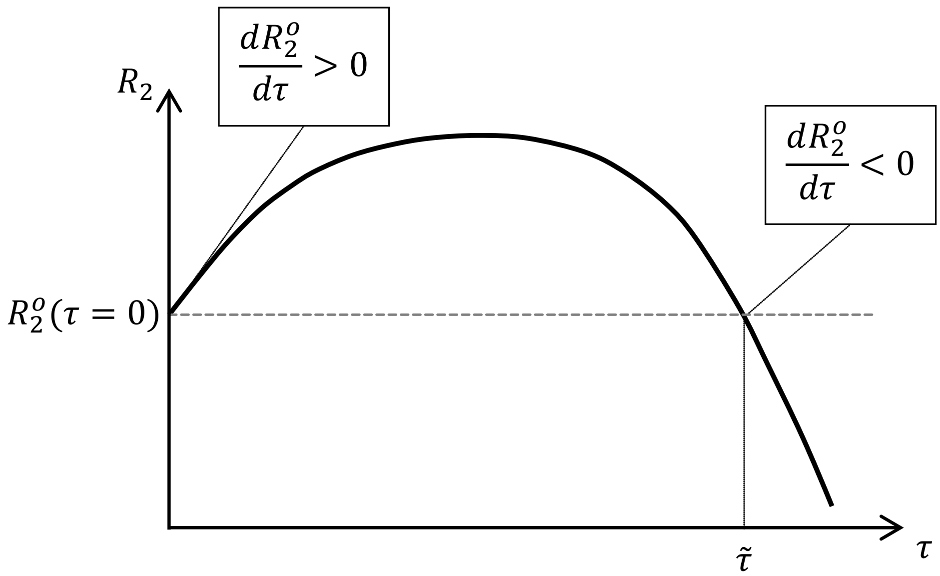

Figure 6.3: Marginal versus discrete increase in the carbon tax

Using this first observation we show next by contradiction that we can infer the sign of the discrete tax effect from the sign of the marginal tax effect, i.e. given any initial tax rate we must have a (reversal of the) green paradox for a marginal increase as well as for a discrete increase in the carbon tax. If this did not hold true, there could be a functional relationship between the equilibrium second period resource supply and the carbon tax as illustrated in figure 6.3. For a zero carbon tax initially, a marginal increase in the tax rate then may lead to a reversal of the green paradox as the slope of the curve, represented by the comparative statics in (6.8), is positive. In contrast, if we consider a sufficiently large discrete increase in the tax rate $\tau > \tilde{\tau}$, the green paradox will arise. However, this implies that there must be at least one tax rate $\tilde{\tau}$ in between for which $R_2(\tau = 0) = R_2(\tilde{\tau})$, i.e. for which the sheikh would not adjust the supply policy at all, given that the numerator is continuous in second period resource supply. In particular, for such a change from a reversal of the green paradox to a green paradox outcome there must be at least one neutral tax rate for which the marginal tax effect is negative so that second period resource supply falls for any further increase in the resource tax τ. But we already know that differing signs of the marginal tax effect for the same extraction policy are excluded as long as the influence of the resource tax on the numerator in (6.8) runs via the resource supply path only. Thus, by contradiction, we can conclude that the sign of the marginal tax effect must prevail for any discrete tax policy change. Moreover, since the same line of reasoning applies to any initial tax rate and extraction policy, second period resource supply must be monotonous in the tax rate. For a unit carbon tax, this line of reasoning holds true analogously.

First, by the monotonicity of the marginal tax effect, we may interpret the comparative statics results for an initially time constant value added resource taxation in both periods, i.e. $\tau_1 = \tau_2 > 0$, or the case where there is no resource taxation at all in the first period and a carbon tax is introduced in the second period. Second, as already suggested by the ambiguity of the comparative statics in (6.8) (and (6.12)), taxing carbon, or the resource, might even be completely neutral with respect to the extraction path so that the (discrete) introduction of such a climate policy does not alter the extraction path at all. In fact, due to the monotonicity we know that this will be the case if both elements in the numerator of the comparative statics are counteracting, i.e. the resource income component is positive, and exactly offsetting each other. This neutrality result is in contrast to the resource economics literature. In standard settings with costless resource extraction, only a time constant value added resource tax rate, or more generally, a tax policy with a constant tax burden on resource rents in present value terms, does not create an incentive to reallocate resources between both periods for a competitive resource sector as well as for a resource monopolist (see, for example, Dasgupta and Heal 1979). The neutrality of a rising value added carbon tax over time is due to the sheikh pursuing the asset motive and due the capital assets endogenously adjusting to the redistribution of resource rents by the carbon tax. Note also that the pattern of such a neutral tax policy scheme crucially depends on our assumption of symmetric consumption preferences, which ensures that the increasingly large transfer of resource rents from country E to country I for a rising carbon tax does not influence aggregate capital accumulation.

Finally, the monotonicity result allows us to show that the effect of the carbon tax does not depend on the distribution of the capital endowments K_1 between both countries. To this end, we can rely on a very similar reasoning as for the monotonicity of second period resource supply. The asset endowments distribution, i.e. s_{0E}, does not have any direct influence on the numerator of (6.8) apart from its influence on the extraction path, just as the resource tax. Redistributing capital endowments to country E (i.e. without increasing K_1) is purely distributive and , therfore, does not alter neither aggregate capital accumulation nor the relationship between resource supply and capital accumulation in the symmetric country case. However, since the households save a constant share of their first period income y_{1E} for a given interest rate i_2 by (4.13), it disproportionally increases the asset holdings of country E in the first period compared to the second period and , therfore, strengthens the first period's over the second period's asset motive. As we already pointed out throughout the discussion of the asset motive in section 5.2.2.2, this induces the sheikh to choose a less conservative extraction policy for any tax rate than before the asset endowment redistribution if the sheikh only pursues the asset motive. For the omniscient sheikh, the extraction incentive is generally more ambiguous as we know from section 5.2.2.3.

Nevertheless, we may restore the initial supply path by changing the tax rate. But since the tax rate as well as the asset endowment distribution are completely neutral with respect to the capital market equilibrium and , therfore, do not have any direct (explicit) influence on the numerator of the comparative statics (6.8), the sign of the numerator – and, given the unambiguously positive sign of the denominator, also the sign of the overall comparative statics – cannot differ for the same extraction path irrespective of the redistribution of the capital endowment. From the monotonicity of second period resource supply with respect to the future carbon tax rate then follows that the arising or the reversal of the green paradox does not depend on the distribution of capital endowments between the resource exporting country and the resource-importing countries for symmetric preferences.

6.4.1.6 Graphical Illustration

We verify our findings graphically by use of the exemplary numerical simulation of the model which we already employed in section 5.2.2.4. We consider here discrete changes in the second period carbon tax, which nevertheless can be interpreted as a verification of our analytical predictions due to the monotonicity of the tax effect.

Figure 6.4 shows the effect of different carbon tax rates on Hotelling condition (5.4) for the naive sheikh. The future value of present period resource supply does not change with the carbon tax due to the neutrality of the resource rent redistribution with respect to the capital market equilibrium for symmetric preferences as predicted. In contrast, the future marginal resource revenue MR_2^n is reduced by the carbon tax rate, which is reflected by the downward shift of the respective curve in the figure and gives rise to the green paradox outcome in this case.

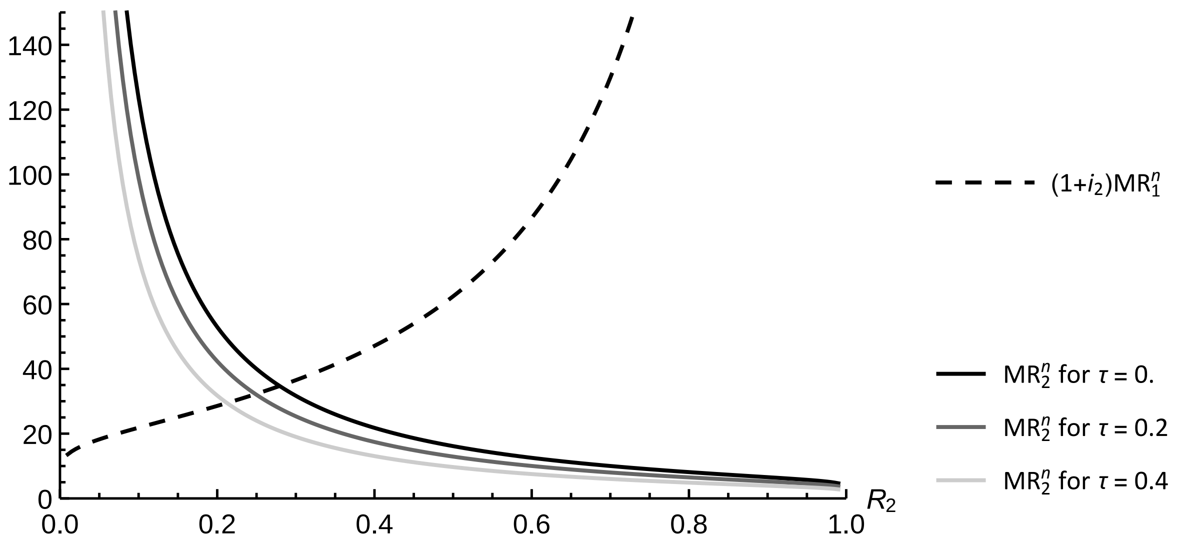

Figure 6.4: The effect of a rising carbon tax if the sheikh is completely naive; assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, total factor productivity $A = 300$

Figure 6.5 illustrates the effect of the same carbon tax rates for the omniscient sheikh. In contrast to the naive monopolist, the green paradox is obviously reversed for the same exemplary parameter specification in this case. The reason is that the carbon tax raises the future marginal value of the resource as the MR_2^o-curve shifts upwards upon an increase in the carbon tax while the first period marginal resource value curve is again not affected for the reasons laid out before.

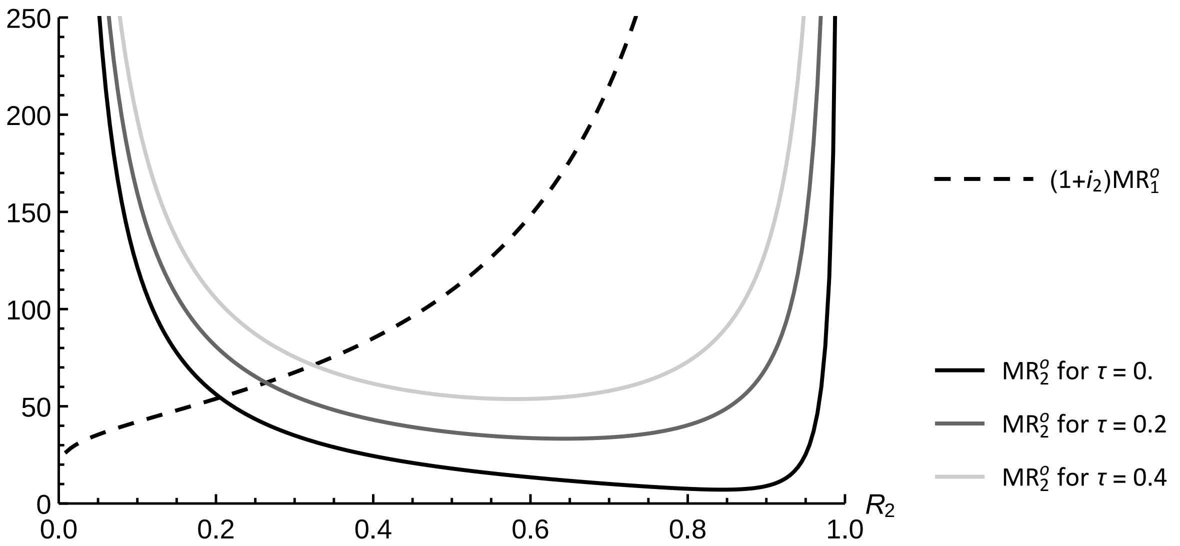

Figure 6.5: Reversal of the green paradox for the omniscient sheikh; assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, total factor productivity $A = 300$

In figure 6.6, we follow our comparative statics analysis and further disentangle the influence of the carbon tax on the resource and the capital income component of the overall marginal resource value MR_2^o. This demonstrates on the one hand that the increase in the overall marginal resource value in figure 6.5 is largely driven by the considerable upward shift in the capital income component. Since the carbon tax is completely neutral with respect to the capital market equilibrium and , therfore, also with respect to the positive relationship between future resource supply and the interest rate, this upward shift must be entirely due to the increase in the asset holdings of country E, which are depicted in figure 6.2. On the other hand, the decomposition of the overall marginal resource value MR_2^o also reveals that the exemplary numerical simulation does not correspond to the special case of a negative resource income component. In fact, the resource income component of MR_2^o is low but positive for the equilibrium extraction paths starting at $\tau = 0$, which demonstrates that the reversal of the green paradox is not restricted to the special case.

The parameter assumptions of the exemplary simulation imply $\frac{dK_2}{dR_2} < 0$ by condition (4.29). In this case, we pointed out in section 6.4.1.3 that a reversal of the green

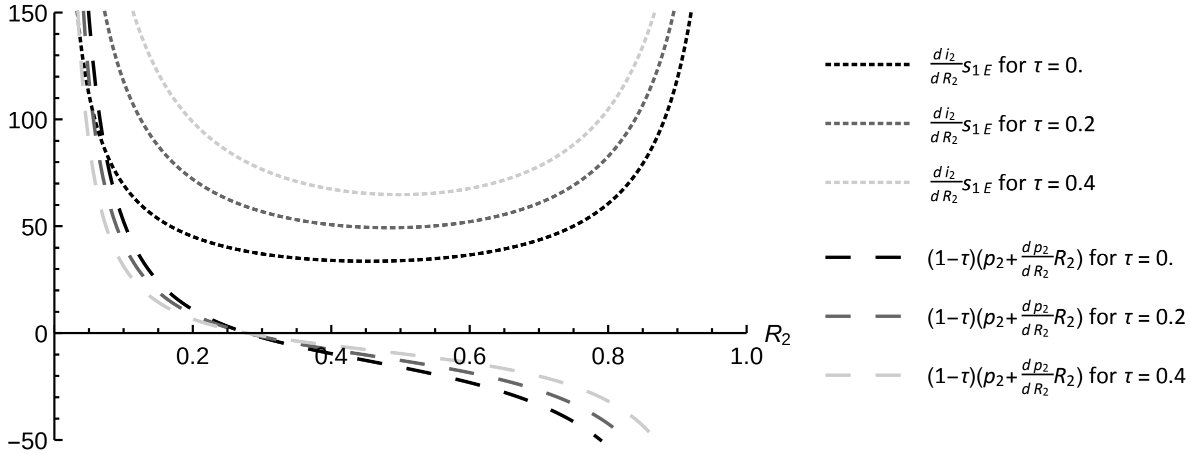

Figure 6.6: The effect of the carbon tax on the resource income and the capital income component of MR_2^o;
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, total factor productivity $A = 300$

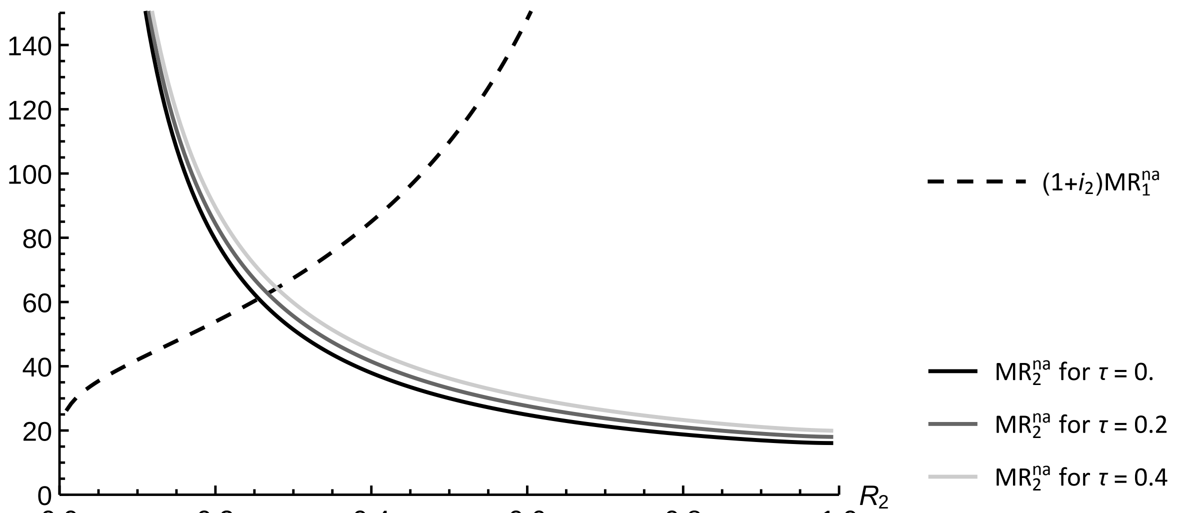

Figure 6.7: Reversal of the green paradox if the sheikh only pursues the asset motive;
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, total factor productivity $A = 300$

paradox is more likely for the omniscient sheikh than for the sheikh just pursuing the asset motive. The reason is that the additional feedback effects from the endogeneity of the capital stock then both work towards the reversal of the green paradox. However, we also demonstrated that for $\sigma < 1$ the carbon tax may induce even the more naive sheikh who just pursues the partial asset motive to postpone extraction. This is confirmed in figure 6.7. The accompanying decomposition of the effect of the carbon tax on the resource income and the capital income component in this case is shown by figure 6.8.

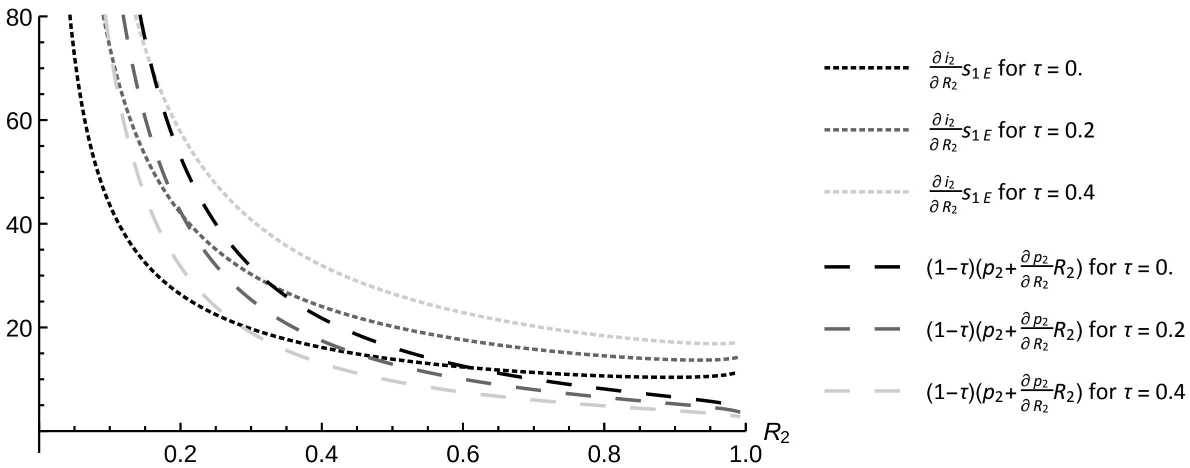

Figure 6.8: The effect of the carbon tax on the resource income and the capital income component of MR_2^{na};
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, total factor productivity $A = 300$

6.4.2 When Is the Green Paradox Reversed Under Imperfect Competition? Numerical Sensitivity Analysis

We have observed that a reversal of the green paradox under imperfect competition and symmetric consumption preferences is, in principle, possible only if the resource monopolist pursues the asset motive and, at least apart from the special case of section 6.4.1.4, if the strengthening of the future asset motive by the adjustment in the future asset holdings of the resource-rich country, which is induced by the redistributive effect of the carbon tax, is sufficiently strong. Moreover, we have found so far that the reversal does not depend neither on the carbon tax policy (i.e. the tax rate), nor the distribution of capital endowments, nor the initial extraction path of the sheikh.

To assess whether the reversal of the green paradox, which we observed before only for an exemplary numerical specification, is a rather specific or a more general outcome, we resort to a numerical sensitivity analysis. We thereby focus on the influence of changes in the production structure of the resource importing economies represented by the elasticity of substitution σ and the productivity (or share) parameters of the resource λ and capital γ in production. The crucial role of the elasticity of substitution has already been identified before when discussing the reversal condition (6.9) but will be scrutinized throughout the discussion of the sensitivity analysis. We also consider variations in the resource and capital endowments of the world economy as well as in the time preferences of households. However, given the fundamental importance of the production structure, we discuss their role also along the variation in the elasticity of substitution and the productivity parameters of fossil resources and capital.

The central result of the numerical sensitivity analysis is represented in figure 6.9, which illustrates for variations in the production structure of the resource importing economy the parameter space for which the green paradox arises and for which it is reversed. A change in the productivity parameter of fossil resources thereby is directly compensated by an accompanying change in the productivity parameter of capital since in the numerical simulations we assume these parameters to sum up to 0.5. This is motivated by the fact that the productivity parameters in the Cobb-Douglas case $\sigma = 1$ represent the (constant) share of the respective production factor's remuneration in total output.[13] The blue line separates the parameter constellations for which future carbon taxation leads to a green paradox from the constellations for which the green paradox is reversed, and , therfore, represents the threshold for which carbon taxation is exactly neutral in case of an omniscient sheikh. Additionally, since resource demand is obviously also strongly dependent on the production structure in the resource importing countries and since we already know that the resource stock may not be binding for a falling elasticity of substitution (see also condition (6.11) and the corresponding discussion), the figure explicitly indicates for

[13] Recall that we denote factor f's share of remuneration in total output as θ_{tf}. The real world labour share, i.e. the share of workers' compensation over gross domestic product, amounts to at least 50% (see, for example, OECD 2015).

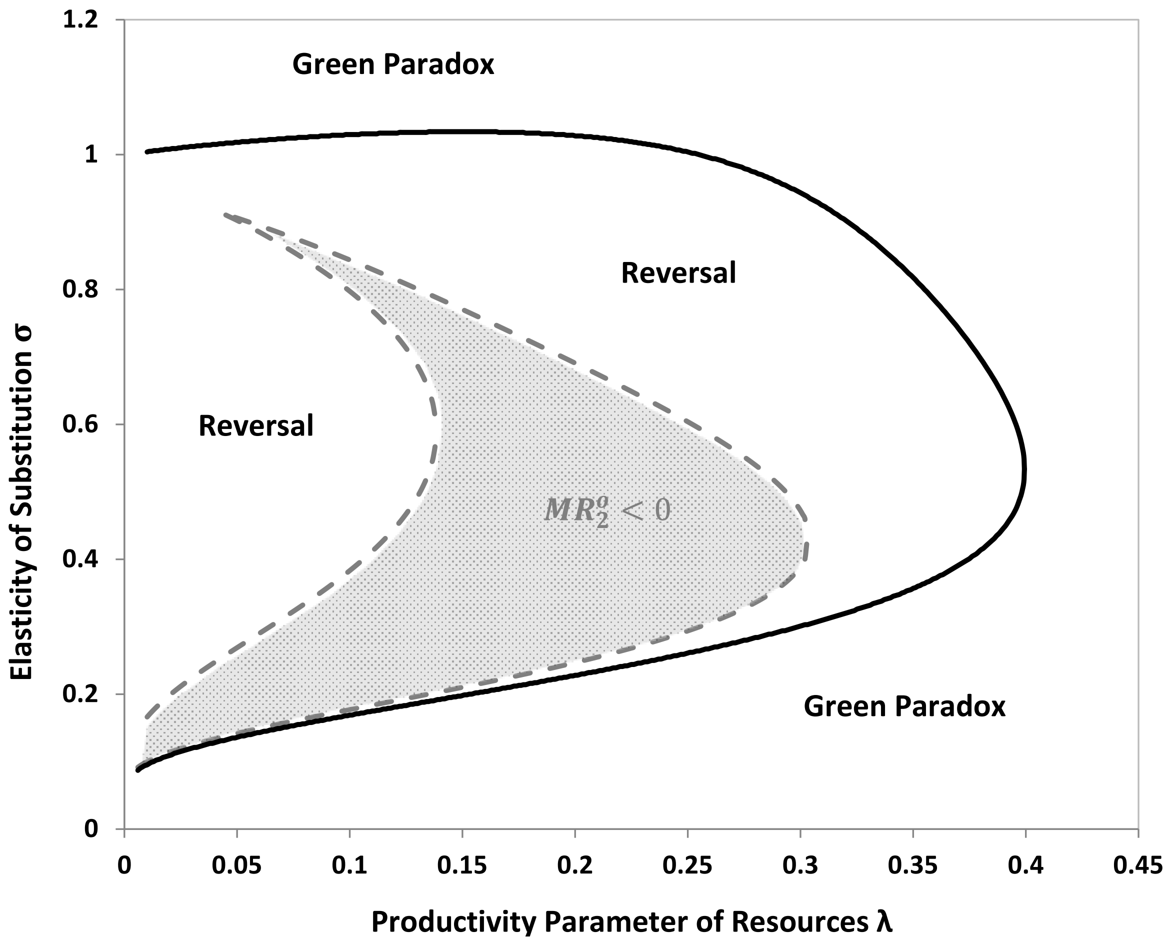

Figure 6.9: Sensitivity analysis with respect to the production structure for the omniscient sheikh's supply reaction to the introduction of a carbon tax of $\tau = 0.1$;
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\gamma = 0.5 - \lambda$, $A = 300$, $\beta_E = \beta_I = 0.3$, $\eta = 2$

which parameter settings the marginal resource value MR_2^o to the omniscient sheikh would be negative if we forced the sheikh to exhaust the given stock completely.

Overall, the figure allows for at least two conclusions. First, the green paradox seems to be more likely the higher the elasticity of substitution and the higher the productivity parameter of oil is compared to that of capital. The former observation is in line with our results from the discussion of reversal condition (6.9). Second, the figure demonstrates that the reversal of the green paradox seems to be a rather general outcome. In fact, if we considered our stylized but still more or less conventional framework as a satisfactory representation of the real oil and capital markets, the reversal of the green paradox could be expected as a more or less robust outcome of an announced future carbon tax increase. The reason is that the elasticity of substitution is typically seen below unity while the productivity parameter of resources λ – approximately corresponding to the income share of fossil resources, or energy, for an elasticity of substitution approaching unity – tends to be below 10%. For example, according to eia (2016) the share of energy expenditures in the gross domestic product (GDP) exceeded 10% only in the 1970s and early 1980s whereas it was constantly below 10% from 2000 to 2013 in the U.S.

6.4.2.1 Structure of the Production Technology I: The Role of the Elasticity of Substitution

To understand the role of the elasticity of substitution in more detail, note at first that the influence of the elasticity of substitution on the production technology is twofold in general. On the one hand, the elasticity of substitution σ determines the substitutability of capital and fossil resources in final goods' production ("substitutability effect"), and , therfore, in our context in particular the mutual dependency of resource and capital demand and the cross market effect of resource supply on capital demand. On the other hand, the elasticity of substitution fundamentally forms the overall production possibilities in the economy given the capital and resource endowments ("scale effect"). The higher the elasticity of substitution the more productively the different production factors can be combined, even if they are in very uneven supply. The prominent role of the elasticity of substitution for the reversal of the green paradox, however, is in particular related to the substitutability effect as the following line of reasoning may show.

If the sheikh only pursues the asset motive and does not internalize the feedback effects from the endogeneity of capital accumulation, or if, although somewhat inconsistent in our framework with endogenous savings of the household in country E, the future capital stock K_2 does not depend on the extraction path, reversal condition (6.9) is reduced to

$$\sigma < 1 - \theta_{2R}\left(1 + i_2 \frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}}\right)$$

The right side, albeit dependent on the elasticity of substitution, is necessarily bounded from above and lower unity by (4.13) and $\theta_{2R} < 1$ by definition. Thus, a reversal of the green paradox eventually must become impossible for a rising elasticity of substitution σ and is excluded for $\sigma \geq 1$ in this case.[14] The reason is that irrespective of the share of the resource remuneration in total output θ_{2R}, the (partial) own-price elasticity of resource demand from (5.6) and the (partial) cross price elasticity of capital demand with respect to the resource price

$$\epsilon_{R_2,p_2} = -\frac{1}{\frac{\partial p_2}{\partial R_2}\frac{R_2}{p_2}} = \frac{\sigma}{1-\theta_{2R}} \qquad \text{and} \qquad \epsilon_{K_2,p_2} = \frac{1}{\frac{\partial i_2}{\partial R_2}\frac{R_2}{i_2}} = \frac{\sigma}{\theta_{2R}}$$

ceteris paribus, i.e. for a constant resource extraction path and a constant capital stock, increase in σ, and necessarily exceed unity for $\sigma \geq 1$ so that resource and capital demand become price-elastic with respect to the resource price for any resource supply path.[15] This implies on the hand that the marginal resource revenue MR^n_t (see (5.5)) and , therfore, also the tax induced loss in future resource value increases. On the other hand, as reflected by the increase in the cross price elasticity of capital demand, the complementarity (cross market) effect of resource supply on the interest rate falls, which ceteris paribus attenuates the asset motive and thereby the influence of the carbon tax induced increase in savings. A rise in the elasticity of substitution , therfore, gives more weight to the resource rent loss and less weight to the stronger asset motive. Overall, this renders a fall in the marginal resource value MR^{na}_2 (and MR^o_2) and consequently a green paradox type acceleration of extraction upon a carbon tax increase more likely. For $\sigma \geq 1$, the (partial) cross price elasticity of capital

[14] Note that this restriction arises whenever the sheikh is unable to internalize the endogeneity of capital accumulation due to a limited level of information of the economic structure and the cross market effects of her supply decision. This again illustrates the crucial role of information for the resource owner's behavior in general equilibrium as already pointed out before.

[15] Since for this line of reasoning we "hold" the resource extraction path and the capital stock constant here, this reflects the "substitutability effect" of the elasticity of substitution σ. With a higher elasticity of substitution production factors can be substituted more easily by each other. Thus, an increase in the resource price induces a larger change in the optimal relative factor input in final goods production the higher the elasticity of substitution, and thereby a larger change in resource and capital demand. Graphically, the substitutability effect is reflected by the curvature of the production isoquant, which decreases in the elasticity of substitution.

demand ϵ_{K_2,p_2} is so high – and , therfore, the elasticity of the capital return with respect to resource supply so low – that the tax induced loss in the marginal resource revenue can never be overcompensated by the strengthening of the asset motive from the savings reaction. Hence, a reversal of the green paradox is excluded, at least as long as we abstract from the endogeneity of capital accumulation.

For the omniscient sheikh and the extended threshold in reversal condition (6.9), the problem is that the elasticity of substitution σ also has some influence on the relationship between capital accumulation and the resource supply path ($\frac{dK_2}{dR_2}$). In fact, we know from (4.29) that a sufficient condition for $\frac{dK_2}{dR_2} < 0$ is $\sigma \geq \frac{1}{\eta}$. By increasing σ for a given intertemporal elasticity of substitution $\frac{1}{\eta}$ we , therfore, are generally more likely to have $\frac{dK_2}{dR_2} < 0$, which, in principle, strengthens the reversal of the green paradox as pointed out before (see section 6.4.1.3). But this implies that not only the left side but also the right side of the reversal condition (6.9) may increase in σ. In order to resolve this ambiguity, we consider the reversal threshold in (6.9) in the limiting cases $\sigma \to \infty$ and $\sigma \to 0$ next. We thereby also analytically proof the observation from figure 6.9 that the green paradox becomes more or less inevitable for a sufficiently high elasticity of substitution even for the omniscient sheikh.

The limiting case $\sigma \to \infty$

For $\sigma \to \infty$, the CES production technology (4.4) becomes linear[16] and we have

$$\lim_{\sigma\to\infty} \frac{\partial i_2}{\partial R_2} = \lim_{\sigma\to\infty} \frac{\partial F_{2K}}{\partial R_2} = 0 \qquad \text{and} \qquad \lim_{\sigma\to\infty} \frac{\partial i_2}{\partial K_2} = \lim_{\sigma\to\infty} \frac{\partial F_{2K}}{\partial K_2} = 0$$

This implies that resource supply no longer influences capital demand, neither directly via the complementarity of production factors nor indirectly via its influence on savings. However, there still is an influence of the resource supply path on the capital market equilibrium via capital supply because, as already argued before throughout the discussion of (4.28), a shift in the resource supply path ceteris paribus transfers aggregate income from one period to the other, to which households adapt their savings, i.e. aggregate capital supply. Moreover, since in the limiting case $\sigma \to \infty$ the extraction profile no longer has a direct complementarity driven influence on the interest rate and , therfore, cannot induce a substitution effect anymore, the endogeneity of

[16] We then have $F(R_t, K_t, L) = \lambda R_t + \gamma K_t + (1 - \lambda - \gamma)L$

the future capital stock according to (4.28) entirely arises from this income transfer from the first to second period. We , therfore, have[17]

$$\lim_{\sigma\to\infty}\frac{dK_2}{dR_2}=\lim_{\sigma\to\infty}\frac{\frac{\partial s_{1E}}{\partial\pi^{\tau}_{2E}}p_2-\frac{\partial s_{1E}}{\partial y_{1E}}p_1+F_{2KR}SE}{1-F_{2KK}SE}=\frac{\partial s_{1E}}{\partial\pi^{\tau}_{2E}}p_2-\frac{\partial s_{1E}}{\partial y_{1E}}p_1$$

Since $p_t=F_{tR}=\lambda$ and $i_t=F_{tK}=\gamma$ for the linear production technology and since the savings reactions are just functions of the interest rate i_2 and the consumption preference parameters by (4.13), we have $|\frac{dK_2}{dR_2}|<1$.[18] Thus, the right side of reversal condition (6.9) is bounded from above for $\sigma\to\infty$, and the condition must be violated for σ sufficiently increasing above unity.

The basic intuition from the case without endogenous capital accumulation (or without explicit internalization of the endogeneity of capital accumulation into the resource supply decision) , therfore, still applies. The switch from regimes for which a reversal of the green paradox is possible to regimes where it is not for a rising elasticity of substitution σ is obviously influenced by the internalization of the endogeneity of capital accumulation since a reversal of the green paradox may even be possible for $\sigma\geq 1$ due to the reasons laid out above. But in the end the change in the production structure, and in particular in the substitutability between production factors, which is brought about by the rising elasticity of substitution and is reflected in the change of the price elasticities of resource demand and of the cross price elasticity of capital demand, excludes a reversal of the green paradox for a sufficiently high elasticity of substitution σ.

Finally, such an increase in the elasticity of substitution may also be interpreted as a form of technological change, which is often seen to be necessary to overcome the dependency of economic growth and development on fossil resources and , therfore, to make climate change mitigation compatible with economic growth in the long term. From this perspective, we arrive at the somewhat surprising conclusion that this form

[17] Regarding the denominator of (4.28) note that $F_{2KK}=0$ for a linear production technology. Moreover, from (4.18) we know that $SE=\frac{\partial s_{1E}}{\partial y_{1E}}\frac{c_{1E}+c_{1I}}{\eta(1+i_2)}$ which is bounded for $\sigma\to\infty$ due to the limited capital and resource endowments, $c_{1E}+c_{1I}=F_1+K_1-K_2=\lambda R_1+(1+\gamma)K_1+(1-\lambda-\gamma)L-K_2$ by the budget constraints (4.9) and (4.10) and $i_2=F_{2K}=\gamma$. Together, this implies that $\lim_{\sigma\to\infty}F_{2KK}SE=0$.

[18] In fact, since $\lambda<1$, we get by (4.13)

$$\lim_{\sigma\to\infty}\frac{dK_2}{dR_2}=-\lambda\frac{1+[\beta_E(1+i_2)]^{\frac{1}{\eta}}}{1+i_2+[\beta_E(1+i_2)]^{\frac{1}{\eta}}}>-1$$

of (exogenous) technological change may deteriorate the effectiveness of future carbon taxation by raising the possibility that a future carbon tax leads to a green paradox outcome if the resource monopolist is not naive and pursues the asset motive.

The limiting case $\sigma \to \mathbf{0}$

Considering the opposite limiting case $\sigma \to 0$, the numerical sensitivity analysis represented in figure 6.9 suggests that for a sufficiently low elasticity of substitution the loss in resource rents is dominating the strengthening of the asset motive by higher asset holdings so that the green paradox arises again. However, we will demonstrate in the following that this does not necessarily hold true in any case.

For $\sigma \to 0$ the CES technology approaches the Leontief production function

$$F(R_t, K_t, L) = \min\{R_t, K_t, L\}$$

This implies first that the complementarity between the production factors is completely resolved, just as in the opposite limiting case of perfect substitutability. Second, the resource is only valuable to the Leontieff economy so that the resource exporting country earns positive resource rents if it is the limiting factor in the sense that $R_t < K_t$ and $R_t < L$. Thus, to analyze the effect of the carbon tax in the Leontieff world we have to distinguish two cases.

If the resource is the limiting factor in both periods as in the numerical simulations represented in figure 6.9, its marginal productivity, and thereby the marginal resource revenue, for $\sigma = 0$ is given by

$$\lim_{\sigma \to 0} F_{tR} = 1 \qquad\qquad \lim_{\sigma \to 0} F_{tK} = 0$$

whereas the marginal productivity of capital vanishes. This implies that in the reversal condition (6.9) the threshold on the right side is zero for $\sigma = 0$ so that the inequality condition can never hold and a green paradox necessarily arises.[19] More intuitively, we already know that the marginal resource revenue is falling with a decreasing elasticity of substitution and is likely to become negative at some point as resource demand becomes price-inelastic (see also section 6.4.1.2). As long as the

[19] Note that $\lim_{\sigma \to 0} \theta_{2R} = \lim_{\sigma \to 0} F_{2R} = 1$ whereas $\lim_{\sigma \to 0} F_{2K} = \lim_{\sigma \to 0} i_2 = \lim_{\sigma \to 0} \theta_{2K} = 0$. Moreover, since $\lim_{\sigma \to 0} F_{2KR} = \lim_{\sigma \to 0} F_{KK} = 0$, we have $\lim_{\sigma \to 0} \frac{dK_2}{dR_2} = \frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} - \frac{\partial s_{1E}}{\partial y_{1E}} = \frac{-1-\beta_E^{\frac{1}{\eta}}}{1+\beta_E^{\frac{1}{\eta}}} = -1$ by (4.28) and (4.13).

asset motive is sufficiently large so that the overall marginal resource value is still positive ($MR_2^o > 0$), we are in the special case of section 6.4.1.4 for which the green paradox is necessarily reversed. However, if fossil resources are the limiting factor for further decreasing $\sigma \to 0$, the marginal resource revenue approaches the positive marginal resource productivity, since the negative own-price effect eventually disappears. At the same time, since capital is abundant and without value to the Leontieff economy and since there is no complementarity between production factors anymore, all the additional cross market effects of resource supply and , therfore, the asset motive disappear. Thus, while the marginal resource value may be negative for some $\sigma < 1$, we know that it is strictly positive at least in the limiting case $\sigma = 0$. But this implies that levying or raising a carbon tax necessarily reduces the (positive) value of resource supply which unambiguously creates an incentive to accelerate extraction and , therfore, unambiguously gives rise to a green paradox in the Leontieff economy.[20]

In contrast, if the resource is not the limiting factor in the Leontieff case because $K_t > R_t$ and/or $L > R_t$, the marginal resource productivity, and thereby also the marginal resource revenue, are zero for $\sigma = 0$.[21] The right side in reversal condition (6.9) approaches unity,[22] but the intertemporal supply decision of the sheikh and , therfore, the condition overall is no longer meaningful in this case. Intuitively, lowering σ reduces the overall production possibilities of the economy in both periods for the given production factor endowments ("scale effect" of the elasticity of substitution), i.e. by more and more approaching the Leontieff world total output over both periods decreases. If fossil resources are not the limiting factor for $\sigma = 0$ and the monopolist is forced to completely exhaust the resource stock in any case, resource consumption relative to output will be increasing and at the same time by the diminishing returns the marginal productivity of resources will be falling. Thus, resource demand becomes less and less price-elastic so that the negative own-price effect becomes stronger and stronger and the marginal resource revenue eventually gets negative (see also the definition of the partial price elasticity ϵ_{R_2,p_2} (5.6)). As long as the additional capital income component from the asset motive ensures that the overall marginal resource value is positive, the green paradox must be reversed in

[20] Note that without a carbon tax, since the interest rate is zero, the resource stock is completely evenly allocated to both periods in the Leontieff economy.

[21] In fact, the marginal resource revenue becomes negative for a positive but falling elasticity of substitution and approaches zero from below.

[22] The reason is that $\lim_{\sigma \to 0} F_{tR} = 0$, $\lim_{\sigma \to 0} \theta_{tR} = 0$, $\lim_{\sigma \to 0} F_{tKR} = 0$, and $\lim_{\sigma \to 0} \frac{dK_2}{dR_2} = 0$ which, in principle, indicates that a reversal of the green paradox arises.

this case, since a negative resource income component is a sufficient condition for the reversal of the green paradox as pointed out in section 6.4.1.2. But since the cross market influence of resource supply is also more and more attenuated with a falling elasticity of substitution, the overall marginal resource value eventually becomes negative so that the resource is effectively no longer scarce to the sheikh. In the end, resource supply entirely looses its influence on final goods production and the capital market because there is actually to much resource available from the given stock for the limited production possibilities of the Leontieff economy. Without a dynamic supply decision, however, there also is no basis for an intertemporal supply reaction to carbon taxation.[23]

6.4.2.2 Structure of the Production Technology II: The Role of the Productivity Parameters

The sensitivity analysis in figure 6.9 suggests that the green paradox at some point necessarily arises when sufficiently increasing the productivity parameter of fossil resources λ at the expense of the productivity parameter of capital γ. This can also be observed from reversal condition (6.9) for the Cobb-Douglas case $\sigma = 1$, in which the factor remuneration shares θ_{tR} and θ_{tK} directly correspond to the productivity parameters. In the limiting case $\lambda = \theta_{2R} = 0.5$, the right side is necessarily lower unity because capital is no longer an input factor to production so that $\theta_{2K} = i_2 = 0$. Since the asset motive disappears completely, the reversal of the green paradox is excluded in this case. Obviously, in the opposite limiting case $\lambda = 0$, fossil resources are no longer required for production and the reversal condition is no longer meaningful as there is no demand for resources from country I.

In between these limiting cases, the change in the production structure induced by an increase in λ in general has an influence on the role of resources versus the role of capital in final goods production, but also an influence on the complementarity relationship between these production factors. By the standard properties of the CES technology, the former crucially depends on the ratio of resource to capital consumption. We generally assume throughout that there is more capital than resources

[23] If resources are the limiting factor in the Leontieff world, the resource income component may never become negative with a falling elasticity of substitution. More importantly, even though the capital income component also disappears as the complementarity is resolved in any case, the resource is definitely scarce to the sheikh in the limiting case $\sigma = 0$ so that the resource income component is positive and the green paradox necessarily arises.

available to the economy, which is more or less ensured by the endowment assumptions ($\bar{R} = 1$ versus $K_1 = 200$) in the numerical simulations even though the second period capital stock is endogenous. In this case, i.e. if $R_t < K_t$, output F_t is decreasing with the structural change represented by an increase in λ for all σ.[24] This illustrates the shift in the weighting, or the role, of resources and capital brought about by such a structural change in the production technology. Intuitively, since we assume resources to be less available than capital, increasing the weight of resources in production reduces total output. For the Cobb-Douglas case $\sigma = 1$, this is even more directly reflected by the accompanying change in the factor remuneration shares.

Moreover, the reduction in output implies that the average productivity of resources and capital is ceteris paribus falling, too. By the standard properties of the CES technology we then know that the marginal productivity of capital unambiguously decreases in λ, whereas the marginal productivity of resources non-monotonously depends on λ (for $\gamma = 0.5 - \lambda$). In fact, for $R_t < K_t$ the marginal productivity of fossil resources increases at first when starting from low levels of λ, but at some point the reduction in the average resource productivity may become dominating so that further increases in λ reduce the marginal resource productivity again.[25] At the same time, such a shift in the production structure has a non-monotonous (inverse U-shaped) influence on the complementarity relationship between resources and capital as measured by the cross derivative F_{tKR}. When starting from a low λ where the fossil resource is only of little influence on production, the complementarity raises at first but at some point, which depends on the input ratio of resources to capital, it decreases in λ again as production then increasingly less relies on capital.[26]

[24] This can be observed by setting $\gamma = 0.5 - \lambda$ and rewriting production technology (4.4)

$$F_t = \left[\lambda\left(R_t^{\frac{\sigma-1}{\sigma}} - K_t^{\frac{\sigma-1}{\sigma}}\right) + 0.5\left(K_t^{\frac{\sigma-1}{\sigma}} + L^{\frac{\sigma-1}{\sigma}}\right)\right]^{\frac{\sigma}{\sigma-1}}$$

For $R_t < K_t$, the first term in curly brackets is positive for $\sigma < 1$ but negative for $\sigma > 1$.

[25] This generally depends on the elasticity of substitution and on the ratio of resource to capital consumption as by the standard properties of the CES technology and $\gamma = 0.5 - \lambda$

$$F_{tR} = \lambda\left(\frac{F_t}{R_t}\right)^{\frac{1}{\sigma}} = \lambda\left\{\lambda\left[1 - \left(\frac{K_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}}\right] + 0.5\left[\left(\frac{K_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}} + \left(\frac{L_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}}\right]\right\}^{\frac{1}{\sigma-1}}$$

[26] If the economy consumes exactly as much resources as capital to produce final goods, the complementarity is maximal for $\lambda = \gamma$. If $R_t < K_t$, complementarity peaks for some $\lambda < \gamma$ and vice versa.

Finally, by (5.6) we can also show that resource demand becomes more price-elastic with such an increase in λ.[27]

What do these observations imply for the reversal of the green paradox? We focus in the following on the implications which directly arise from the change in the production technology for the supply reaction of the sheikh given in the numerator of (6.8). In principle, of course, such a change in the production structure also affects the capital dynamics as captured by (4.28) and how the internalization of the capital dynamics influences the supply decision of the omniscient sheikh.[28] Still, the patterns displayed in figure 6.9 can already be understood from these fundamental structural changes in the production technology. This also suggests that the more indirect effects from the changes in the process of capital accumulation are secondary in the end.

First, consider the left end of figure 6.9 for λ close to zero. Fossil resources are rather unimportant to production in this case. This is reflected in a low marginal productivity but also in a low complementarity effect of resources on the marginal productivity of capital. However, since the price elasticity of resource demand positively depends on λ, resource demand is likely to be price-inelastic for low $\lambda \to 0$ and $\sigma < 1$ so that the resource income component is negative. Hence, the green paradox is necessarily reversed as long as the overall marginal resource value (MR_2^o) is still positive (see section 6.4.1.4). However, as we already know from the previous section, approaching a Leontieff world for very low $\sigma \to 0$ with the resource being the limiting factor ($R_t < K_t$ and $R_t < L_t$) as in our numerical simulations implies that the resource

[27] We have again by the standard properties of the CES technology and by setting $\gamma = 0.5 - \lambda$

$$\theta_{tR} = \lambda \left(\frac{F_t}{R_t}\right)^{\frac{1-\sigma}{\sigma}} = \frac{\lambda}{\lambda\left[1 - \left(\frac{K_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}}\right] + 0.5\left[\left(\frac{K_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}} + \left(\frac{L_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}}\right]}$$

Thus, by (5.6), the price elasticity of resource demand rises for any $\sigma > 0$ in λ since

$$\frac{\partial \theta_{tR}}{\partial \lambda} = \frac{0.5\left[\left(\frac{K_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}} + \left(\frac{L_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}}\right]}{\left\{\lambda\left[1 - \left(\frac{K_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}}\right] + 0.5\left[\left(\frac{K_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}} + \left(\frac{L_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}}\right]\right\}^2} > 0$$

[28] For example, an increase in the complementarity from an increasing λ tends to strengthen the induced substitution effect in the numerator of (4.28). But since at the same time the marginal productivity of resources is likely to rise, the production change from a shift in the resource extraction path, which is captured by the first terms in the numerator, is larger with an increasing λ and thereby counteracting the stronger substitution effect.

income component will be positive even for low λ while there is virtually no complementarity between production factors. Thus, in this case the green paradox arises even for low $\lambda \to 0$. For $\sigma \geq 1$, in contrast, resource demand is price-elastic throughout so that the resource income component is positive. Since the complementarity relationship between resources and capital is rather weak due to $\lambda \to 0$ but also due to the high substitutability for $\sigma > 1$, as argued in the previous section, the green paradox necessarily arises. Still, with the strengthening of the complementarity for higher λ a reversal may be possible.

Second, increasing λ when going from the left to the right in figure 6.9 in general brings about two counteracting effects, in particular since we assume a rather small resource stock $\bar{R} = 1$ suggesting that $R_2 < K_2$ is very likely. Increasing the role of fossil resources in production tends to rise the resource income component and thereby also the negative impact of carbon taxation from the sheikh's perspective due to the rise in the marginal resource productivity and in the price elasticity of resource demand. When starting at the left end of the figure from a low λ, this, however, is counteracted by an increase in the complementarity of resources and capital, which strengthens the asset motive and thereby works towards the reversal of the green paradox. The latter is also the reason why for some $\sigma > 1$ we get a reversal of the green paradox for increasing λ. However, since capital becomes less and less important and eventually is completely redundant in production, the strengthening of the complementarity relationship between capital and resources is attenuated and at some point even reversed as λ further increases and $\gamma \to 0$, as pointed out before. Hence, for sufficiently high λ we must get a green paradox outcome independent of the elasticity of substitution.

6.4.2.3 Variations in Factor Endowments and Time Preference

We now discuss variations in the resource stock and capital endowments of the world economy along the familiar variations in the elasticity of substitution and the productivity parameters. Figure 6.11 illustrates the effect of an increase in the resource endowment and the effect of a reduction in the capital endowments on the parameter spaces for which the green paradox arises or is reversed. Obviously, both variations shift the neutrality threshold upward so that even for $\sigma < 1$ and high λ as well as for low $\sigma \to 0$ there is no longer a green paradox outcome.

Both, increasing the resource stock $\bar{R}$ as well as reducing capital endowment K_1, tend to raise the relative factor input R_t/K_t in either period. Intuitively, this development alleviates the restriction on the overall production possibilities from the resource stock underground so that the scarcity rent represented by the marginal resource revenue and correspondingly the resource income component falls. This is obvious for increases in the resource stock while a reduction in the capital stock decreases the production possibilities via the complementarity of production factors. Moreover, for $\sigma < 1$, we know that resource demand can be price-inelastic (see e.g. (5.6)), and we can show that the price elasticity of resource demand is falling in the relative factor input R_t/K_t.[29] Thus, increasing the relative factor input ceteris paribus increases the parameter space for which marginal resource revenue and correspondingly the resource income component is negative for $\sigma < 1$. The reversal of the green paradox may become more likely as we may have the special case of section 6.4.1.4 more often. However, this is not necessarily the case as the overall marginal resource value may be negative more often, too. For the sake of illustrative clarity, we do not include the $MR_2^o < 0$-area(s) here. Finally, with an increase in the resource stock and a thereby rising resource consumption in either period, the fossil resource is less likely to be the limiting factor when approaching the Leontieff economy for $\sigma \to 0$. Hence, in contrast to our standard specification where the resource is scarce in the sense of the Leontieff production function, the marginal value of fossil resources may no longer be positive even in the limiting case $\sigma = 0$.

These observations explain why there is no longer a green paradox for very low σ in figure 6.10 for a higher relative factor input. Furthermore, to see why the green paradox is reversed even for higher λ (i.e. and lower γ) recall first that the price elasticity of resource demand is increasing in λ as we pointed out before in section 6.4.2.2. However, since the price elasticity of demand is lower with a higher relative factor input R_t/K_t for $\sigma < 1$, the marginal resource revenue ceteris paribus becomes positive only for higher λ. At the same time, we also argued above that as long as we have $R_t < K_t$ the complementarity as captured by the cross derivative F_{tKR} is concave in λ (if $\gamma = 0.5 - \lambda$) but peaks for a higher $\lambda \to \gamma$ the higher the relative factor input

[29] This can be observed from (5.6) and

$$\theta_{tR} = \frac{F_{tR}R_t}{F_t} = \frac{\lambda}{\lambda + \gamma\left(\frac{K_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}} + (1-\lambda-\gamma)\left(\frac{L_t}{R_t}\right)^{\frac{\sigma-1}{\sigma}}}$$

since the denominator increases with a rising resource consumption and a falling capital stock for $\sigma < 1$.

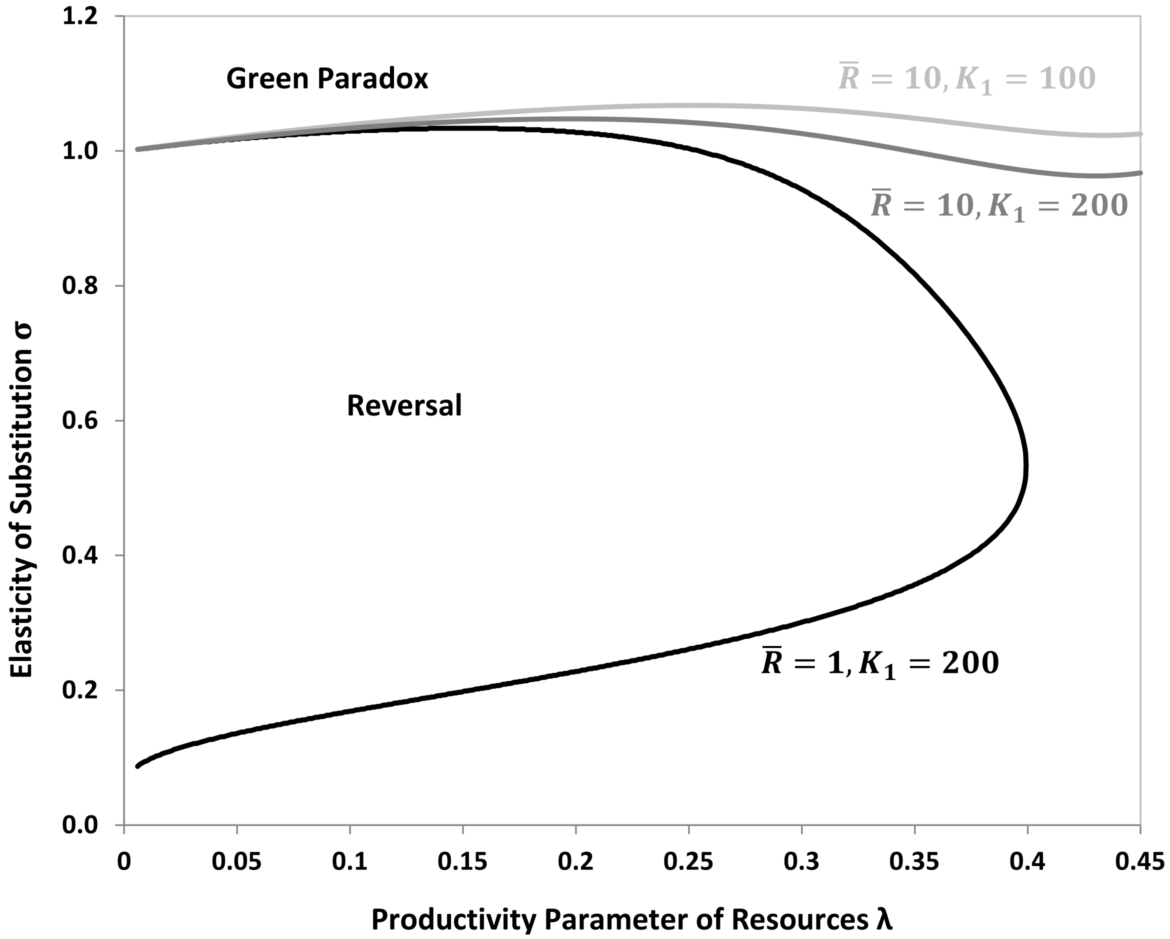

Figure 6.10: Sensitivity analysis for the omniscient sheikh's supply reaction with respect to a variation in resource and capital endowments; assumptions: $s_{0E} = 20$, $L = 1$, $\gamma = 0.5 - \lambda$, $A = 300$, $\beta_E = \beta_I = 0.3$, $\eta = 2$

$R_t/K_t \to 1$. As long as $R_t/K_t < 1$, which we more or less assume throughout for intuitive reasons, this implies that when increasing λ, i.e. the weight or role of fossil resources in production, from the left to the right in figure 6.10 the capital income component tends to increase and the resource income component tends to be negative up to a higher λ with a higher relative factor input R_t/K_t. Hence, a reversal of the green paradox is more likely up to a higher λ, too. For the limiting case $\lambda \to 0.5$ ($\gamma \to 0$), which is not captured in the figure, the green paradox, however, necessarily arises as pointed out before in section 6.4.2.2.

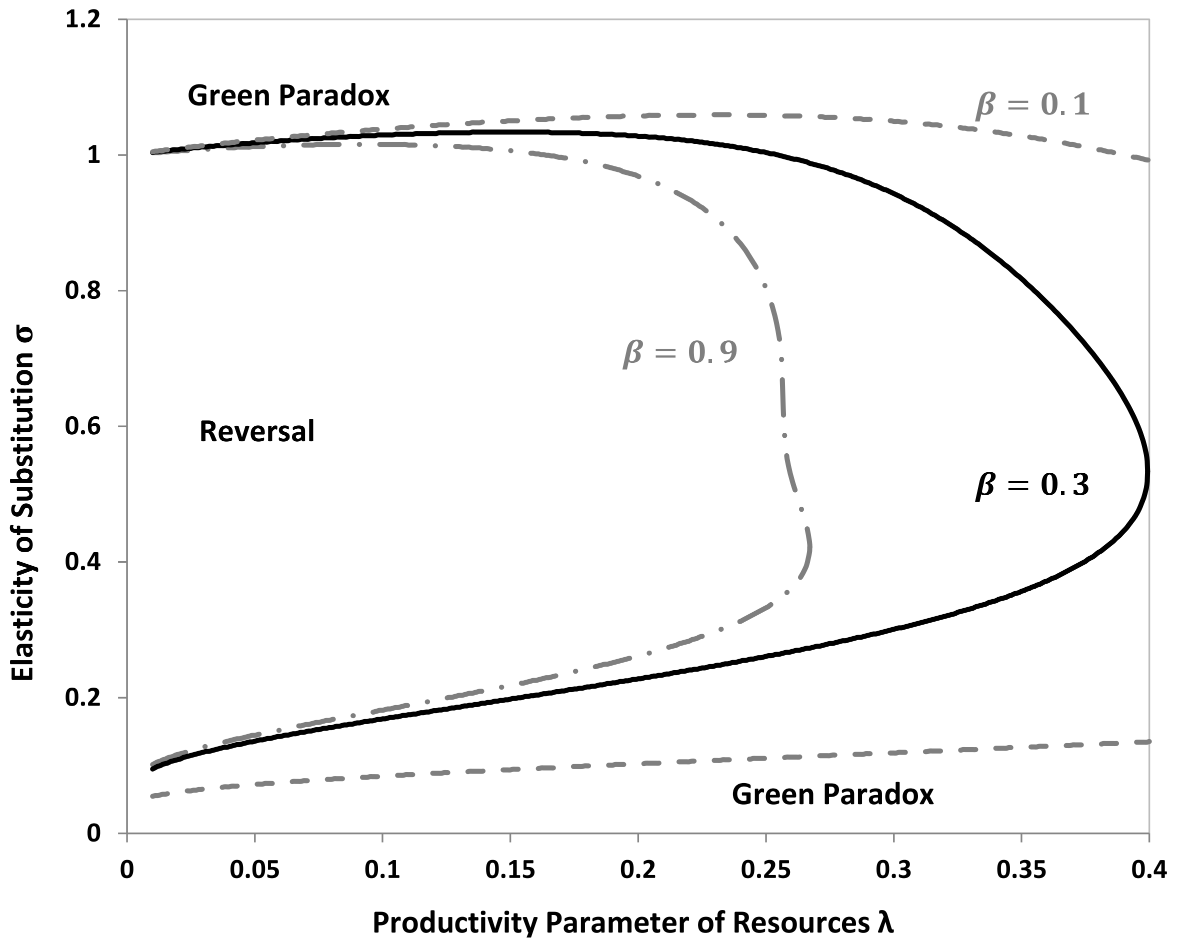

Figure 6.11: Sensitivity analysis for the omniscient sheikh's supply reaction with respect to the utility discount factor;
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\gamma = 0.5 - \lambda$, $A = 300$, $\eta = 2$

We next consider the influence of the time preferences of households on the arising or reversal of the green paradox. Figure 6.11 demonstrates that the reversal of the green paradox generally becomes less likely the higher the utility discount factor β_E ($= \beta_I$ in this setting), and therefore the lower the preference of households for current over future consumption. The reason is that with a higher discount factor, i.e. a lower rate of time preference, households less strongly react to changes in future income which can be observed from the savings reaction defined in (4.13). This implies that with a higher discount factor the introduction or rising of the future carbon tax and the accompanying ceteris paribus loss in future resource rents induces a lower increase in the asset holdings in country E so that the strengthening of the future asset motive via carbon taxation and thus the driver for the reversal of the green paradox is attenuated.

The savings behavior of households generally is also crucially dependent on the intertemporal elasticity of substitution $1/\eta$. This, however, in particular holds true for the savings reaction to an increase in the interest rate i_2. In general, by (4.14) the lower the intertemporal elasticity of substitution the more likely the substitution effect dominates the income effect induced by an increase in the interest rate i_2, as we already discussed in section 4.1.3.1.[30] Whether the green paradox is reversed or not due to the change in the future asset motive, however, does not primarily depend on the savings reaction to interest rate changes but on the strength of the savings reaction to changes in the second period income. But with respect to the latter the intertemporal elasticity of substitution is only of quantitative effect, similar to the discount factor β_E before, and especially does not change the sign of the savings reaction. In general, the higher the intertemporal elasticity of substitution the lower the savings reaction to future income changes tends to be, and therefore the less likely the green paradox is reversed. Our overall observation that the green paradox may be reversed due to the savings reaction and the related strengthening of the asset motive, however, does not require a restriction of the intertemporal elasticity of substitution to values below or above unity.

[30] From (4.14) we know that the substitution effect is always dominating for $\eta < 1$. For $\eta = 1$, income and substitution effect exactly cancel out. However, due to the positive second period income separate from savings the interest rate even in this case has a positive influence on savings.

6.5 Conclusion

In this chapter, we studied the implications of general equilibrium effects, which arise from the interaction of the resource and the capital market, for the influence of future climate policies on the extraction decision of resource owners and the arising of the green paradox. From the contribution of Smulders et al. (2012) we observed that with an endogenous formation of the capital stock over time and with a complementarity based relationship between the capital stock and resource demand the credible announcement of future climate policies can lead to an increase in resource use and emissions in the short term, even without resource scarcity and the accompanying intertemporal relationship between future and current supply in the familiar Hotelling framework. The reason is that with an imperfect substitutability of fossil resources even in the long run the credible announcement of future restrictions on the use of fossil resources induces precautionary savings which in the short term increase the capital stock, resource demand and thereby resource use. While the endogeneity of the interest rate does not have any implications for the use of fossil resources in this case, Long and Stähler (2014a) point out the role of endogenous interest rate adjustments by illustrating that changes in the interest rate, which are induced by cost-reducing technological change, may lead to a (strong) green paradox outcome even without physical but economic resource scarcity. In our stylized but still rather conventional two country general equilibrium setting with physical resource scarcity, we focus on somewhat different transmission channels and in particular on the redistributive effect of a carbon tax by explicitly differentiating between resource-rich and -poor countries. We studied both, the competitive market case, which represents an extensive review and adaption of the contribution by van der Meijden et al. (2015b), and the extreme opposite case of a resource monopolist.

The competitive case with symmetric countries illustrates the implications of the general equilibrium feedback effects which arise from any shift in the extraction path via the capital market. We showed that the green paradox necessarily arises but that the supply reaction of competitive resource owners may either be attenuated or amplified compared to the partial equilibrium setting from chapter 2 due to the endogeneity of the capital market equilibrium, namely the endogeneity of the second period capital stock and of the interest rate, with respect to the resource supply path in general equilibrium. In fact, the incentive to accelerate extraction is attenuated as the interest rate always falls with an acceleration of extraction for symmetric countries. In contrast, the future capital stock generally may increase or decrease with an acceleration of extraction. Obviously, if there is negative relationship between future resource supply and the future capital stock, the green paradox necessarily gets attenuated as a simultaneous increase in future resource demand by the complementarity of production factors renders future supply even more attractive. In contrast, if the future capital stock falls with the shift of extraction to the first period, the decrease in future resource demand may even overcompensate the fall in the interest rate and thereby give rise to an amplification of the green paradox.

We further followed van der Meijden et al. (2015b) and also considered asymmetric countries. In contrast to a partial equilibrium setting and also the symmetric country case, the redistribution of resource rents then is no longer neutral with respect to the capital market equilibrium as the counteracting savings adjustments in both countries do not offset each other anymore. If this redistributive effect of a carbon tax has a positive net effect on aggregate savings and therefore leads to an increase in the capital stock, the green paradox can even be reversed because the increase in the second period capital stock creates an incentive to postpone resource supply, which counteracts the familiar incentive to accelerate extraction by the reduction in the resource producer price from a higher carbon tax. This illustrates that a partial equilibrium assessment of the resource supply reaction to climate policies in general may not only be quantitatively but also qualitatively misleading. Moreover, taking a slightly different perspective than in van der Meijden et al. (2015b), we might argue that this result in the end also points to the role of the capital investments of resource exporting countries for the effect of climate policies. In fact, the increase in the future capital stock upon the climate policy induced redistribution of resource income, which is necessary for a reversal of the green paradox, is driven by the (precautionary) savings reaction of the resource-rich country E, which seeks to at least partly maintain its future consumption level. Since we consider redistributive effects of climate policies, the capital market influence is, however, not reflected in the overall amount of investments from the resource exporting country but in the strength of its savings reaction as compared to the savings reactions in the resource importing countries.

Our main objective in this chapter, however, was to investigate which implications resource market power has for the effect of a carbon tax. To this end, we extended the analysis of the competitive market from van der Meijden et al. (2015b) by assuming resource market power, but considered just the symmetric country case as to focus on the role of market power. We thereby also abstracted from extensions such as exploration investments or stock-dependent extraction costs, which we briefly discussed for the competitive market. We first pointed out that similar to partial equilibrium there is no fundamental qualitative difference between the resource supply reaction in the competitive and the monopolistic case as long as the monopolist is completely naive with respect to the additional (cross-market) effects of her supply decision in general equilibrium. In fact, in this case, the feedback effects from the endogeneity of the interest rate and of the future capital stock may attenuate or amplify the green paradox, just as for the competitive resource market.

However, building upon our observations from section 5.2, we additionally accounted for the potential modifications of the monopolistic supply decision in general equilibrium. We thereby demonstrated that even for symmetric consumption preferences the redistributive effect of a carbon tax can be of crucial effect for the supply reaction if the monopolist is no longer completely naive and at least pursues the asset motive. The reason is that while the resource rent redistribution by the carbon tax is entirely neutral with respect to the overall capital market equilibrium, it is not with respect to the asset holdings of the individual country. Since an introduction or tightening of a future climate policy incurs a loss in future resource income, there is an incentive to increase savings for reasons of consumption smoothing in the resource-rich country, which, given that the sheikh no longer is completely naive, strengthens the future asset motive and thereby renders future resource extraction more attractive. If this incentive to postpone extraction is sufficiently strong, it may overcompensate the familiar conventional incentive to accelerate extraction by the devaluation of future resource supply and thereby lead to a reversal of the green paradox. Thus, the asset motive may not only alter the extraction policy, as discussed in section 5.2, but also establishes a new transmission channel of climate policies and its rent redistributive effect given the asymmetry in resource endowments, through which climate policies affect the resource supply decision. The influence of the asset motive on the extraction policy itself can, however, crucially alter the effect of future carbon taxation, too. In fact, since the asset motive increases the value of fossil resources (at the margin), the sheikh may choose to supply to the market and to follow a Hotelling type extraction policy even with a negative marginal resource revenue, which can be due to abundant resources underground but also due to a completely inelastic resource demand. In this case, an increase in a value added carbon tax no longer reduces but raises the overall value of resources so that the green paradox is reversed even without a precautionary, endogenous savings reaction of resource owners.

We also discussed the conditions under which the green paradox is reversed in more detail. In general, for a reversal the tax influence on the capital income component must dominate that on the resource income component, at least in the standard case where the latter is positive. But while the distribution of capital endowments between both countries directly affects the influence of the asset motive on the speed of resource extraction, it is completely neutral with respect to the effect of the carbon tax. This is not the least due to our assumption of homothetic preferences by which the savings reactions to income changes are independent of the wealth level of households. Similarly, we also found that the effect of the carbon tax does not depend on whether we consider only a marginal tightening of an existing policy scheme or the introduction of a strict new climate policy.

A crucial, if not the most crucial, role for the weighting of the carbon tax effect on the capital over the resource income component has the structure of final goods production. More specifically, it is foremost the combination (or interplay) of the role of fossil resources compared to capital in production measured by the factor productivity parameters and the substitutability between capital and the fossil resource captured by the elasticity of substitution which fundamentally determines whether the carbon tax increase or introduction leads to a reversal of the green paradox or not. The reason is that the interplay of these parameters, on the one hand, characterizes the dependence of production on resources which then is reflected in the size of the resource rent and thereby in the impact of the carbon tax on the resource income component. On the other hand, they obviously also define the strength of the complementarity relationship between both factors, from which the asset motive derives. Generally, our sensitivity analysis revealed that a lower substitutability combined with a lower role of resources in production renders the reversal of the green paradox more likely. Such a combination also implies that the sensitivity of resource demand is rather low whereas the sensitivity of capital return with respect to shifts in the resource supply path tends to be high. However, we also observed that the interplay of these two dimensions of the production structure, which is required for a reversal of the green paradox, is to some extent dependent on the consumption preferences but also on the relative factor input. The former is rather obvious as the consumption preferences determine the strength of the savings reaction of resource owners to the redistribution of the resource rents. The latter followed from our discussion of changes in the world economy’s endowment of capital and fossil resource.

The role of the production structure, the influence of the factor endowments, and their interaction illustrated in the sensitivity analysis can also be related to the scarcity of the fossil resource in the economy. From this perspective, the scarcity of the fossil resource is not only vital for the arising of the green paradox already in partial equilibrium, as pointed out in section 2.2, but also in our general equilibrium setting with a non-naive sheikh. The reason is that within a finite time horizon the scarcity of the resource does not just follow from the exhaustibility of the resource stock underground but strongly depends on how large aggregate resource demand in the economy is in relation to the resource stock underground. With imperfect competition, we also have pointed out throughout our discussion in section 5.2 that the exact valuation of the resource by the resource owner is of crucial importance for the "‘effective"’ scarcity of the resource. The relation between resource demand and availability underground is obviously altered with a change in the resource endowment but also with a change in capital endowments due to the complementarity of production factors. The same holds true with respect to the considered changes in the factor productivities and/or the substitutability between production factors when resource demand is derived from final goods production. Overall, while the scarcity of the resource establishes the intertemporal supply behavior and thereby the influence of future climate policy actions on current extraction in partial equilibrium (without extraction costs), it additionally influences the weighting between the resource and the capital income component in our general equilibrium setting with the extended supply decision of the non-naive sheikh. In fact, the scarcer the resource the higher the resource rents, and the more weight has the resource income compared to the capital income component. This is also in line with our discussion of the Leontieff economy, where the green paradox necessarily arises if the resource is the limiting and thereby scarce factor in the economy, and the special case of a negative resource revenue where the fossil resource actually is abundant and the green paradox necessarily is reversed. The latter may also be interpreted as a special form of economic resource scarcity for a resource monopolist as the resource constraint is only binding due to the additional asset motive.

From a macroeconomic perspective, a reversal of the green paradox implies in our framework that the current output is always reduced. Future output will increase if the induced shift of resources to the future comes along with a higher capital accumulation, but may fall if the postponement of extraction lowers capital accumulation. In either case, due to the redistribution of resource rents between the resource-rich and the resource importing country and the induced savings reactions, the future share of the resource-rich country in the global capital stock in such a scenario increases. This may give rise to a discussion about the capital market influence of "petrodollars". We leave this for future research, as well as the effect of stock dependent extraction costs and of asymmetric consumption preferences. The latter would imply that the capturing of resource rents by the resource-importing country is no longer neutral with respect to aggregate capital accumulation, and therefore that the change or introduction of a future resource tax induces additional effects via the endogeneity of capital accumulation. Not only considering the timing of resource extraction but also endogenizing overall resource extraction and thereby aggregate emissions could be interesting as we already observed that the presence of the asset motive directly affects the valuation of the resource stock by the sheikh. For example, the climate policy induced increase in asset holdings and the strengthening of the future asset motive also creates an incentive to increase aggregate extraction which clearly counteracts the environmental benefits from the reversal of the green paradox.

The mechanisms which can lead to the reversal of the green paradox – on the one hand, the endogenous savings reaction to the resource rent redistribution and the induced strengthening of the asset motive, and, on the other hand, the negative resource income component (resource revenue) due to the asset motive – both crucially depend on the monopolist's ability to internalize at least the complementarity related positive influence of resource supply on capital return into her supply decision, and to pursue the asset motive. Recognizing the relationship between resource supply and capital accumulation and thus accounting for the additional feedback effects from the endogeneity of capital accumulation, in contrast, turned out to be of less importance for the effect of the carbon tax. But since the relationship between the future capital stock and resource supply also affects the sensitivities of resource and capital demand with respect to shifts in the resource supply path, internalizing this relationship can enlarge or reduce the range of parameter constellations for which we may observe a reversal of the green paradox. Hence, our results for the effect of carbon taxes again illustrate the role of information about the economic relationships in general equilibrium, and support our view that just transferring the familiar supply decision of a monopolist from partial to general equilibrium can be completely misleading. This holds true all the more as resource-rich countries own considerable capital assets abroad, as shown in section 3.1.2, and since the recognition of at least some of the real economy cross-market effects does not seem too implausible for fossil resources and especially oil, as already argued before, too. Moreover, our results also illustrate that resource market power can be of much greater importance for the effect of climate policies than what has been concluded from the rather rare partial equilibrium assessments of the role of resource market power for the arising of the green paradox (see e.g., van der Ploeg and Withagen 2012a). Even though the omniscient sheikh, or more general the sheikh who is non-naive with respect to her influence on capital return, may choose an extraction path close or even identical to the competitive market, her reaction to the credible announcement or tightening of future climate policies can be completely different: Whereas the green paradox always arises in the competitive market setting for symmetric homothetic preferences, it may get reversed as soon as we introduce market power and a non-naive resource owner.

7 A Capital-Intensive Renewable Energy Technology

In section 3.2.4, we already have pointed out that climate policies and the necessary decarbonization of economies are likely to bring about an, albeit generally overall moderate, (net) increase in investments in the energy system. This implies that the extraction policies of resource owners may not only be affected by the direct competition from new energy technologies in the energy market, which has already been extensively studied in the literature (see section 2.2), but also by the increase in the demand for capital and the accompanying changes in the capital market equilibrium which arise from a wider deployment of these technologies in the energy market. To study this transmission channel in more detail, we will extend our two-country-two-period setting in the following to give the resource importing countries access to a new energy technology in the second period which by use of physical capital can substitute fossil resources in final goods production.

After laying out the additional model components, we will proceed along the by now familiar lines: After deriving the conditional market equilibrium we will study the resource supply response to climate policies in the competitive as well as in the monopolistic market setting. We thereby do not only consider the effect of a (second best) carbon tax but also the effect of subsidy payments to the new substitutive energy technology, which typically are seen as second best instruments prone to induce green paradox outcomes (see section 2.2). Additionally, we study exogenous technological change improving the competitiveness of the substitutive energy technology.

To illustrate the role of this transmission channel for the effect of climate policies and technological change, we will constrain the analysis for the moment to the naive monopolist's case, which, however, already yields new insights into the role of resource market power. The detailed analysis of the interplay between the asset motive and the capital market influences of the new energy technology is left for future research.

7.1 Capital Intensity and Economics of Renewable Energies

The real world counterparts to the capital intensive new energy technology we have in mind in the following analysis are in particular renewable energy technologies like wind and solar energy which are generally expected to substantially contribute to the decarbonization of energy systems necessary along mitigation pathways (see, for example, IPCC 2014, and IEA 2015b). We start by looking in little more detail into the characteristics of the renewable energy technologies and in particular their capital intensity.[1]

The widely expected increase in the capital intensity of energy systems with deployment of renewable energy technologies derives on the one hand from the cost structure of renewable as compared to conventional generation technologies, and on the other hand from the need for additional provisions in the energy system for reasons of the reliability and security of energy supply. Table 7.1 provides an overview over the cost components and the levelised costs of generation technologies in different countries. It illustrates the significant regional differences in the costs of renewable energies which are essentially due to varying solar and wind conditions in different regions of the world. With respect to levelised costs, renewable energies currently are obviously already or close to being competitive. Moreover, technological change is very likely to reduce the costs of renewable energies further over the coming years (see e.g. IEA 2015a). The table also demonstrates that while conventional, i.e. coal or natural gas fired, power plants have significant (variable) fuel costs, the levelised costs of solar and wind energy in particular are almost entirely determined by the (up-front) capital investment costs. This cost structure already implies that a larger deployment of these technologies in the system will increase the share of capital costs in the total costs of energy generation and thereby increase the capital intensity of the overall system, while the operating (variable) costs of energy generation will fall.

Renewable energy generation from wind or solar energy obviously directly depends on the variable and to some extent uncertain weather conditions and therefore is intermittent and non-dispatchable. This necessarily limits the degree of utilization of the installed capacities, which is measured by the capacity factor, to substantially lower levels than for conventional and fully dispatchable technologies, which apart

[1] More extensive discussions of the economics of renewable energies are, for example, provided by Heal (2009), Borenstein (2012), or Edenhofer et al. (2013b).

Table 7.1: Cost components and levelised cost of electricity generation (LCOE): conventional versus intermittent renewable technologies in different countries

Country	**Technology**	**Capacity factor**	**Overnight cost** (US $/kWe)	**Fuel cost** (US $/MWh)	**O&M costs*** (US $/MWh)		**LCOE**** (US $/MWh)	
					3%	7%	3%	7 %
Germany	CCGT	85%	974	74	7.82	7.76	98.49	102.56
	Coal (Hard coal)	85%	1,643	26.38	9.24	9.17	67.01	75.53
	Solar PV (commercial)	11%	1,467		24.15	23.98	116.62	161.13
	Wind Onshore	34%	1,841		35.6	35.17	77.15	93.53
	Wind Offshore	48%	5,933		51.46	50.48	144.31	182.68
U.S.	CCGT	85%	1,143	36.90	4.78	4.7	49.74	54.85
	Coal (supercritical pulverised)	85%	2,496	28.42	11.41	11.24	57.44	68.59
	Solar PV (commercial)	15%	1,739		14.30	13.23	105.92	156.12
	Wind Onshore (medium)	43%	1,716		13.49	13.22	39.60	52.23
	Wind Offshore (medium)	45%	4,997		30.13	29.47	102.34	137.37
China	CCGT	85%	627	71.47	3.32	3.28	79.15	81.77
	Coal (ultra-supercritical)	85%	813	35.67	4.13	4.09	44.73	43.84
	Solar PV (commercial)	12%	728		17.07	16.64	58.99	78.70
	Wind Onshore	26%	1,400		10.55	10.19	45.96	59.92

Source: IEA 2015c, all cost figures in 2013 U.S. dollar, assumed commissioning date 2020;
*O&M: operation and maintenance costs including (levelised) costs of refurbishment and decommissioning; **LCOE: carbon cost excluded;

from periods of maintenance can, in principle, continuously produce energy.[2] Using a back-of-the-envelope calculation, we could take the costs for a reliably operational unit of capacity as basis of comparison by weighting the technology's investment costs with the respective capacity factor. This approach suggests a drastic increase in the capital intensity of a generation system based on intermittent renewable energies instead of conventional technologies. However, it does not adequately capture the problems of intermittency and non-dispatchability from a power system's perspective. The stability of the electricity system requires supply to correspond to demand at each instant of time, even though demand is fluctuating within days and between seasons and is generally rather inflexible. In such an environment, intermittent and non-dispatchable generation technologies can ensure the system stability only to a limited extent and therefore can only imperfectly substitute conventional dispatchable generation capacities in the system, although there is perfect substitutability in terms of the pure energy output fed into the system. Thus, simply scaling up the capacities of intermittent renewable energies, as suggested by the aforementioned back-of-the-envelope calculation to capture the lower capital utilization rate, in the end cannot overcome the problem of intermittency.

Instead, decarbonizing power systems by use of intermittent renewable energies will require a combination of a geographical more dispersed distribution of generation capacities to exploit (negative) correlations of weather conditions between different locations with additional energy storage and dispatchable back-up generation capacities, which only ramp up in times of no sun or wind. The need for such a more decentralized infrastructure, and storage and mostly idle generation capacities can of course be reduced by increasing the low flexibility and price sensitivity of energy demand via a more intelligent ("smart") demand infrastructure. But in the end, all these provisions to cope with the intermittency problem of renewable energies require additional investments and thus tend to increase the capital intensity of the overall power system.

This also implies that comparing the costs of dispatchable and non-dispatchable intermittent technologies on the basis of the respective levelised costs is prone to be

[2] This is also reflected in table 7.1 where the underlying assumption is that all the conventional technologies provide baseload energy given a uniform adjustment in the capacity factor for maintenance and service. In reality, the capacity factor of these fully dispatchable technologies directly depends on the generation structure and the fluctuations of demand. For example, in the German electricity market, the capacity factor for natural gas fired power plants is typically substantially lower than 85% as these plants currently produce only in times of peak demand.

entirely misleading (see also Joskow 2011). In fact, as argued for example by Hirth et al. (2016), while physically completely homogenous, electricity is economically a heterogeneous good in the system since its economic value depends especially on the time when it is supplied to the system, but also on the location where the electricity is fed into the system compared to the load centers, and on the lead time between contract and delivery. The dependency on weather conditions renders renewable energies non-dispatchable, which implies that they cannot necessarily supply electricity to the system when it is worth the most, and their electricity output to some degree uncertain, which incurs costs to balance forecast errors. The dependency on weather conditions also determines to some extent the location choice of installations. The best locations in terms of weather conditions are not necessarily close to the load centers so that the deployment of renewable energies often incurs additional infrastructure costs.[3] Due to the additional system costs for balancing and infrastructure and the lower market revenues from the variability and non-dispatchability the economic value of variable intermittent energy technologies is often seen to be lower than that of fully dispatchable generation units and tends to fall with their share in overall generation increasing (see e.g. Lamont 2008).

For example, Hirth (2013) focuses on the so-called profile costs from the variability and non-dispatchability of renewable generation and finds that at low penetration rates variable renewable generation from solar and wind tends to be even more valuable than the average base price of electricity, which a continuously producing unit would earn, due to a positive correlation between renewable generation and electricity demand. However, the market value of wind decreases significantly to about 50-80% of the base price with its market share reaching 30%. For solar energy, this depreciation is even more pronounced. Based on data for energy generation in south eastern Arizona, Gowrisankaran et al. (2016) estimate that reaching a 20% share of energy generation from solar photovoltaic (solar PV) incurs system costs of US$ 23.50 per MWh (mega-watt hour) of electricity produced in addition to the difference in levelised costs of US$ 114.90 per MWh between electricity from solar PV and from a conventional combined cycle natural gas power plant. Overall, “social” costs of a MWh of electricity from solar PV over a MWh produced from a natural gas power plant amount to US$ 138.40 (given a 20% share of solar PV in total generation). Analysing

[3] Fully dispatchable technologies can have different and specific roles in the system, for example by providing either peak- or baseload electricity supply. With technologies differing in their cost structure, a technology mix can therefore be the cost minimizing approach to adjust generation to the demand profile given the so far limited possibilities to store electricity and the so far rather low flexibility or price sensitivity of demand.

the components of these social costs reveals that the non-dispatchability and the high capital requirements of capacity are the most important cost drivers. A decrease in the (fixed) capital costs of solar capacity by about 55% (from US$ 4.41 to US$ 2 per watt of capacity installed) by technological change would reduce the social costs by about 70% to US$ 39.40 and thereby even way below the levelised costs of a gas power unit of US$ 66.30. In contrast, hypothetically completely eliminating the non-dispatchability of solar PV reduces to social costs only by 20%. Since the former is, in principle, feasible with technological change while the latter is excluded in any case, this result can at least give rise to some optimism that a renewable energy system in the long run will come at lower costs even when taking into account system costs. Overall, as pointed out by Hirth et al. (2016), a levelised cost comparison, or concepts as the so-called grid parity, therefore tend to be biased towards the lower value intermittent renewable energy technologies as they do not account for the differences in the system value of dispatchable and non-dispatchable technologies.

The discussion in section 3.2.4 revealed that the transition to a low carbon energy system leads to substantially savings on investments in the exploration and extraction of fossil resources. The overall net impact on investment needs, albeit most probably still positive, may therefore be more moderate than the previous overview over the characteristics of renewable energy generation might suggest. Even though this clearly illustrates that resource extraction costs also introduce an important additional linkage between the capital and resource market, we will abstract from extraction or exploration costs in the following. Still, our analysis can be justified by interpreting the setting as the rather likely scenario where the deployment of renewable energies increases the net capital demand from energy-related investments.

7.2 Relation to the Literature

The development and future availability of new energy technologies and their implicit or explicit support by climate policies in form of carbon taxes or subsidy payments obviously crucially affect the future sales potentials of fossil resource owners and the resource extraction path. Whether subsidizing or cost reducing technological change leads to a (weak or strong) green paradox if a substitutive technology is available has already been extensively studied in the literature, which we surveyed in section 2.2. The main focus in this literature has been on the second margin introduced by a substitutive backstop technology in combination with positive (stock-depending) extraction costs, i.e. the endogeneity of overall resource extraction, and its implications for the arising (and the welfare implications) of a green paradox. This literature so far, however, has taken a purely partial equilibrium perspective on the resource, or energy, market so that fostering the deployment of the substitutive perfect or imperfect backstop technology has no influence on the capital market equilibrium, which is typically represented just by some market interest rate.

As laid out before, we abstract from this second margin by still assuming away extraction costs but adopt a general equilibrium perspective to capture in particular the additional interaction between the resource/energy and the capital market which is established by the capital intensity of substitutive low carbon energy technologies. The capital need from backstop technologies in the context of resource extraction and climate policies so far has only briefly been mentioned by Long (2015) who argues that a debt financed "Green New Deal" is likely to increase the interest rate and thereby may give rise to a green paradox without providing a more in-depth analysis. Moreover, the only contributions to the literature considering backstop technologies in a general equilibrium setting which we are aware of are Long and Stähler (2014a) and Long and Stähler (2014b). As we already have discussed before in section 6.1, they emphasize the role of the "interest rate channel" for the effect of cost reducing technological change. They show that while a green paradox would be excluded in their setting with an exogenous interest rate the endogenous adjustment of the interest rate necessary to readjust the intertemporal consumption equilibrium of households may give rise to a weak or even a strong green paradox. Thus, they also take into account the endogeneity of overall resource extraction. However, in their framework there is no full representation of a capital market with an endogenous formation of the capital stock by endogenous savings decisions of households. More fundamentally, they consider a different general equilibrium transmission channel by focusing on the income effects of cost reducing technological change and the accompanying adjustments in capital supply. In fact, since in their setting the backstop technology generates energy from final goods, or households' income, there is no direct influence from energy generation of the backstop technology on the capital market (via capital demand). The exogenously given and constant capital stock is used in final goods production and extraction of fossil resources but not for the backstop technology.[4]

[4] Hence, capital is not substitutive to fossil resources in their setting, whereas in our framework, as will become clear later on, capital becomes complementary and substitutive at the same time in the second period due to the availability of the new energy technology.

We will in the following elaborate on the implications of the need for physical capital of substitutive backstop technologies for the effect of climate policies and technological change on the resource supply path. We will also assume that the new energy technology is available to the resource importing countries only in the future period and is not able to satisfy the market demand for energy completely so that there is parallel use of both sources of energy. Different to Long and Stähler (2014a) and Long and Stähler (2014b) and our previous framework, this implies that there is technological change over time which alters the structure of the demand side in the resource market but obviously also has an influence on the relationship between resource supply and the capital market.

To the best of our knowledge this is the first approach to include a substitutive backstop technologies in such a general equilibrium model of trade in resources, capital and final goods, and in particular to point out the role of the capital intensity of typical backstop technologies for the effects of climate policies and technological change on the supply path of fossil resources in a consistent model framework. We will provide an analysis for the competitive resource market case as well as for the monopolistic resource market, which additionally separates our contribution from Long and Stähler (2014a) and Long and Stähler (2014b) who only consider the competitive market case. To focus on the implications of the additional interaction effects from the capital intensity of the backstop technology, we restrict our analysis to the naive monopolist and leave the potential implications for the asset motive for future research. Similarly, in this chapter, we will concentrate on the symmetric country case again and thereby abstract from the redistributive effects of substitutive technologies. Clearly, substitutive backstop technologies, especially when employed by countries which are net importers of fossil resources, in principle also have strong redistributive effects as they reduce the resource rents by at least partly alleviating the scarcity of fossil resources.

The naive monopolist's case still turns out to be of some interest as the capital intensive backstop technology has a direct influence on the price elasticity of resource demand which is crucial for the extraction decision of the monopolist in comparison to the competitive market as we already know from section 2.1.2. That a continuously arriving substitutive technology may influence the price elasticity of resource demand and thereby the extraction decision of a resource monopolist has been noted before by Hillman and Long (1982). They, however, postulate that a substitutive backstop technology more and more enters the market with depletion of the resource stock and thereby continuously shifts (residual) resource demand downwards. As already reviewed previously (see section 2.1.2), they show that a monopolist when explicitly taking into account this continuous market entry of a competitive backstop is induced to choose a more conservative extraction policy as to slow down the depletion of the resource stock and therefore the market entry of the competitive technology. In our setting, the market entry of the renewable substitutive technology is not conditional on the depletion of the resource stock, which is somewhat arbitrary, but depends on market equilibrium conditions. In particular, while Hillman and Long (1982) study just the extraction decision itself, we focus on the effect of climate policy interventions. In fact, we point out that subsidies to the substitutive renewable energy technology, or similarly technological change, directly influence the equilibrium conditions determining the deployment of the renewable energy technology and thereby alter the price elasticity of (residual) resource demand. Moreover, when sufficiently increasing the price elasticity of (residual) resource demand, climate policies can actually induce even the naive monopolist to postpone extraction whereas a green paradox necessarily arises under competition.

7.3 Extended Model Framework: Introducing a Renewable Energy Technology

We extend our analytical framework basically by two assumptions. First, we reinterpret the resource input into final goods production and assume that the production technology uses energy, physical capital, and labour to produce final goods. Second, the resource importing country I shall have access to a new energy technology in the second period which generates energy by use of physical capital and can substitute fossil resources in final goods production. We present this extension of our existing framework in the following by focusing on the new, or additional, elements compared to the standard framework laid out in chapter 4.

7.3.1 Energy Supply

We denote the energy input factor by Q_t. In the first period, the only source of energy are fossil resources. As before, we therefore have

$$Q_1 = R_1$$

Thus, the marginal productivity of fossil resources in energy generation is constant.

In the second period, there is an additional source of energy available to the resource importing countries. We want to include particularly three key characteristics of currently available renewable energy technologies like wind or solar energy which we discussed before in section 7.1, but aim to keep the exposition as tractable as possible. First, since the (levelized) energy generation costs of many renewable energy technologies are largely driven by the capital investment costs for the installation of the capacities, we assume that the renewable (carbon-free) technology allows the generation of "wind" energy W_t just by use of physical capital where[5]

$$W_2 = W_2(K_W) \qquad \text{with } W_{2K} > 0, W_{2KK} < 0 \tag{7.1}$$

We thereby abstract from other cost components of renewable energies such as labour costs.[6]

Second, and as indicated in (7.1), the technology exhibits a positive but decreasing marginal productivity of physical capital. This reflects the limited availability of locations with optimal solar or wind yield or cheap construction costs within a country, or more generally a geographically constrained energy system.

Finally, the energy produced by renewable energies physically perfectly substitutes energy generated from fossil resources but economically, from the perspective of the overall energy system, renewable energies like wind and solar energy are only an imperfect substitute in existing power systems due their dependency on weather conditions as discussed before. To keep the analysis tractable, we assume on the one hand that energy supply is a linear combination of renewable and fossil energy which reflects the homogeneity of both generation technologies in terms of the physical energy output. On the other hand, however, to capture the economic (system) costs of the non-dispatchability, variability and the uncertainty of generation, and the costs for additional infrastructure, i.e. the heterogeneity of these technologies from an economic point of view, we introduce a parameter μ which measures the system value of renewable energy, or the "usability" of renewable energy in the system. Thus, second period energy supply with parallel use of both energy sources is given by

$$Q_2 = R_2 + \mu W_2 \qquad \text{with } \mu \leq 1 \tag{7.2}$$

[5] As before, subscripts denote partial derivatives with respect to the respective input factor, i.e. $\frac{\partial W_2}{\partial K_W} = W_{2K}$.

[6] The reason is that we are primarily interested in the interplay of the resource and the capital market, its role for the effects of climate policies and technological change, and in the additional transmission channels which are established by a capital intensive energy technology which is substitutive to fossil resources.

We assume $\mu \leq 1$ as the system value of intermittent non-dispatchable energy sources is typically found to be lower than that of fully dispatchable generation units already for low market shares. As our discussion in section 7.1 demonstrates, this is, of course, a rather simplified modeling approach, for example because in reality the value difference between renewable and conventional dispatchable generation units crucially depends on the market penetration by renewable energies. Yet, this approach allows us to capture the system costs of renewable energies and to consider the effects of (exogenous) technological change which may reduce these costs by bringing forward, for example, low cost energy storage facilities or refined weather forecasts.

7.3.2 Final Goods Production and Factor Demand

Final goods are now produced with three input factors, physical capital K_{tF}, energy Q_t and labour L_t, which is again in constant supply from the representative household,[7] by use of a CES production technology

$$F_t = F(K_{tF}, Q_t) = A\left[\gamma K_{tF}^{\frac{\sigma-1}{\sigma}} + \lambda Q_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma-\lambda)L^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

This is completely analogue to (4.4). However, with the capital intensive renewable energy technology in the second period, we have to distinguish between physical capital invested in machinery of final goods production K_{2F} and physical capital invested in renewable energy generation capacity K_{2W} so that

$$K_2 = K_{2F} + K_{2W} \tag{7.3}$$

Letting competitive final goods producers directly invest in renewable energies, the profit maximization problem of a representative firm in the second period reads

$$\max_{R_2, K_{2W}, K_{2F}} F_2 - p_2 R_2 - (1-\omega) i_2 K_{2W} - i_2 K_{2F} \tag{7.4}$$

for given market prices for fossil resources p_2 and capital i_2.[8] Alternatively, but completely equivalently, we may introduce a new competitive energy sector to produce the composite input factor energy Q_2 in the resource importing countries. The governments in the resource importing countries may subsidize investments into renewable energies which we denote by the subsidy rate ω. This subsidy will be lump-sum

[7] To simplify notation, we therefore again set $L_t = L$.

[8] Recall that we choose final goods as the numeraire good.

financed by taxing the second period income of households in the resource importing countries.

By the first-order conditions of the maximization problem (7.4), we find that in market equilibrium the market price of energy and physical capital must equal the marginal productivity of the respective production factor in final goods production. Hence, we have[9]

$$F_{2Q} = p_2 \tag{7.5}$$

and

$$F_{2K} = i_2 \tag{7.6}$$

Moreover, final goods producers will invest capital into renewable energy generation as long as the marginal productivity of capital in terms of final goods output from renewable energy generation exceeds the market costs of renewable energy generation. Thus, in market equilibrium

$$F_{2Q}\mu W_{2K} = (1-\omega)i_2 \tag{7.7}$$

These first-order conditions implicitly define the competitive final goods producers' demand for energy and physical capital as well as for physical capital used in renewable energy generation for given market prices of energy p_2 and capital i_2. Also note that for $\mu \to 0$ we are back in the standard setting because this additional first-order condition on the demand side completely drops out and second period energy supply from (7.2) is just given by resource supply.

By totally differentiating the first-order conditions (7.5) and (7.6) with respect to factor inputs Q_2 and K_{2F} we can show that just as in the standard framework (see section 4.1.2) energy demand is a function of the market prices for energy and capital only

$$Q_2^d = Q_2^d(p_2, i_2) \qquad \text{with} \qquad dQ_2^d = \frac{F_{2KK}}{\Gamma_W}dp_2 - \frac{F_{2KQ}}{\Gamma_W}di_2 \tag{7.8}$$

The same holds true for the demand for physical production capital

$$K_{2F}^d = K_{2F}^d(p_2, i_2) \qquad \text{with} \qquad dK_{2F}^d = \frac{F_{2QQ}}{\Gamma_W}di_2 - \frac{F_{2KQ}}{\Gamma_W}dp_2 \tag{7.9}$$

9 Under competitive factor demand and given our assumption on conventional energy generation the resource market price must equal the market price of energy.

Analogue to (4.5), we define here[10]

$$\Gamma_W = F_{2QQ}F_{2KK} - F_{2KQ}^2 = \frac{1}{\sigma^2}\frac{F_{2Q}F_{2K}}{Q_2K_{2F}}\left(1-\theta_{2Q}-\theta_{2K}\right) > 0 \tag{7.10}$$

The positive sign again must hold due to Euler's theorem and our assumption of a third constant input factor "labour". Due to the concavity of the CES production technology and the complementarity of production factors, energy demand and production capital demand therefore negatively depend on the market prices p_2 and i_2, which competitive final goods producers take as given.

The demand for capital for renewable energy generation is implicitly defined by the first-order condition (7.7). By totally differentiating with respect to production factors Q_2 and K_{2F} and with respect to market prices, the state of renewable energy technology μ, and the renewable subsidy ω as well as by substituting from (7.8) and (7.9) we observe that

$$\begin{aligned}
&K_{2W}^d = K_{2W}^d(p_2, i_2, \mu, \omega)\\
&\text{with}\\
&dK_{2W}^d = -\frac{\mu W_{2K}}{F_{2Q}\mu W_{2KK}}dp_2 + \frac{1-\omega}{F_{2Q}\mu W_{2KK}}di_2 - \frac{F_{2Q}W_{2K}}{F_{2Q}\mu W_{2KK}}d\mu\\
&\qquad\quad - \frac{i_2}{F_{2Q}\mu W_{2KK}}d\omega
\end{aligned} \tag{7.11}$$

As expected, a higher market price for energy increases the profitability of renewable investments and thereby raises the demand for capital invested into renewable energy generation. The same holds true for technological progress represented by an increase in μ and for a stronger support of renewable energies from the government. Obviously, a higher market price of capital implies a higher cost of renewable energies so that investments become less attractive and the capital demand for renewable energy generation is reduced.

Following our line of analysis of the standard framework, our objective here is again to derive a market equilibrium conditional on some resource extraction path defined by the market equilibrium conditions for all three international markets, the resource market, the capital market, and the market for final goods. We therefore next consider the modified demand for fossil resources and the aggregate demand for physical capital. With renewable energy capital demand from (7.11) and simultaneous use of

[10] $\theta_{tf} = \frac{F_{tf}f_t}{F_t}$ again denotes the share of (competitive) remuneration of factor f in output in period $t = 1, 2$.

renewable and fossil energy, resource demand in the resource importing economies can be represented by residual energy demand

$$R_2^d = Q_2^d - \mu W_2(K_{2W}^d) = R_2^d(p_2, i_2, \mu, \omega)$$

with

$$\begin{aligned} dR_2^d = & \frac{F_{2KK}\mu W_{2KK} + \Gamma_W \left(\mu W_{2K}\right)^2}{\Gamma_W F_{2Q}\mu W_{2KK}} dp_2 \\ & - \frac{F_{2KQ}F_{2Q}\mu W_{2KK} + (1-\omega)\Gamma_W \mu W_{2K}}{\Gamma_W F_{2Q}\mu W_{2KK}} di_2 \\ & + \frac{W_{2K}^2 - W_{2KK}W_2}{W_{2KK}} d\mu + \frac{i_2 \mu W_{2K}}{F_{2Q}\mu W_{2KK}} d\omega \end{aligned} \tag{7.12}$$

This characterization of resource demand resembles the reduced resource demand concept in Long (2014) who studies the effects of changes in the substitutability between an also simultaneously used renewable and a fossil energy source for the fossil resource supply path in a partial equilibrium setting (see also section 2.2). Residual resource demand in our setting still negatively depends on the market price of energy but may in contrast to the standard setting (see (4.6)) positively depend on the market price of capital. This is due to the fact that a higher cost of capital on the one hand decreases the demand for capital in the final goods production which by the complementarity of energy and physical capital in production lowers resource demand as before. But on the other hand, it also reduces capital demand from renewable energy generation which obviously tends to increase residual resource demand. Resource demand now also depends on the state of the renewable energy technology (μ) and on the renewable energy subsidy (ω). An increase in the technology parameter μ, i.e. any improvement in the usability or system integration of renewable energies which increases the actual energy supply to the economy from the existing generation capacities, will lower residual resource demand. Similarly, a higher renewable energy subsidy attracts additional investments in renewable energy generation which ceteris paribus crowds out fossil resources and thereby reduces residual resource demand.

Finally, the aggregate demand for physical capital is given by

$$K_2^d = K_{2F}^d + K_{2W}^d = K_2^d(p_2, i_2, \mu, \omega)$$

with

$$\begin{aligned} dK_2^d = & -\frac{F_{2KQ}F_{2Q}\mu W_{2KK} + \Gamma_W \mu W_{2K}}{\Gamma_W F_{2Q}\mu W_{2KK}} dp_2 \\ & + \frac{F_{2QQ}F_{2Q}\mu W_{2KK} + (1-\omega)\Gamma_W}{\Gamma_W F_{2Q}\mu W_{2KK}} di_2 \\ & - \frac{W_{2K}}{\mu W_{2KK}} d\mu - \frac{i_2}{F_{2Q}\mu W_{2KK}} d\omega \end{aligned} \tag{7.13}$$

In contrast to the standard setting (see (4.7)), the aggregate capital demand no longer unambiguously decreases with a higher market price of energy p_2. The reason is that a higher energy price reduces capital demand from final goods production, but raises capital demand from energy generation as the market value of renewable energy increases. However, as in (4.7), capital demand still negatively depends on the interest rate, i.e. the cost of capital, which is intuitively plausible as higher capital costs deter investments in final goods production as well as in renewable energy generation. Moreover, aggregate capital demand now also depends on the state of the renewable energy technology (μ) and the renewable energy subsidy (ω). Technological progress improving actual energy output from renewable generation capacities increases the value of capital investments in energy generation and therefore also increases capital demand ceteris paribus. Obviously, a higher subsidy reduces the capital costs in renewable energy generation and thereby makes investments in renewable energy more attractive which ceteris paribus raises capital demand, too.[11]

7.3.3 Capital Supply

As in the standard model setup without renewable energies, capital supply derives from the exogenously given capital endowments of households in the first period and from the endogenous savings of households in the resource importing and exporting countries in the second period. Again, in the following, we just point out the differences to the standard setting in section 4.1.3.

Whereas the first period budget constraint in the resource importing country I is obviously still given as in (4.9), the second period budget constraint, in principle, also includes the refinancing of the renewable energy subsidy. The renewable energy subsidy redistributes capital income to final goods producers by lowering the costs of renewable energy generation and therefore, due to the constant production factor labour and the Euler theorem, increases the labour income of households in country

[11] Note that this discussion of capital and residual resource demand crucially depends on the renewable energy technology, in particular on the assumption of positive but decreasing marginal productivity of capital in energy generation $W_{2K} > 0$, $W_{2KK} < 0$.

I. However, since we assume a lump-sum refinancing by taxation of the household's labour income, we have

$$\begin{aligned} c_{2I} &= F_2 - p_2 R_2 - i_2 K_{2F} - (1-\omega) i_2 K_{2W} + \tau p_2 R_2 \\ &\quad - \omega i_2 K_{2W} + (1+i_2) s_{1I} \\ &= \pi_{2I}^{\tau} + (1+i_2) s_{1I} \end{aligned}$$

which obviously is completely equivalent to (4.9) from the standard setting, too. The budget constraints in the resource exporting country(-ies) are also not directly influenced by the presence of the renewable energy technology and hence are still given by (4.10).

Optimal savings in both countries are again implicitly characterized by the Euler equation (4.11) as functions of the period income streams and the interest rate. Correspondingly, the savings reactions defined in (4.13) and (4.14) still hold true. Using these together with the total derivative of the budget constraints in both countries we can decompose the determinants of the aggregate capital supply function, just as in the standard setting. In appendix 9.2.1 we show that aggregate capital supply for symmetric homothetic consumption preferences is again a function of the resource supply path, given that the resource constraint is binding and there is competitive factor demand, and the interest rate i_2 but also a function of the renewable energy technology parameter μ even for symmetric countries. We have

$$\begin{aligned} &K_2^s = K_2^s(R_2, i_2, \mu) \\ &\text{with} \\ &dK_2^s = \left[\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right] dR_2 + SE di_2 + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2Q} W_2 d\mu \end{aligned} \tag{7.14}$$

where the aggregate substitution effect SE is defined in (4.18). As we already know, the resource, or carbon, tax does not have any influence on capital supply for symmetric countries as the redistribution of resource rents is completely neutral for aggregate savings in this case. The renewable energy subsidy would be neutral with respect to aggregate capital accumulation even for asymmetric countries because the redistribution of capital income to labour income is completely offset by the lump-sum refinancing of this subsidy scheme within country I. For the effects of a shift of resources from the first to the second period and of an increase in the interest rate i_2 we can directly refer to our discussion in section 4.1.3. Increases in the usability parameter μ, which we may interpret as (cost-reducing) technological change in our setting, improve the contribution of the renewable energy output W_2 to the energy supply that is available to the economy for given capital investments and given resource supply.

This comes along with a positive production effect in the second period which is captured by the marginal productivity of energy F_{2Q} and which in the end induces the households following the by now familiar consumption smoothing motives to save less.

7.3.4 Simultaneous Use of Renewable and Fossil Energy

We focus on constellations where there is simultaneous use of both energy sources, fossil resources and renewable energies. Final goods producers will invest into renewable energy generation if for $K_{2W} = 0$ and $Q_2 = R_2$ we have

$$\mu W_{2K} > (1-\omega)\frac{F_{2K}}{F_{2Q}} = (1-\omega)\frac{\gamma}{\lambda}\left(\frac{Q_2}{K_{2F}}\right)^{\frac{1}{\sigma}} = (1-\omega)\frac{\gamma}{\lambda}\left(\frac{R_2}{K_2}\right)^{\frac{1}{\sigma}}$$

by the properties of the CES final goods production technology (4.4). Thus, there must be a positive incentive to at least marginally increase investments in renewable energies in the second period if energy supply solely comes from the fossil resource and the available capital K_2 is completely invested in final goods production. Of course, as we know from the standard setting, resource supply R_2 and the capital stock K_2 are not independent of each other with endogenous savings. Still, we can at least generally conclude that this condition holds with a sufficiently high productivity of capital in renewable energy generation and rather high fossil resource scarcity as compared to the capital stock available to the economy.

Since we now have a setting where exogenous technological change brings forward access to a new energy technology in the second period, renewable energy generation in principle may also completely crowd out fossil resource supply in the second period. However, this opposite limiting case cannot be generally characterized as it directly depends on the (intertemporal) supply decision of the resource owner(s) and therefore on the structure of the resource market. The latter, however, is left unspecified in the characterization of the conditional market equilibrium as before.

To further study the conditions under which at least some renewable energy will be supplied simultaneously with fossil resources, we would need a concrete specification of the renewable energy technology (7.1). For example, later on we will again use numerical simulations to illustrate our results. Thereby, we assume a log specification

$$W_2 = \ln(1 + K_{2W}) \tag{7.15}$$

Using this and $p_2 = F_{2Q}$ and $i_2 = F_{2K}$ by (7.5) and (7.6) in equilibrium, we first can solve the first-order condition (7.7) for the optimal renewable investment

$$K_{2W} = \frac{\mu}{1-\omega}\frac{p_2}{i_2} - 1 = \frac{\mu}{1-\omega}\frac{\lambda}{\gamma}\left(\frac{K_{2F}}{Q_2}\right)^{\frac{1}{\sigma}} - 1$$

Thus, following our above reasoning, there will be investments in renewable energies and therefore simultaneous use of both energy sources if

$$\frac{K_{2F}}{Q_2} = \frac{K_2}{R_2} > \left(\frac{1-\omega}{\mu}\frac{\gamma}{\lambda}\right)^{\sigma}$$

holds for all $R_2 \leq \bar{R}$.

7.4 Conditional Market Equilibrium

We proceed along the lines of the standard setting (see section 4.2) and define the overall market equilibrium of the world economy again by use of the market clearing conditions for the resource, the capital, and the final goods market conditional on some resource extraction path. By considering the resource, instead of the energy, market equilibrium, we do only implicitly include renewable energy generation in the definition of the conditional market equilibrium via equilibrium residual resource demand and the modified aggregate market demand for capital. To investigate the influence of the resource supply path, we again resort to a comparative statics analysis of the conditional market equilibrium.

7.4.1 Definition of the Conditional Market Equilibrium

For the final goods market equilibrium, we can directly refer to our corresponding discussion in section 4.2.1.

Resource Market Equilibrium

The resource market equilibrium is first characterized by the market clearing conditions for each period. We have

$$R_1^d(p_1, i_1) = R_1^s$$

by (4.22) for the first period. First period resource demand is derived from competitive final goods production and defined in (4.6). For the second period, the market clearing condition reads

$$R_2^d(p_2, i_2, \mu, \omega) = R_2^s \tag{7.16}$$

where with simultaneous use of renewable and fossil energy, resource demand is modified and given by residual resource demand from (7.12). Moreover, by construction of the conditional market equilibrium, the resource market equilibrium requires aggregate resource demand over both periods to exactly equal aggregate supply given by the resource stock, i.e.

$$R_1^d + R_2^d = \bar{R}$$

As before, the equilibrium resource extraction path will be defined later on by imposing additional structure on the supply side of the resource market.

Capital Market Equilibrium

For the first period, with fixed and price-inelastic capital supply from aggregate capital endowments the market clearing condition in the capital market is given in (4.23). In the second period, we must have

$$K_2^d(i_2, p_2, \mu, \omega) = K_2^s(R_2, i_2, \mu) \tag{7.17}$$

in equilibrium. In contrast to the standard setting and (4.24), aggregate capital demand from (7.13) includes both, demand for production capital and for renewable generation capacities. Moreover, aggregate capital supply is a function of the resource supply path and the interest rate but even in the symmetric country case also a function of the technology parameter μ according to (7.14).

Overall, whereas the first period factor market prices obviously only depend on the resource extraction path, the market clearing conditions in all three international markets in the end define the future factor market prices p_2 and i_2, and the equilibrium capital stock K_2 as functions of the resource extraction path, the renewable energy subsidy, and the state of the renewable energy technology μ even for symmetric countries.

7.4.2 Comparative Statics of the Conditional Market Equilibrium

Since the definition of the conditional market equilibrium in the previous section only implicitly includes renewable energy production, the comparative statics analysis is divided into two steps. We at first study equilibrium investments in renewable energy generation in more detail before we investigate the influence of the resource supply path on the overall conditional equilibrium. The latter, as in the standard setting, is our actual objective in this section as to prepare the analysis of the resource supply decision and reactions for the competitive and the monopolistic resource market.

7.4.2.1 Equilibrium Investments in Renewable Energies

Investments in renewable energies are only implicitly included in the definition of the conditional market equilibrium in section 7.4.1 via the second period residual resource demand function from (7.12) and the aggregate capital demand from (7.13). To fully disentangle how the endogenous factor market prices and the second period capital stock depend on the resource extraction path, the climate policy instruments (the carbon tax τ and the subsidy ω), and the state of the renewable energy technology μ in market equilibrium we first investigate the equilibrium investments in renewable energies in more detail.

The first-order conditions (7.7) and (7.6) simultaneously have to hold in market equilibrium, which implies

$$F_{2Q}\mu W_{2K} = (1-\omega)F_{2K} \tag{7.18}$$

and thereby implicitly define optimal renewable energy investments as a function of the input factors in final goods production, the state of technology μ, and the renewable energy subsidy ω. To study these relationships, we totally differentiate (7.18) with respect to the parameters of interests – the climate policy instruments and the state of technology – and the resource and capital inputs R_2, K_{2W} and K_{2F}. Since we again want to separate the feedback effects arising from the endogenous adjustment of the overall capital stock K_2 from the "direct" effects of resource supply and the parameters of interest in the following, we establish the relationship to the aggregate capital stock K_2 by setting $dK_{2F} = dK_2 - dK_{2W}$, which holds true by construction (see (7.3)).

An increase in the fossil resource input R_2 ceteris paribus, i.e. in particular neglecting the induced change in the aggregate capital stock K_2, crowds out renewable energies in the energy market which directly reduces renewable energy investments. Intuitively, on the one hand, by the concavity of the final goods production technology higher resource supply reduces the marginal productivity of energy, and thereby the market price energy. Thus, the market value of capital investments in renewable energy generation decreases. On the other hand, and this again illustrates the interaction of the capital and the resource market, a higher fossil resource supply also increases the marginal productivity of capital via the complementarity of capital and energy in final goods production, and thereby the interest rate i_2 and the capital costs of renewable energy generation. Both effects obviously deter investments in renewable energies so that for a constant overall capital stock K_2 capital unambiguously gets reallocated to final goods production. For the induced reallocation of capital we therefore get[12]

$$\left.\frac{dK_{2W}}{dR_2}\right|_{K_2} = \frac{(1-\omega)F_{2KQ} - F_{2QQ}\mu W_{2K}}{\Xi} < 0 \tag{7.19}$$

where we simplify notation by defining

$$\begin{aligned} \Xi = F_{2Q}\mu W_{2KK} + F_{2QQ}\left(\mu W_{2K}\right)^2 + (1-\omega)F_{2KK} \\ - (1-\omega)F_{2KQ}\mu W_{2K} - F_{2KQ}\mu W_{2K} < 0 \end{aligned} \tag{7.20}$$

The negative sign is due to the concavity of both, the final goods production technology and the renewable energy technology (7.1).

Somewhat surprisingly, technological change improving the usability of renewable energies, i.e. an increase in μ, does not necessarily induce renewable energy generation to attract capital from the final goods production according to

$$\left.\frac{dK_W}{d\mu}\right|_{K_2} = \frac{\left[(1-\omega)F_{2KQ} - F_{2QQ}\mu W_{2K}\right]W_2 - F_{2Q}W_{2K}}{\Xi} \gtrless 0 \tag{7.21}$$

The reason for this is the ambiguous effect of technological change on the marginal market value of capital investments in renewable energies ($F_{2Q}\mu W_{2K}$). On the one hand, the marginal market value raises with μ as the marketable energy output per capital investment ($F_{2Q}W_{2K}$) increases. But on the other hand, the total energy input available in the economy increases with μ ceteris paribus, too. This implies first that the market price of energy is reduced due to the decreasing marginal productivity

[12] We use the notation $|_{K_2}$ throughout the text to clarify that K_2 is held constant.

of energy ($F_{2QQ} < 0$), and second that the market price of capital increases by the complementarity of energy and physical capital in final goods production ($F_{2KQ} > 0$). These changes in the factor market prices obviously deter investments in renewable energies. Using condition (7.18) we can show that in market equilibrium the sign of (7.21) depends on the energy mix, i.e. the share of renewable energy in total energy used in the economy, relative to the elasticity of substitution σ between the energy and capital input factor in final goods production:

$$\left.\frac{dK_W}{d\mu}\right|_{K_2} = -\frac{F_{2Q}W_{2K}}{\sigma}\frac{\sigma - \frac{\mu W_2}{Q_2}}{\Xi} \gtrless 0 \qquad \leftrightarrow \qquad \sigma \gtrless \frac{\mu W_2}{Q_2}$$

Note that for $\sigma \geq 1$ (i.e. including the Cobb-Douglas case) the renewable energy generation unambiguously attracts capital from final goods production when μ increases.[13] Nevertheless, we can show that ceteris paribus the total energy supply Q_2 to the resource importing economies unambiguously raises with μ as

$$\left.\frac{dQ_2}{d\mu}\right|_{K_2} = W_2 + \mu W_{2K}\left.\frac{dK_{2W}}{d\mu}\right|_{K_2} > 0 \tag{7.22}$$

Hence, with respect to energy generation, the improvement in the usability, or the productivity of renewable energy capacities in terms of usable energy output, dominates in any case.

A higher subsidy on renewable energy investments unambiguously directs capital to the energy sector ceteris paribus

$$\left.\frac{dK_W}{d\omega}\right|_{K_2} = -\frac{i_2}{\Xi} > 0 \tag{7.23}$$

This is intuitively expected. The subsidy reduces the capital cost of renewable energy generation compared to capital used in production so that there is an incentive to substitute production capital by energy generated from the renewable energy technology.

Finally, we also find that if the overall capital stock K_2, for whatever reason, increases a share

$$\phi = \frac{(1-\omega)F_{2KK} - F_{2KQ}\mu W_{2K}}{\Xi} \tag{7.24}$$

[13] A rather high elasticity of substitution $\sigma \geq 1$ implies that energy demand is price-elastic (see (5.6)). This also implies that the marginal productivity of energy and capital more weakly react to an increase in the energy input, and therefore that the counteracting own-price effect F_{2QQ} is weaker.

of the additional physical capital available will be invested in renewable energies whereas a share of

$$1 - \phi = \frac{F_{2Q}\mu W_{2KK} + F_{2QQ}\left(\mu W_{2K}\right)^2 - (1-\omega)F_{2KQ}\mu W_{2K}}{\Xi}$$

will be invested in the production capital stock K_{2F}. These shares generally are not constant but change with the extraction path, the capital stock and the other parameters of interest, namely the climate policy instruments and the state of technology.

7.4.2.2 Influence of the Resource Extraction Path

If the market clearing conditions of all three markets hold simultaneously, they define equilibrium relationships between the market prices for energy (resources) p_2 and capital i_2 as well as the aggregate capital accumulation K_2 and the resource extraction path (R_1, R_2), the policy instruments (τ and ω) as well as the state of renewable energy technology measured by the parameter μ. By use of a comparative static analysis we further investigate these equilibrium relationships in the following.

For the first period, we can directly refer to the standard framework and section 4.2.2.1. We have

$$\frac{dp_1}{dR_1} = \frac{\partial p_1}{\partial R_1} = F_{1RR} < 0 \qquad \text{and} \qquad \frac{di_1}{dR_1} = \frac{\partial i_1}{\partial R_1} = F_{1KR} > 0$$

from (4.26) and (4.27). The resource and capital market prices in the first period therefore do not depend directly on the climate policy instruments or the state of technology μ.

For the second period, we show in appendix 9.2.2.1 that the second period capital stock reacts to a postponement of resource extraction according to

$$\frac{dK_2}{dR_2} = \frac{\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + \left.\frac{di_2}{dR_2}\right|_{K_2} SE}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE} \tag{7.25}$$

Analogue to (4.28), the denominator again captures the feedback effect from an increase in the aggregate physical capital stock K_2 on the savings incentives of households in both countries. With symmetric homothetic preferences, this feedback effect solely arises from the accompanying change in the interest rate which induces the aggregate substitution effect SE from (4.18). However, since in contrast to the standard setting a share ϕ (cf. (7.24)) of any addition to the overall physical capital stock is distributed to the renewable energy generation, the induced change in the interest rate is now composed of two, in principle counteracting, effects: On the one hand, additional capital in final goods production reduces the marginal productivity of capital in final goods production due to diminishing returns. On the other hand, since renewable energy generation ceteris paribus increases, there is also a positive effect on the interest rate by the complementarity of energy and capital in final goods production. Overall, however, we can show by use of the definition of ϕ in (7.24) that

$$\left.\frac{di_2}{dK_2}\right|_{R_2} = (1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K} < 0 \tag{7.26}$$

Thus, the negative effect from the diminishing returns to capital in production always dominates and the interest rate ceteris paribus, i.e. for a given resource supply path, unambiguously decreases with an increase in the overall capital stock K_2.[14] This also implies that the denominator is unambiguously of positive sign. As we demonstrated in section 4.2.2.2, the positive sign is also ensured by the optimal savings decisions of households, for example in the more generally case of asymmetric countries.

Completely analogue to the corresponding term in the standard framework (see (4.28)), the first two terms in the numerator capture the intertemporal shift in aggregate production and the accompanying effect on savings which comes along with a postponement of extraction. Since second period income ceteris paribus increases at the expense of first period income, this income shift unambiguously lowers savings due to the familiar consumption smoothing motives of households. The last term in the numerator captures the aggregate substitution effect SE which a change in the resource supply path triggers. In contrast to the standard setting, second period resource supply now does not only affect the market interest rate via the complementarity of energy and capital in final goods production but also by crowding out renewable energy generation in the energy market, which frees up capital ceteris paribus for investment in production as we know from (7.19).[15] Total energy supply

[14] In fact, using (7.24) we get upon rearranging

$$(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K} = \frac{F_{2KK}F_{2Q}\mu W_{2KK} + \Gamma_W\left(\mu W_{2K}\right)^2}{\Xi} < 0$$

[15] In general, the substitution effect arises as long as fossil resource supply has a separate, or direct, effect on the marginal productivity of capital.

to the economy still rises with resource supply despite the crowding out of renewable energy generation as by definition in (7.19)

$$\left.\frac{dQ_2}{dR_2}\right|_{K_2} = 1 + \mu W_{2K} \left.\frac{dK_{2W}}{dR_2}\right|_{K_2} > 0 \tag{7.27}$$

The complementarity effect, therefore, still works towards a positive influence of resource supply on the interest rate. But due to the reallocation of capital to final goods production and the diminishing returns, we overall have for the extended influence on the interest rate for a given capital stock K_2

$$\begin{aligned} &\left.\frac{di_2}{dR_2}\right|_{K_2} = F_{2KQ} + \left(F_{2KQ}\mu W_{2K} - F_{2KK}\right) \left.\frac{dK_{2W}}{dR_2}\right|_{K_2} \gtrless 0 \\ &\text{with} \\ &\left.\frac{di_2}{dR_2}\right|_{K_2} \gtrless 0 \qquad \leftrightarrow \qquad -\frac{W_{2KK}}{W_{2K}} \gtrless \frac{\Gamma_W}{F_{2KQ}F_{2Q}} \end{aligned} \tag{7.28}$$

Note that this ambiguity represents a fundamental difference to the standard setting.[16]

If the direct effect of resource supply on the interest rate given in (7.28) is negative, the numerator in (4.28) is negative, too, and a postponement of extraction unambiguously reduces the aggregate physical capital stock K_2. Otherwise, the numerator is generally of ambiguous sign, just as in the standard setting. However, from our discussion of the respective relationship there (see (4.28) and (4.29)) we know that $\sigma \geq \frac{1}{\eta}$ is a sufficiency condition for a negative relationship between the aggregate equilibrium capital stock K_2 and a shift of resources to the future period for symmetric countries. Since the induced reallocation of physical capital away from renewable energy gener-

[16] By using (7.19), the ambiguity and the inequality condition can directly be derived from

$$\left.\frac{di_2}{dR_2}\right|_{K_2} = \frac{F_{2KQ}F_{2Q}\mu W_{2KK} + \Gamma_W \mu W_{2K}}{\Xi}$$

Interestingly, since the right side of the inequality condition in (7.28) is always positive, resource supply can only have a positive influence on the market interest rate for a renewable energy technology with a decreasing marginal productivity of capital $W_{2KK} < 0$. Moreover, since the crowding out of resources leads to a higher capital stock in production, there would be a direct effect of resource supply on the interest rate even for an additive separable production technology with a zero cross derivative F_{2KQ}, but not for a linear production technology in the limiting case $\sigma \to \infty$ for which the marginal productivity of all production factors is constant.

ation always counteracts the positive complementarity driven direct effect of resource supply on the interest rate, we have

$$F_{2KQ} > F_{2KQ} + (F_{2KQ}\mu W_{2K} - F_{2KK}) \left.\frac{dK_{2W}}{dR_2}\right|_{K_2}$$

by (7.19). Hence, a positive interest rate influence, if any, is weaker with simultaneous use of renewable energies. This implies that (4.29) constitutes a sufficiency condition for a negative relationship between capital accumulation and future resource supply with renewable energies, too. A postponement of extraction will reduce the aggregate capital stock whenever it does so in the standard setting.

Comparing the relationship between the resource supply path and the aggregate capital stock with and without renewable energies, this observation also suggests that the numerator of (7.25) in absolute value terms tends to be greater with renewable energies. Moreover, since by (7.26) we have

$$\left| \left.\frac{di_2}{dK_2}\right|_{R_2} \right| < |F_{2KK}|$$

the denominator seems to be of lower value with renewable energies, too. Thus, the availability of a capital intensive renewable energy technology seems to strengthen the reaction of the overall capital stock to postponements of resource extraction. However, we generally will have different capital stocks K_2 with and without such a renewable energy technology even if we compare (7.25) and (4.28) for exactly the same extraction path, and thereby also different energy and capital market prices p_2 and i_2. Strictly speaking, a comparison of the strength, i.e. the absolute value, of the capital stock reaction to postponements of resource extraction is therefore analytically impossible.

We discuss the equilibrium influence of the resource supply path on the capital investments in final goods production K_{2F} and in renewable energy generation K_{2W} as well as the effect of resource supply on the overall market energy supply Q_2 in appendix 9.2.2.2. In the following, we focus on the relationship between the resource supply path and the market (consumer) prices of energy and capital. Thereby and similar to (4.30) and (4.31), we again aim to separate the direct from the indirect effect which arises solely from the induced change in the overall capital stock according to (7.25).

To decompose the equilibrium influence of resource supply on the interest rate i_2 we can directly build upon the definitions in (7.28) and (7.26) as well as (7.25) to get

$$\frac{di_2}{dR_2} = \left.\frac{di_2}{dR_2}\right|_{K_2} + \left.\frac{di_2}{dK_2}\right|_{R_2} \frac{dK_2}{dR_2} \tag{7.29}$$

In contrast to the respective reaction in the standard setting without renewable energies given in (4.31), the interest rate no longer necessarily rises with a shift of resource extraction to the second period even for symmetric preferences. This is again due to the crowding out of renewable energy by fossil resources and the corresponding deduction of capital from renewable energy generation. Intuitively, by reducing the economic attractiveness of renewable energies, higher resource supply decreases aggregate capital demand, but at the same time capital demand from final goods production rises via the complementarity of production factors. Given $\left.\frac{di_2}{dK_2}\right|_{R_2} < 0$ from (7.26), we can conclude from the decomposition in (7.29) that irrespective of the sign of (7.25), the interest rate will unambiguously increase with a shift of resources to the second period if $\left.\frac{di_2}{dR_2}\right|_{K_2} > 0$, but may fall if $\left.\frac{di_2}{dR_2}\right|_{K_2} < 0$.

Analogously we decompose the general equilibrium relationship between the energy market price and future resource supply according to

$$\frac{dp_2}{dR_2} = \left.\frac{dp_2}{dR_2}\right|_{K_2} + \left.\frac{dp_2}{dK_2}\right|_{R_2} \frac{dK_2}{dR_2} \tag{7.30}$$

where analogue to (7.28) we define the direct effect of resource supply as

$$\left.\frac{dp_2}{dR_2}\right|_{K_2} = F_{2QQ} + (F_{2QQ}\mu W_{2K} - F_{2QK}) \left.\frac{dK_{2W}}{dR_2}\right|_{K_2} < 0 \tag{7.31}$$

Thus, resource supply still reduces the energy market price for a given overall capital stock K_2. This directly follows from (7.19) and $\Gamma_W > 0$ from (7.10). However, the negative direct own-price effect is dampened by the induced reallocation of physical capital away from renewable energy generation. On the one hand, this partly offsets the increase in energy supply to the economy (see above), and, on the other hand, it raises the capital stock in final goods production which by the complementarity of both factors increases the marginal productivity of energy, and correspondingly the energy market price.

In addition, there is the indirect effect from the induced change in the aggregate capital stock according to (7.25). With simultaneous use of fossil and renewable energy, a share $1 - \phi$ of additional physical capital is (at the margin) distributed to final goods production while a share ϕ goes to energy generation. We summarize the two counteracting effects arising from such an increase and distribution of the overall capital stock on the marginal productivity of energy analogue to (7.26) by

$$\left.\frac{dp_2}{dK_2}\right|_{R_2} = (1-\phi)F_{2QK} + \phi F_{2QQ}\mu W_{2K} \gtrless 0$$
$$\text{with} \quad \left.\frac{dp_2}{dK_2}\right|_{R_2} \gtrless 0 \quad \leftrightarrow \quad -\frac{W_{2KK}}{W_{2K}} \gtrless (1-\omega)\frac{\Gamma_W}{F_{2KQ}F_{2Q}} \tag{7.32}$$

which is, however, generally of ambiguous sign. Since the right side of the inequality condition is always positive, the positive complementarity effect of additional physical capital can only dominate if the marginal productivity of capital in renewable energy generation is decreasing ($W_{2KK} < 0$). The ambiguity of (7.32) implies that even if condition (4.29) holds and the aggregate capital stock is always reduced with a shift of resource extraction to the future period according to (7.25), the marginal productivity of energy, and therefore the energy price, no longer needs to fall with higher resource supply. Obviously, given that we assume $\sigma > \frac{1}{\eta}$, the sign of the market price reaction crucially depends on the influence which a change in the capital stock has on the marginal productivity of energy. If the complementarity effect dominates and a sufficiently large share $1-\phi$ of additional physical capital is invested directly into final goods production, the negative sign of the standard setting prevails. If, however, changes in the aggregate physical capital stock predominantly affect the renewable energy generation so that (7.32) is negative, the induced change in the capital stock may even reverse the negative own-price effect and higher resource supply will come along with a higher energy price.[17] This ambiguity is obviously in contrast to the standard setting, in which according to (4.30) the energy price always decreases with a postponement of extraction for symmetric preferences, even irrespective of the sign of the capital stock reaction in (4.28).

[17] This ambiguity can also be observed by decomposing the influence of future resource supply on the energy market price along the changes in energy supply and production capital

$$\frac{dp_2}{dR_2} = F_{2QQ}\frac{dQ_2}{dR_2} + F_{2KQ}\frac{dK_{2F}}{dR_2}$$

because we know by (9.16) and (9.17) from appendix 9.2.2.2 that resource supply has an ambiguous influence on both variable factors of final goods production.

7.5 Optimal Resource Supply

In the competitive resource market, resource owners have rational expectations regarding the future market prices p_2 and i_2. As long as there is positive (residual) demand for the fossil resource from the competitive final goods producers, the competitive market equilibrium can be derived by considering a representative resource extraction firm in the resource-rich countries which takes the market prices of fossil resources and capital as given and chooses its supply policy as to maximize the present value of aggregate profits, just as in the standard framework without the renewable energy technology. In equilibrium, the optimal extraction path is therefore again characterized by the familiar Hotelling condition (2.3).

If we assume that country E has monopoly power in the resource market, we in principle can adapt our discussion of section 5.2 to the modified setting with simultaneous use of the renewable energy technology in the second period. In the following, however, we just focus on the naive sheikh from section 5.2.2.1. The naive sheikh takes the market interest rate i_2 and future (inverse) resource demand function $p(R_2)$ as given, i.e. as not affected by her supply decision. Thus, the optimal extraction path in this case is in principle also again characterized by the familiar Hotelling condition (5.4). However, in contrast to the previous setting, future resource demand is now represented by residual resource demand given that there are optimal competitive investments in renewable energy generation.[18] Hence, since the sheikh is completely naive with respect to the cross market effects of her resource supply decision, the "partial" energy market price reaction corresponds to (7.31). This implies that the second period marginal resource revenue is given by

$$MR_2^n = p_2 + \left.\frac{dp_2}{dR_2}\right|_{K_2} R_2 \tag{7.33}$$

analogue to (5.5). With the residual resource demand function, we can also redefine the partial price elasticity of (residual) resource demand in the second period

$$\epsilon^W_{R_2,p_2} = -\frac{1}{\left.\frac{dp_2}{dR_2}\right|_{K_2}\frac{R_2}{p_2}} = \epsilon_{Q_2,p_2}\frac{\frac{Q_2}{R_2}}{1+\left(\mu W_{2K}-\frac{F_{2KQ}}{F_{2QQ}}\right)\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}} \tag{7.34}$$

whereas ϵ_{Q_2,p_2}, which is defined according to (5.6), measures the price elasticity of (overall) energy demand. The price elasticity of resource demand is greater than the

[18] In the end, this construction implies that the naive monopolist internalizes the reaction of the competitive fringe in the energy market and therefore can be seen as a Stackelberg leader in the energy market in the second period.

price elasticity of energy demand by definition from (7.31) and $Q_2 \geq R_2$ (see (7.2)). First, with simultaneous use of both energy sources, a one percent increase in resource supply raises the total energy supply by less than one percent. This is captured by the term $\frac{Q_2}{R_2}$, which effectively weighs the price elasticity of energy demand ϵ_{Q_2,p_2} by the share of fossil resources in total energy supply. Second, fossil resources crowd out renewable energies in the energy market and thereby induce a reallocation of physical capital which directly follows from the additional interrelationship between the resource and the capital market introduced by the capital intensive renewable energy technology. This capital reallocation raises the price elasticity of resource demand for two reasons as captured in the denominator of the second component. On the one hand, the energy supply to the economy rises more weakly as any increase in the supply of fossil resources is partly offset by the decrease in renewable energy generation (see (7.27)). On the other hand, the reallocation of physical capital to final goods production raises the marginal productivity of energy due to the complementarity of energy and physical capital in production. Both effects counteract the decrease in the marginal productivity of energy from a higher resource supply by the diminishing returns to energy in final goods production and hence increase the price elasticity of residual resource demand.

The increase in the price elasticity of resource demand due to the availability and simultaneous use of the renewable energy technology also implies that the naive sheikh will extract more conservatively than the competitive market even if production is of Cobb-Douglas type for $\sigma = 1$. The reason is that the latter only implies that energy/resource demand in the first period and energy demand in the second period are iso-elastic, whereas resource demand in the second period is more price-elastic. This also implies that at least for the Cobb-Douglas cas the monopolist chooses a more conservative extraction policy than the competitive market. Since we know by (9.15) from appendix 9.2.2.2 that renewable energy generation is the higher the lower second period resource extraction and, correspondingly, the larger the degree of depletion of the resource stock at the beginning of the second period, this conservationist's extraction bias is, at least in the Cobb-Douglas case, somewhat similar to the one found by Hillman and Long (1982).

7.6 Revisiting the Effect of Climate Policies

We proceed along the lines of chapter 6 and study in the following first the influence of both climate policy instruments, the carbon tax τ and the renewable energy subsidy ω, on the modified conditional market equilibrium. We then again resort to a comparative statics analysis to investigate the equilibrium changes in the resource extraction path which are induced by more ambitious climate policies for the competitive market and the naive sheikh.

7.6.1 Influence of Climate Policies on the Conditional Market Equilibrium

The comparative statics with respect to the carbon tax τ and the renewable energy subsidy ω is derived in appendix 9.2.2.1. The carbon tax τ, in principle, redistributes resource rents from country E to country I ceteris paribus, as we previously discussed in section 6.2, and thereby generally influences aggregate capital supply. However, for symmetric countries, the net effect of any pure income redistribution between countries is neutral with respect to the aggregate savings and therefore with respect to the overall capital market equilibrium. Thus,

$$\frac{dK_2}{d\tau} = 0 \tag{7.35}$$

The simultaneous use of the renewable energy technology in the second period does not affect these observations from our previous analysis.

The renewable energy subsidy ω, in contrast, directly impacts the equilibrium conditions which characterize the optimal deployment of the renewable energy technology. It reduces the capital costs of renewable energy generation incurred by final goods producers and thereby influences the optimal allocation of capital between renewable energy generation and final goods production as can be observed from (7.23). In this way, the subsidy affects the market demand for capital and the residual demand for fossil resources (see (7.12) and (7.13)). Since the subsidy is lump-sum financed within country I and households derive income from both, capital investments and labour supply, a higher subsidy is completely neutral with respect to the overall second period household income and therefore also with respect to capital supply. Hence, the influence of the renewable energy subsidy on the conditional market equilibrium, and the capital market equilibrium in particular, only arises from capital demand.

With a higher subsidy, renewable energy generation does not only attract capital from final goods production ($\frac{dK_{2W}}{d\omega}\Big|_{K_2} > 0$ from (7.23)) but also leads to a higher aggregate capital demand in the economy. This can be observed from (7.13).[19] Thus, driven by this increase in capital demand, the aggregate equilibrium capital stock increases in ω, i.e.

$$\frac{dK_2}{d\omega} = \frac{(F_{2KQ}\mu W_{2K} - F_{2KK}) \frac{dK_{2W}}{d\omega}\Big|_{K_2} SE}{1 - \frac{di_2}{dK_2}\Big|_{R_2} SE} > 0 \tag{7.36}$$

The interpretation of the numerator is similar to that of (7.25). The induced reallocation of physical capital from final goods production to renewable energies leads to an increase in the market interest rate i_2 (i.e. the marginal productivity of capital), on the one hand via the increase in the energy supply available to the economy and the complementarity of energy and capital in production, on the other hand due to the decrease in the capital stock invested in final goods production and the concavity of the production technology. This increase in the interest rate induces a substitution effect (SE from (4.18)) so that households are willing to save more and the aggregate capital stock rises. As before, the (positive) denominator captures the feedback effect on the savings incentives of households which a change in the aggregate capital stock K_2 has for symmetric countries.

Obviously, with a higher overall capital accumulation and with a rising attractiveness of capital investments in renewable energy generation over investments in final goods production, the subsidy rate also increases the equilibrium capital stock in renewable energy generation

$$\frac{dK_{2W}}{d\omega} = \frac{dK_{2W}}{d\omega}\Big|_{K_2} + \phi\frac{dK_2}{d\omega} = \frac{(1 - F_{2KK}SE) \frac{dK_{2W}}{d\omega}\Big|_{K_2}}{1 - \frac{di_2}{dK_2}\Big|_{R_2} SE} > 0 \tag{7.37}$$

Given that we evaluate the comparative statics for some constant extraction path (R_1, R_2), this also implies directly that the energy supply to the resource importing economies increases:

$$\frac{dQ_2}{d\omega} = \mu W_{2K}\frac{dK_{2W}}{d\omega} > 0 \tag{7.38}$$

[19] In the end, a higher subsidy creates "additional" capital demand for a given market interest rate from the renewable energy generation.

Moreover, since the energy subsidy induces a reallocation of capital to renewable energy generation, the capital stock invested in final goods production decreases

$$\frac{dK_{2F}}{d\omega} = \frac{dK_2}{d\omega} - \frac{dK_{2W}}{d\omega} = \frac{\left[\frac{di_2}{dK_2}\Big|_{R_2} - 1\right] SE\ \frac{dK_{2W}}{d\omega}\Big|_{K_2}}{1 - \frac{di_2}{dK_2}\Big|_{R_2} SE} < 0 \tag{7.39}$$

Thus, overall, the factor input relation K_{2F}/Q_2 falls, i.e. production becomes more energy-based. Note that by (7.26) the negative sign always holds true even though the aggregate capital stock K_2 increases.

With energy supply increasing and the capital stock invested in final goods production K_{2F} decreasing, the marginal productivity of energy has to fall, too. In fact, we have

$$\begin{aligned} \frac{dp_2}{d\omega} &= (F_{2QQ}\mu W_{2K} - F_{2KQ}) \left.\frac{dK_{2W}}{d\omega}\right|_{K_2} + \left.\frac{dp_2}{dK_2}\right|_{R_2} \frac{dK_2}{d\omega} \\ &= F_{2QQ}\frac{dQ_2}{d\omega} + F_{2KQ}\frac{dK_{2F}}{d\omega} < 0 \end{aligned} \tag{7.40}$$

Obviously, these production factor changes also imply that the marginal productivity of capital in final goods production, or the equilibrium interest rate, has to increase with a higher subsidy

$$\begin{aligned} \frac{di_2}{d\omega} &= (F_{2KQ}\mu W_{2K} - F_{2KK}) \left.\frac{dK_{2W}}{d\omega}\right|_{K_2} + \left.\frac{di_2}{dK_2}\right|_{R_2} \frac{dK_2}{d\omega} \\ &= F_{2KQ}\frac{dQ_2}{d\omega} + F_{2KK}\frac{dK_{2F}}{d\omega} > 0 \end{aligned} \tag{7.41}$$

7.6.2 The Resource Supply Reaction: Competitive Market

We now assess the effect of future climate policies on the competitive resource extraction path if there is simultaneous use of both energy sources in the second period and if countries have symmetric homothetic consumption preferences. Since the carbon tax again does not have any separate influence on the conditional market equilibrium in this case, the reaction of the competitive resource extraction path to a (marginal) increase in the future carbon tax is given by

$$\frac{dR_2^c}{d\tau} = \frac{-p_2}{\frac{di_2}{dR_2}p_1 - (1+i_2)\frac{\partial p_1}{\partial R_1} - (1-\tau)\frac{dp_2}{dR_2}} < 0$$

which directly corresponds to (6.4) in the standard framework without renewable energies. The denominator must be of positive sign, although $\frac{dp_2}{dR_2}$ from (7.30) and $\frac{di_2}{dR_2}$

from (7.29) now are generally ambiguous even in the symmetric country case. As before, the reason is that we evaluate the comparative statics again along the equilibrium extraction path (R_1^c, R_2^c) which maximizes the profits of the competitive resource owners. Hence, we again can refer to the second-order condition of the representative firm's profit maximization to argue that the denominator must be of positive sign, as laid out in section 6.3. Thus, the green paradox again necessarily arises in the competitive resource market with symmetric countries.

In contrast to the carbon tax, we know from the previous section that the factor market prices in the second period directly depend on the renewable energy subsidy even in the symmetric country case. With (7.40) and (7.41), we get for the comparative statics from the total derivative of Hotelling condition (2.3)

$$\frac{dR_2^c}{d\omega} = \frac{-\frac{di_2}{d\omega}p_1 + (1-\tau)\frac{dp_2}{d\omega}}{\frac{di_2}{dR_2}p_1 - (1+i_2)\frac{\partial p_1}{\partial R_1} - (1-\tau)\frac{dp_2}{dR_2}} < 0 \tag{7.42}$$

Since we already have discussed the denominator, we focus on the numerator in the following. The overall negative sign directly follows from the equilibrium relationship between the subsidy level and the factor market prices (7.40) and (7.41) derived before.

This green paradox result, in principle, is in line with the effect of subsidy schemes for backstop technologies in partial equilibrium settings, in which backstop technologies are typically represented by defining a choke price $\bar{p}$ via the marginal production costs of the backstop technology. In these settings, lowering the choke price by governmental support schemes unambiguously induces an acceleration of extraction if the choke price is or becomes binding. The reasoning is completely analogue to the standard tax case: The (climate) policy devaluates future resource supply by reducing the future resource market price so that resource owners with perfect foresight/rational expectations adjust their extraction policy (see also section 2.2).

In contrast, the renewable energy subsidy in our general equilibrium setting gives rise to additional effects. This is primarily due to the capital intensity of the backstop technology and the fact that we consider a scenario with simultaneous use of both, fossil resources and renewable energies. First, since the renewable energy technology is capital intensive, the subsidy increase directly raises capital demand and thereby the market interest rate i_2. Following Hotelling condition (2.3) and the underlying non-arbitrage principle, this creates a separate incentive to shift resources from the second to the first period because the opportunity costs of leaving resources underground rise. Second, as we already know from the decomposition of the energy market price effect in (7.40), stronger support for renewable energy generation reallocates capital away from final goods production (even without a change in the aggregate capital stock K_2). On the one hand, this implies that ceteris paribus the energy amount available to the economy increases, which reduces the marginal productivity of energy and thereby the energy market price. From the resource owners' perspective, this may be interpreted as the counterpart to the subsidy driven reduction in the choke price of a backstop technology in the standard setting. On the other hand, the capital stock invested in production decreases with this reallocation of capital so that the energy market price is further reduced due to the complementarity of energy and capital in final goods production. Finally, the renewable energy subsidy also induces an increase in the aggregate stock of physical capital (see also (7.36)) via capital demand which is distributed between renewable energy generation and final goods production. This dampens the increase in the interest rate according to (7.26) and (7.41) whereas the energy market price generally may increase or decrease depending on the sign of (7.32). However, we know from the market price reactions (7.40) and (7.41) in section 7.6.1 that in the end the effect of this increase in the capital stock on the interest rate and the energy market price is always dominated by the effect of the subsidy induced reallocation of capital from production to renewable energy generation.

Quantitative comparisons between the more standard representation of backstop technologies and the effect of subsidies in partial equilibrium and the present general equilibrium approach with capital intensive renewable energies are generally not meaningful. Yet, the endogeneity of the interest rate and of the capital stock K_2 with respect to the support policy at least point to additional transmission channels in general equilibrium which both tend to intensify the resource owners' incentive to accelerate extraction. The green paradox, therefore, tends to be amplified compared to the case where the backstop technology does not have such a direct influence on the capital market.

We further illustrate our findings by use of numerical simulations of the model. In figure 7.1, we first observe that for a low resource endowment $\bar{R} = 1$, which we assumed throughout the discussion of the standard setting without renewable energies,[20] the

[20] Moreover, note that we assume Cobb-Douglas production here. This is also in contrast to the exemplary numerical simulations of our standard setting in the previous chapters but proofs useful for the analysis of the monopolistic supply reaction as will become clear later on.

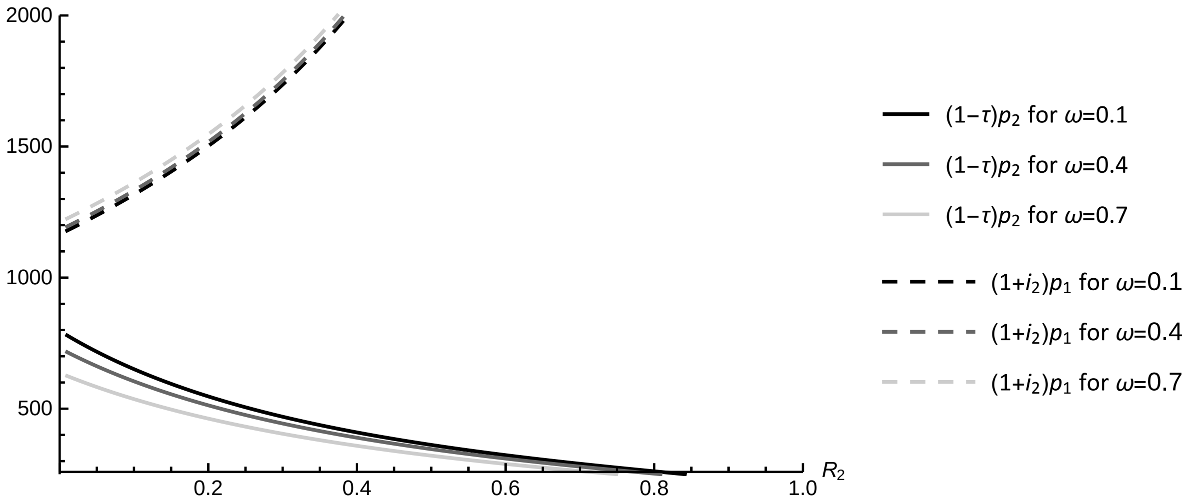

Figure 7.1: Corner solution in the competitive case for $\bar{R} = 1$;
assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\mu = 0.1$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

availability of the renewable energy technology in the second period gives rise to a corner solution (see also section 7.3.4). In this case, the resource stock is completely extracted in the first period as to build up a large capital stock for energy generation and final goods production in the second period. Such a corner solution also implies that climate policy interventions in the second period are completely neutral with respect to the competitive extraction of the fossil resource. With an interior solution and simultaneous use of both energy sources in the second period for a larger resource stock $\bar{R} = 10$, however, figure 7.2 confirms our previous findings. In this case, the economy is less bound by the natural limits to resource extraction: Despite of the availability of the substitutive renewable energy technology in the second period there is so much resource available underground that the economy does no longer completely exhaust the resource stock in the first period but uses fossil resources also in the second period. Given the intertemporal nature of resource supply in this case, the renewable subsidy affects the resource supply path as laid out before. On the one hand, a higher subsidy ceteris paribus, i.e. for any given future resource quantity R_2, decreases the market price of energy p_2 as more renewable energy gets produced. On the other hand, the increasing demand for capital from renewable energy generation raises the interest rate i_2 which shifts the future value of first period supply upwards. Together, these effects unambiguously give rise to a green paradox, although the effect is rather small quantitatively.

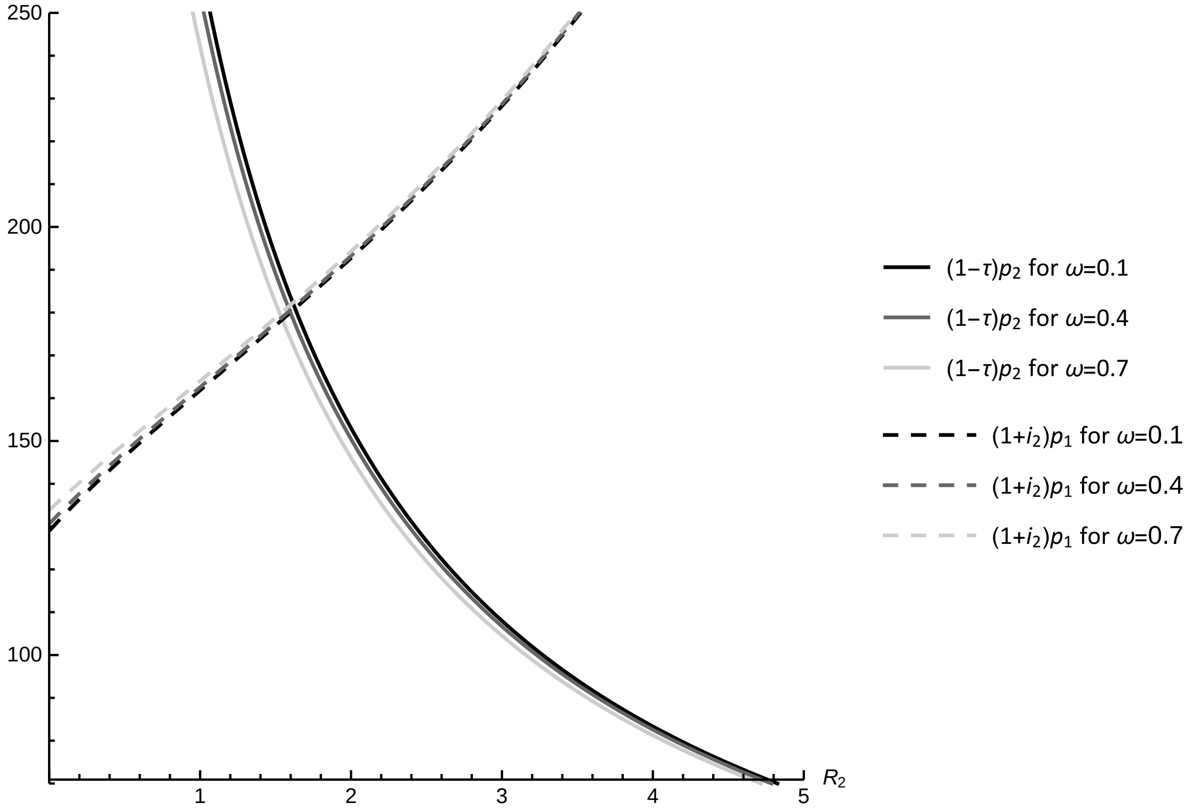

Figure 7.2: The effect of the renewable energy subsidy on the competitive resource extraction path for $\bar{R} = 10$;
assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\mu = 0.1$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

7.6.3 Resource Supply Reaction: Naive Monopolist

We now consider the effect of climate policies on the extraction decision of the naive sheikh. For the same reason as in the competitive case before, the carbon tax always induces the naive sheikh to accelerate extraction. The comparative statics from totally differentiating the Hotelling condition (5.4), in principle, completely coincides with (6.7). We have

$$\frac{dR_2^n}{d\tau} = \frac{-p_2\left(1 - \frac{1}{\epsilon^W_{R_2,p_2}}\right)}{\frac{di_2}{dR_2}MR_1^n - (1+i_2)\frac{dMR_1^n}{dR_1} - \frac{dMR_2^n}{dR_2}} < 0$$

The only difference is the modified price elasticity of resource demand from (7.34), which no longer equals the price elasticity of energy demand from final goods producers due to the simultaneous use of both energy sources in the second period. Otherwise, we can again refer to our discussion in section 6.4 to conclude that market power qualitatively does not alter the effect of the carbon tax on the resource extraction path with symmetric countries. In fact, the carbon tax does not directly impact the market equilibrium conditions which determine the equilibrium deployment of the renewable energy technology, and therefore does not alter neither residual resource demand nor the interest rate separately.

This conclusion, however, does not hold true with respect to the renewable energy subsidy. Totally differentiating the Hotelling condition (5.4) and taking into account (7.40) and (7.41), we get

$$\frac{dR_2^n}{d\omega} = \frac{-\frac{di_2}{d\omega}MR_1^n + \frac{dMR_2^n}{d\omega}}{\frac{di_2}{dR_2}MR_1^n - \frac{dMR_1^n}{dR_2} - \frac{dMR_2^n}{dR_2}} \tag{7.43}$$

To simplify notation in the comparative statics, we therein summarize the influence of the renewable energy subsidy on the future period's marginal resource revenue MR_2^n defined in (7.33) by

$$\frac{dMR_2^n}{d\omega} = (1-\tau)\left[\frac{dp_2}{d\omega}\left(1 - \frac{1}{\epsilon_{R_2,p_2}^W}\right) + p_2 \frac{1}{\left(\epsilon_{R_2,p_2}^W\right)^2}\frac{d\epsilon_{R_2,p_2}^W}{d\omega}\right] \tag{7.44}$$

As already discussed for the competitive case, due to the capital intensity of renewable energy generation, the renewable energy subsidy increases the market interest rate by more or less “creating” additional demand for capital (see also (7.41)). This establishes an (additional) incentive to accelerate extraction by raising the opportunity costs of leaving resources underground, which tends to amplify the green paradox.

Regarding (7.44), we first know from (7.40) that a higher renewable energy subsidy reduces the energy market price. The reason is that for given resource supply the final goods production becomes more energy based because the aggregate capital stock increases according to (7.36) but even more capital goes into renewable energy generation. Overall, residual energy and therefore resource demand fall, which obviously has a negative effect on the marginal resource revenue. Second, by directly influencing the market equilibrium conditions determining the deployment of the renewable energy technology, the renewable energy subsidy generally also affects the price elasticity of (residual) resource demand in contrast to the carbon tax. If the residual resource demand becomes less price-elastic, the green paradox necessarily arises and tends even to be amplified due to the downward shift in resource demand and the increase in the interest rate. However, if the price elasticity of resource demand increases, there is a positive effect on the future marginal resource revenue from the stronger renewable energy support, which generally counteracts the downward shift in (inverse) residual resource demand and the increase in the interest rate. If this increase in the price elasticity of residual resource demand is sufficiently strong, the future marginal resource revenue may increase with a stronger support for renewable energies and may even dominate the rise in the interest rate so that an incentive to postpone and to reverse the green paradox may be established.

7.6.3.1 The Influence of the Renewable Subsidy on the Price Elasticity of Resource Demand

In this section, we investigate the determinants of the price elasticity of residual resource demand according to its definition in (7.34) and the influence of the renewable energy subsidy in more detail. In particular, we discuss whether and why the price elasticity of residual resource demand may increase with a higher renewable energy subsidy.

In general, the renewable energy subsidy influences the price elasticity of resource demand directly as the reaction of renewable energy investments is a function of the subsidy rate according to (7.19), and indirectly because with a higher subsidy more capital is invested in energy generation for any given resource supply path so that the energy supply increases (see (7.38)) and final goods production is more energy based than before (see (7.37) and (7.39)). The various effects of the renewable energy subsidy on the price elasticity of residual resource demand arising from these developments can generally be disentangled as

$$\begin{aligned}\frac{d\epsilon^W_{R_2,p_2}}{d\omega} = \frac{\epsilon^W_{R_2,p_2}}{1+\left(\mu W_{2K}-\frac{F_{2KQ}}{F_{2QQ}}\right)\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}} & \left\{\frac{\mu W_{2K}}{R_2}\frac{\epsilon_{Q_2,p_2}}{\epsilon^W_{R_2,p_2}}\frac{dK_{2W}}{d\omega}\right.\\ & + \left(\frac{\partial\epsilon_{Q_2,p_2}}{\partial Q_2}\mu W_{2K}\frac{dK_{2W}}{d\omega}+\frac{\partial\epsilon_{Q_2,p_2}}{\partial K_{2F}}\frac{dK_{2F}}{d\omega}\right)\frac{\frac{Q_2}{R_2}}{\epsilon^W_{R_2,p_2}}\\ & - \frac{\partial\left[\left(\mu W_{2K}-\frac{F_{2KQ}}{F_{2QQ}}\right)\left.\frac{\partial K_{2W}}{dR_2}\right|_{K_2}\right]}{\partial K_{2W}}\frac{dK_{2W}}{d\omega}\\ & - \frac{\partial\left[\left(\mu W_{2K}-\frac{F_{2KQ}}{F_{2QQ}}\right)\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}\right]}{\partial K_{2F}}\frac{dK_{2F}}{d\omega}\\ & \left. - \left[1+\left(\mu W_{2K}-\frac{F_{2KQ}}{F_{2QQ}}\right)\right]\frac{\partial\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}}{\partial\omega}\right\}\end{aligned} \tag{7.45}$$

Since more capital is invested in energy generation with a higher subsidy rate for any given resource supply ((7.37)), the total energy supply increases and the share of fossil resources in the energy market decreases. This is captured by the first element in the curly brackets and tends to increase the price elasticity of resource demand. The reason is that a one percent increase in resource supply raises overall energy supply in percentage terms the less the lower the market share of resources. The second element measures the change in the price elasticity of energy demand which is induced by the change in the relative factor input in final goods production (K_{2F}/Q_2). As we already have pointed out before, by (7.38) and (7.39) production becomes more energy based for a higher subsidy. By (5.6) and (5.8) we know that, for example, for $\sigma < 1$ this development has counteracting effects on the price elasticity of energy demand. Energy demand becomes less price-elastic with a higher energy input but more price-elastic with a decreasing production capital stock. In case of a Cobb-Douglas production technology for $\sigma = 1$, energy demand is iso-elastic and we can abstract from these counteracting changes in the price elasticity of energy demand to focus on the difference in the price elasticity of energy and resource demand, which is primarily introduced by the supply reactions of the renewable energy generation, i.e. the competitive fringe in the energy market. Finally, the last three terms in curly brackets capture how the renewable energy subsidy influences the reaction of renewable energy supply and investments to increases in the supply of fossil resources. We thereby have to distinguish between the effects which arise due to the change in the capital stocks invested in energy generation and final goods production according to (7.37) and (7.39), and the more direct implication of a change in the subsidy rate for the relationship between the renewable investments and resource supply according to (7.19) given in the last term.[21]

Unfortunately, even in the Cobb-Douglas case, in which the second line in (7.45) drops out, the overall effect of the subsidy on the price elasticity of resource demand is ambiguous, in general. The decrease in the share of fossil resources, which necessarily comes along with a higher subsidy rate, always works towards an increase in the price elasticity of resource demand. However, the reason for the ambiguity is

[21] For the latter, we can show by the definition of (7.20) and (7.28) that

$$\frac{\partial \left.\frac{dK_{2W}}{dR_2}\right|_{K_2}}{\partial \omega} = -\frac{F_{2KQ}F_{2Q}\mu W_{2KK} + \Gamma_W \mu W_{2K}}{\Xi^2} = -\frac{\left.\frac{di_2}{dR_2}\right|_{K_2}}{\Xi} \gtrless 0$$

Thus, since $\Xi < 0$, the sensitivity of the capital investments in renewable energy generation increases in absolute value with a higher renewable subsidy if there is a negative relationship between future resource supply and the future interest rate.

that the subsidy rate influences the crowding out effects of fossil resource supply, i.e. how strongly fossil resource supply R_2 crowds out renewable energy generation, but also how much capital thereby is reallocated to final goods production. Hence, the ambiguity is also not resolved if we additionally assume away the endogeneity of savings and take the overall second period capital stock K_2 as given so that the induced changes in the renewable energy and the production capital stocks are just given by the induced capital reallocation measured by (7.19) (i.e. $\frac{dK_{2W}}{d\omega} = \frac{dK_{2W}}{d\omega}\Big|_{K_2} = -\frac{dK_{2F}}{d\omega}$).

To better understand the ambiguity, we consider the influence of the renewable energy subsidy on the crowding out of renewable energy supply and capital investments by fossil resources from a more intuitive point of view, in the following. In general, the price elasticity of resource demand will be high if the energy market share of fossil resources is low and/or if there is a strong crowding out of renewable energy generation. The reason is that an increase in resource supply then induces only a low increase in total energy supply and thereby only a small fall in the marginal productivity of energy. Moreover, a large reallocation of capital to final goods production contributes to a high price elasticity of resource demand, because it raises the marginal productivity of energy and thereby energy demand via the complementarity of production factors so that there is again a smaller reduction in the marginal productivity of energy upon an increase in resource supply.

However, both, the equilibrium reduction in renewable energy generation and the equilibrium amount of capital reallocated are interlinked, on the one hand by the renewable energy technology and on the other hand by how strongly the marginal productivity of energy and capital in production react to changes in production factor inputs. To disentangle these relationships, consider condition (7.18), which characterizes the optimal investments in the renewable energy technology. If resource supply increases, the marginal productivity of energy falls whereas that of capital rises so that renewable energy investments are no longer in equilibrium. Obviously, and as we already know from (7.19), the capital investments in renewable energy generation are reduced. This restores the renewable energy investment equilibrium, on the one hand by decreasing the energy supply Q_2, but on the other hand also by increasing the production capital stock K_{2F}. Via the complementarity of production factors and the concavity of the production technology, both implications of the crowding out of renewable energies by higher resource supply work towards the new renewable energy investment equilibrium. This implies that to restore the energy investment equilibrium given in (7.18) the renewable energy supply does not need to completely offset the increase in the fossil resource supply ceteris paribus (see also (7.27)). How much the renewable energy generation falls depends on the reaction of the factor market prices, or the marginal productivity of energy and capital, to the reduction in energy supply on the one hand and to the increase in the production capital stock K_{2F} on the other hand. For example, if the sensitivity with respect to energy supply is greater, the restoration of the investment equilibrium will predominantly rely on the reduction in the renewable energy generation and less on the capital redistribution. This sensitivity of factor prices with respect to changes in the input factors depends on the production structure – i.e. the elasticity of substitution σ and the share parameters λ and γ – and the relative factor input. In the Cobb-Douglas case,[22] for example, the reduction in renewable energy output will have a stronger effect on the factor prices p_2 and i_2 than the induced capital reallocation if[23]

$$|F_{2QQ}| \gtrless F_{2QK} = F_{2KQ} \gtrless |F_{2KK}| \qquad \leftrightarrow \qquad \frac{K_{2F}}{Q_2} \gtrless \sqrt{\frac{\gamma}{\lambda}\frac{1-\gamma}{1-\lambda}}$$

and vice versa. Additionally, we have to take into account that the relation between the reduction in renewable energy generation and the amount of physical capital redistributed is – for a given the state of technology μ – not constant. In fact, with a non-linear renewable energy technology W_2 from (7.1) it depends on the marginal productivity of capital in energy generation W_{2K}, and therefore on the concavity of the energy technology W_2 and on how much initially has been invested in renewable energies K_{2W}. For example, if the production structure requires a strong reduction in renewable energy output for restoring the investment equilibrium but the marginal productivity of capital in renewable energy generation is low, there must be a large reallocation of capital together with a large reduction in energy supply. In this case, since both implications of the competitive fringe's reaction strongly counteract the fall in the marginal productivity of energy from a higher resource supply, the negative own-price effect will be low and the price elasticity of residual resource demand will be high. In contrast, if the final goods production structure is such that primarily the redistribution of capital leads to the new investment equilibrium but the marginal productivity of capital in renewable energy generation W_{2K} is high, there will be only a rather small reduction in the energy supply and a small increase in the production capital stock K_{2F}. Hence, increasing resource supply then has a rather strong nega-

[22] The final goods production technology then reads $F_2 = Q_2^{\lambda} K_{2F}^{\gamma} L^{\xi}$ with $\xi = 1 - \lambda - \gamma > 0$.

[23] The first inequality on the right implies that energy supply has a stronger influence on the marginal productivity of energy, and thereby on the energy market price, than capital in production. The second inequality establishes that the influence of energy supply on the marginal productivity of capital, and thereby the market rate of interest, is stronger than for production capital. Note that $\frac{1-\gamma}{1-\lambda}\frac{\gamma}{\lambda} \gtrless 1$ for $\lambda \gtrless \gamma$.

tive effect on the marginal productivity of energy so that the price elasticity of energy demand is rather low.

Finally, the question is how (marginally) increasing the renewable energy subsidy ω influences these relationships, which characterize the strength of the crowding out of renewable energies and the amount of capital thereby redistributed, and in the end the price elasticity of residual resource demand. Considering the crowding out of renewable energies, there are two counteracting effects, which more or less follow from the fact that with a higher renewable energy subsidy the renewable energy generation and thereby total energy supply is higher for any given resource supply path. First, by (7.37) and (7.39) final goods production becomes more energy based for a higher renewable energy subsidy and a given resource supply path. Considering again the Cobb-Douglas case, we can conclude that the redistribution of physical capital therefore tends to become more important for restoring the renewable energy investment equilibrium. However, second, the (effective) marginal productivity of capital in energy generation μW_{2K} is lower for a higher subsidy rate and a concave energy technology (7.1). Thus, reducing the renewable energy generation requires a larger redistribution of capital. If the first effect is sufficiently strong, just a small redistribution of capital and an even lower reduction of renewable energy output will be sufficient to restore the investment equilibrium. In this case, the strength of the crowding out effect falls and the price elasticity of resource demand tends to decreases with a higher subsidy rate. However, if the first effect is rather weak and the reduction in the renewable energy output is still crucial for counterbalancing the influence of higher resource supply on the investment equilibrium, the crowding out of renewable energies in terms of energy supply will be more or less constant, but will lead to a larger redistribution of physical capital which by the complementarity of energy and capital in production stabilizes the energy market price. Thus, in this case, the influence of the renewable energy subsidy on the crowding out effects of resource supply increases the price elasticity of resource demand.

7.6.3.2 Reversal of the Green Paradox: Numerical Observations

Given the numerous analytical ambiguities, we must rely on numerical simulations to demonstrate that the renewable energy subsidy may induce the naive sheikh to postpone resource extraction, in contrast to the competitive market and to more standard settings, for which the backstop technology does not have an influence on the capital market. For the two exemplary specifications, which we already have used in the competitive case, we again graphically present the Hotelling condition of the naive sheikh in figures 7.3 and 7.4.[24] Following the decomposition of the subsidy effect on the price elasticity of resource demand in (7.45), we restrict the exposition to the Cobb-Douglas specification as to rule out effects which arise from changes in the price elasticity of energy demand.

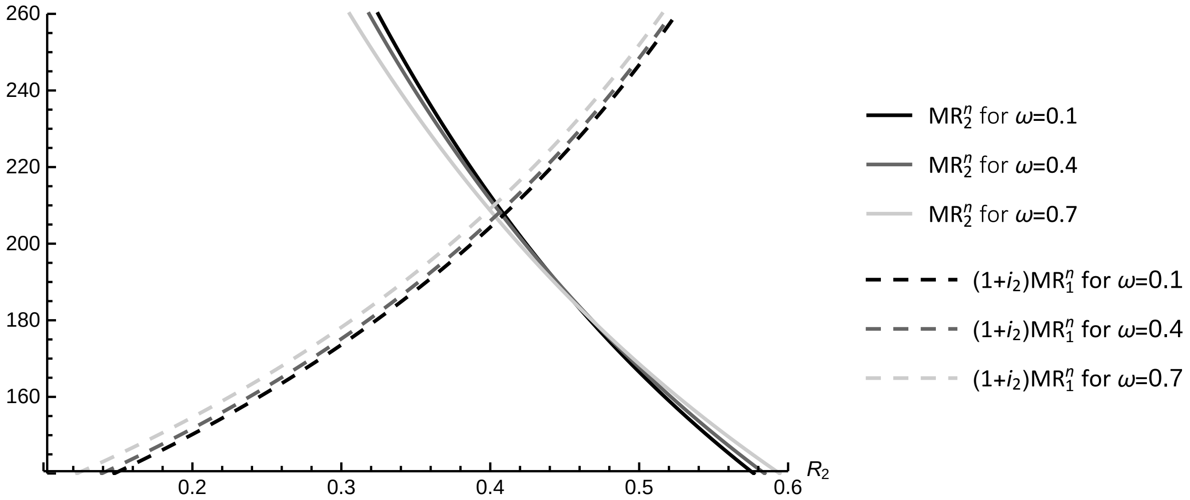

Figure 7.3: The naive sheikh's supply reaction to a renewable energy subsidy with high resource scarcity: green paradox outcome for $\bar{R} = 1$; assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\mu = 0.1$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln 1 + K_{2W}$

We may at first note that while for $\bar{R} = 1$ the competitive economy arrives at a corner solution as depicted in figure 7.1, resource supply in the second period is obviously so valuable to the naive sheikh that she distributes resources to both periods even in this case of high resource scarcity. This reflects the sheikh's incentive for a more conservative extraction policy than the competitive market even in the Cobb-Douglas case (see section 7.5), which arises from the increase in the price elasticity of resource demand due to the availability and the simultaneous use of the renewable energy technology in the second period. The figure also demonstrates that for $\bar{R} = 1$ the naive sheikh is overall induced to accelerate extraction with a higher subsidy.

[24] Note that strictly speaking we thereby demonstrate again that the green paradox can be reversed for non-marginal changes in the subsidy rate, whereas the comparative statics in (7.44) only captures the effect of a marginal increase in the subsidy rate.

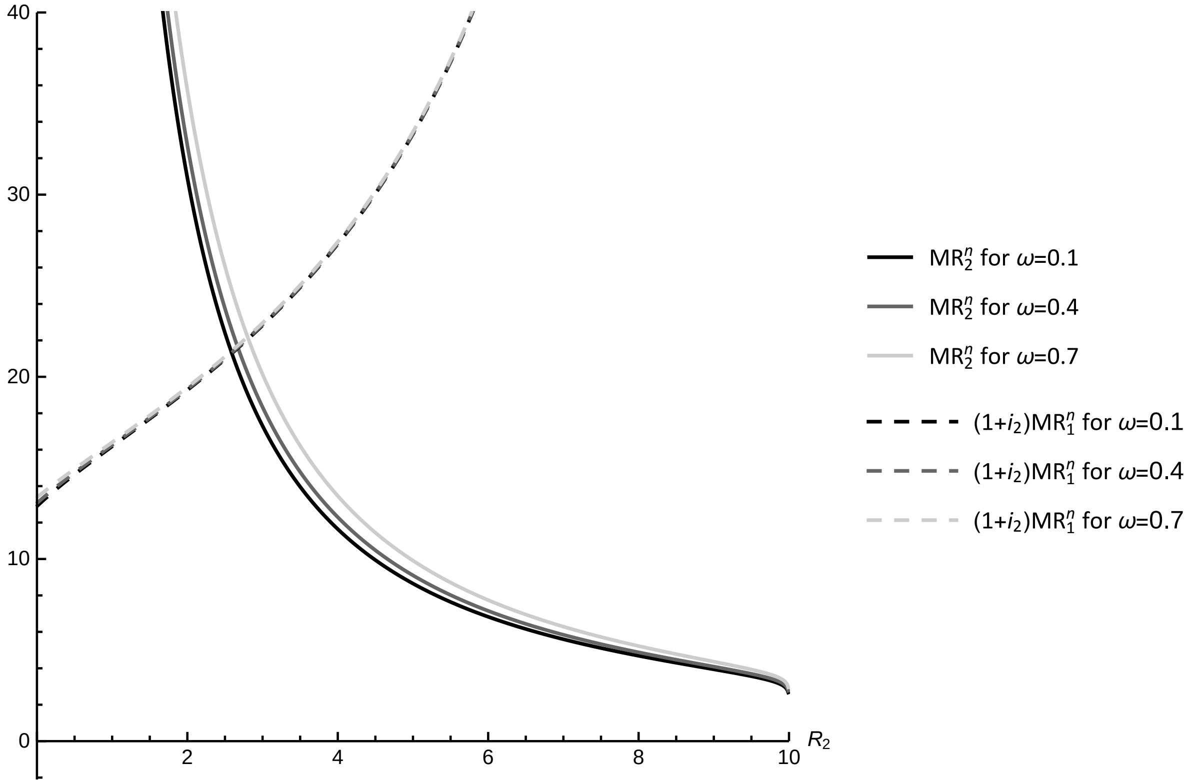

Figure 7.4: The naive sheikh's supply reaction to a renewable energy subsidy with lower resource scarcity: reversal of the green paradox for $\bar{R} = 10$; assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\mu = 0.1$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln 1 + K_{2W}$

For a higher resource endowment $\bar{R} = 10$ in figure 7.4, the opposite holds true and the green paradox is indeed reversed. This observation more or less corresponds to our conclusions from the previous chapter 6 that the green paradox overall is a phenomenon which is more relevant the scarcer the fossil resource is. The reversal of the green paradox is due to the significant increase in the price elasticity of resource demand, which is illustrated in figure 7.5. Given our previous analytical discussion of the reasons for the increase in the price elasticity of resource demand, we follow the decomposition in (7.45) and present the influence of the subsidy rate on the various components in figures 7.5 and 7.6.

In line with our assumption of Cobb-Douglas production, the price elasticity of energy demand ϵ_{Q_2,p_2} is constant with respect to the resource supply path as well as with respect to the climate policy intervention. As shown in the last panel of figure 7.6 and as expected, the share of fossil resources in the energy market decreases with a higher subsidy rate, which tends to increase the price elasticity of resource demand.

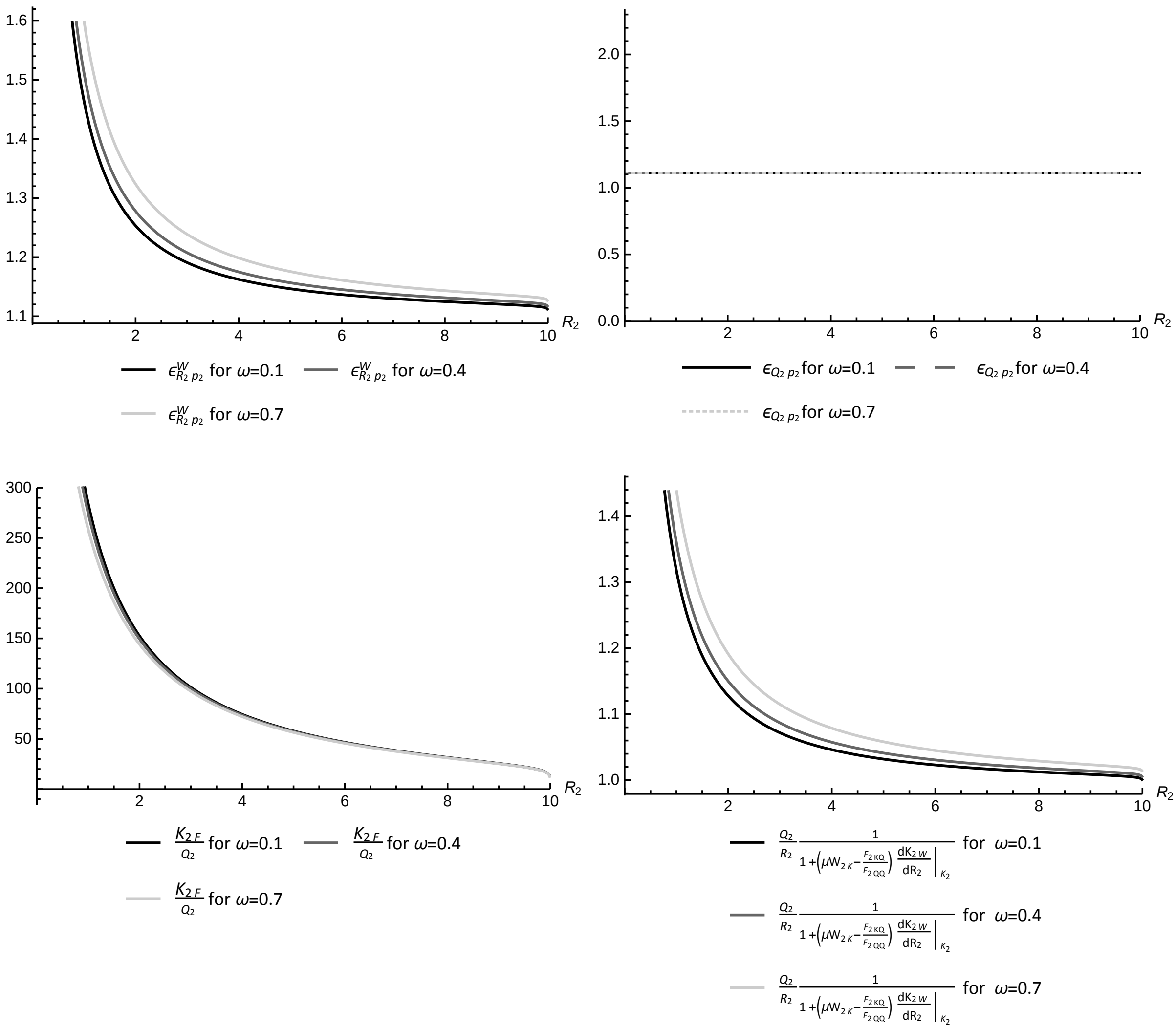

Figure 7.5: Decomposition 1: the influence of the renewable energy subsidy on the price elasticity of residual resource demand and the price elasticity of energy demand for $\bar{R} = 10$;
assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\mu = 0.1$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

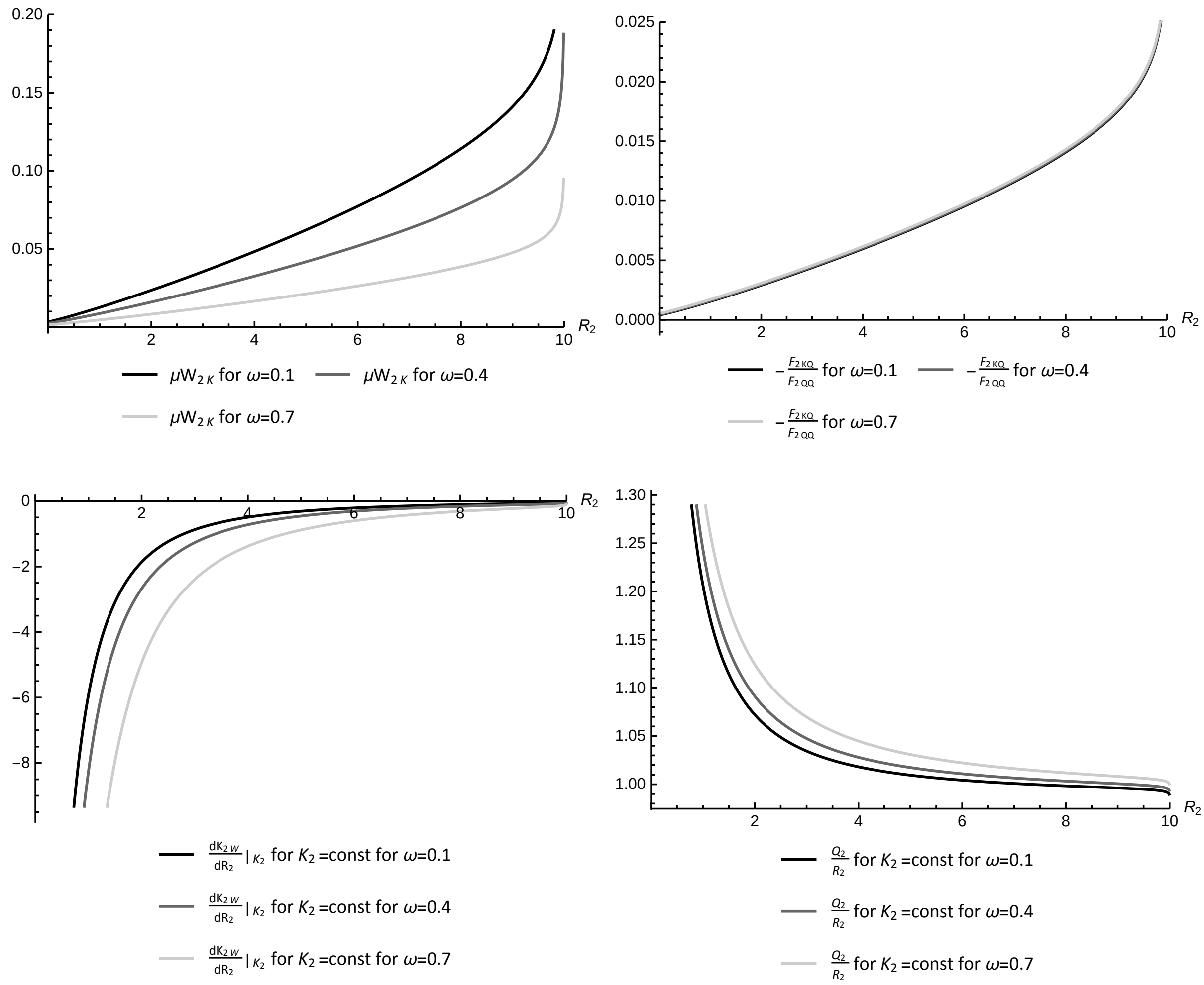

Figure 7.6: Decomposition 2: the influence of the renewable energy subsidy on the price elasticity of residual resource demand for $\bar{R} = 10$; assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\mu = 0.1$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 0.91$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

From the diagram on the upper right and the absolute values therein we observe that in the given numerical specification we have

$$|F_{2QQ}| > F_{2KQ} = F_{2QK}$$

Thus, referring back to our discussion in the previous section, the reduction in the renewable energy output is of greater importance for restoring the renewable energy investment equilibrium upon an increase in the supply of fossil resources than the simultaneous redistribution of capital to final goods production. Moreover, this weighting is almost constant for an increasing renewable energy subsidy.[25] The reason is that in the exemplary numerical specification, capital is (still) rather abundant compared to energy. This also explains why the relative production factor input K_{2F}/Q_2 is virtually not affected by the renewable energy subsidy in figure 7.5. In contrast, the rising capital investments in renewable energy generation with a higher subsidy rate considerably reduce the marginal productivity of capital in energy generation μW_{2K} as can be seen in the first diagram in figure 7.6. This implies that whereas more capital must be reallocated to final goods production with a higher subsidy rate the crowding out of renewable energies in terms of energy supply is virtually not affected by the renewable energy subsidy. From our previous discussion of the determinants of the price elasticity of resource demand we know that this increases the price elasticity of resource demand since an increasingly strong capital reallocation to final goods production raises the overall energy demand by the complementarity of production factors.

7.7 The Effect of Technical Change

In this section, we study the influence of the technological state of the renewable energy technology measured by the parameter μ on the equilibrium resource extraction path, again for the competitive market as well as for the naive monopolist. We consider exogenous technological change and just analyze the comparative statics effects of an (marginal) increase in μ. This form of technological change improves the productivity of capital in terms of the actual usable energy output from the renewable energy generation capacities. Having renewable energies like wind or solar energy in mind, one may think of the existing capital stock invested in renewable energy

[25] There is only a tiny upward shift in the curves, which implies that this inequality is reduced by a higher renewable energy subsidy and the thereby induced lower relative input factor K_{2F}/Q_2.

generation becoming better equipped to cope with the intermittency problem. In fact, we can interpret an increase in μ, for example, as a reduction in the costs for energy storage facilities, which directly reduces the system costs of intermittent renewable energies. However, such a development does not affect the concavity of the renewable generation technology (7.1), which may reflect the decreasing availability of high-yield locations for solar or wind generation as already pointed out. We start again by investigating the effect of the technological state on the conditional market equilibrium and then build upon this analysis to consider the influence on the equilibrium resource depletion path.

7.7.1 The Influence of Technical Change on the Conditional Market Equilibrium

Increases in μ raise the productivity of the existing renewable generation capacities in terms of their actual contribution to the energy supply of the economy. Hence, a rising μ increases the energy supply to the economy ceteris paribus. This in turn tends to reduce the attractiveness of investments in the renewable energy generation, on the one by raising the market interest rate due to the complementarity of production factors, and on the other hand by reducing the energy market price due to the diminishing returns to energy in final goods production. At the same time, technological change also increases the marginal productivity of capital in terms of final goods production when invested in energy generation, and therefore the market value of investments in renewable generation capacities (μW_{2K}). We already have observed these counteracting effects of technological change when we discussed the determinants of the equilibrium energy investments and the ambiguity of (7.21) in particular in section 7.4.2.1.

We derive the comparative statics of the conditional market equilibrium with respect to μ in appendix 9.2.2.1. From there we know that the equilibrium aggregate capital stock K_2 depends on the technological state μ according to

$$\frac{dK_2}{d\mu} = \frac{\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2Q} W_2 + \left.\frac{di_2}{d\mu}\right|_{K_2} SE}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE} \tag{7.46}$$

Since we discussed the denominator and its positive sign already before for (7.35), we just focus on the numerator here. The first term captures the productivity gain of the existing renewable energy generation capacities. With a marginal increase in μ, the contribution of the renewable generation capacities to the energy system rises by W_2

(cf. (7.2)). This leads to a production and income gain in the second period as measured by F_{2Q}, which, due to the familiar consumption smoothing motives captured in the savings reactions from (4.13), induces households to save less.[26] At the same time, an increase in μ directly affects the marginal productivity of physical capital and thereby the market interest rate i_2. This induces a (aggregated) substitution effect SE as captured by the second term in the numerator.

The interest rate, on the one hand, tends to increase due the complementarity of energy and physical capital in production and the improved energy productivity of the existing renewable generation capacities. On the other hand, we know from (7.21) that this generally may be complemented or counteracted by the simultaneously induced reallocation of physical capital between renewable energy generation and final goods production.[27] As before, we capture these various, and potentially counteracting, "direct" effects of technological change on the market interest rate by defining

$$\left.\frac{di_2}{d\mu}\right|_{K_2} = F_{2KQ}W_2 + (F_{2KQ}\mu W_{2K} - F_{2KK})\left.\frac{dK_{2W}}{d\mu}\right|_{K_2} \tag{7.47}$$

with

$$\left.\frac{di_2}{d\mu}\right|_{K_2} \gtrless 0 \qquad \leftrightarrow \qquad -\frac{W_{2KK}}{W_{2K}} \gtrless \frac{\Gamma_{2W}}{F_{2KQ}F_{2Q}} - \frac{F_{2KQ}\mu W_{2K} - F_{2KK}}{F_{2KQ}\mu W_2}$$

which is ambiguous, just as the influence of the future resource supply in (7.28). The last inequality condition is derived completely analogue to the inequality condition in (7.28).[28]

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[26] This "income effect" more or less represents the channel which Long and Stähler (2014a) and Long and Stähler (2014b) focus on.

[27] If technological change makes renewable energy generation to attract physical capital, it unambiguously raises the marginal productivity of capital by the complementarity of energy and capital in final goods production. Thus, $\sigma > \frac{\mu W_2}{Q_2}$ (see (7.21)) is a sufficient condition for $\left.\frac{di_2}{d\mu}\right|_{K_2}$ to be positive. Otherwise, the induced reallocation of capital away from energy generation and the accompanying reduction in energy generation capacities will counteract, or even overcompensate, the positive complementarity effect from the improved efficiency of the existing generation capacities.

[28] Since the second term on right side negatively adds to the first, the comparison of both inequality conditions indicates that technical change may have a positive direct effect on the interest rate even if resource supply does not. But if resource supply does have a positive direct effect, i.e. if (7.28) is positive, the interest rate must also rise with technical change. This is plausible as technical change, by increasing the energy output from existing generation capacities, has on the one hand exactly the same effect on the optimal renewable energy investments as a higher resource supply R_2, but on the other hand counteracts this negative investment incentive by increasing the marginal value and productivity of renewable capital investment in terms of final goods production (see the

If technological change ceteris paribus increases the interest rate, the substitution effect in (7.46) is counteracting the savings disincentive from the higher second period income. Hence, K_2 may increase or decrease. Otherwise, if technological change ceteris paribus reduces the interest rate, the aggregate capital stock will unambiguously fall. Assuming $\sigma \geq \frac{1}{\eta}$ from (4.29), which ensures that the aggregate capital stock shrinks with any postponement of resource extraction with and without renewable energies, does not resolve this ambiguity.[29]

This ambiguous effect of technological change on the aggregate capital stock transfers to its influence on the capital stock invested in renewable energy generation, which by (7.21), (7.24), and (7.46) is determined by

$$\begin{aligned}\frac{dK_{2W}}{d\mu} &= \left.\frac{dK_{2W}}{d\mu}\right|_{K_2} + \phi\frac{dK_2}{d\mu} \\ &= \frac{\left.\frac{dK_{2W}}{d\mu}\right|_{K_2}(1 - F_{2KK}SE) + \phi W_2\left(\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}F_{2Q} + F_{2KQ}SE\right)}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE} \gtrless 0\end{aligned} \tag{7.48}$$

The reason is again the ambiguous effect of technological change on the renewable energy investment incentives which we pointed out before.[30] Moreover, it is evident

corresponding discussion for (7.21)). Moreover, note that a positive influence of technical change on the interest rate may even be possible for $W_{2KK} \leq 0$, whereas resource supply in this case never has a positive direct effect on the interest rate.

[29] To show this, we rewrite the numerator of (7.46) by use of (7.47):

$$\begin{aligned}W_2\left[\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}F_{2Q} + F_{2KQ}SE\right] - \left(F_{2KQ}\mu W_{2K} - F_{2KK}\right)SE\left.\frac{dK_{2W}}{d\mu}\right|_{K_2} &= \\ W_2\left[\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}F_{2Q} + \left.\frac{di_2}{dR_2}\right|_{K_2} SE\right] - \left(F_{2KQ}\mu W_{2K} - F_{2KK}\right)SE\frac{F_{2Q}W_{2K}}{\Xi}\end{aligned}$$

The condition $\sigma \geq \frac{1}{\eta}$ only ensures that the first bracketed term is negative.

[30] This can be observed upon rearranging by use of (7.21) so that we get

$$\frac{dK_{2W}}{d\mu} = W_2\frac{dK_{2W}}{dR_2} + \frac{-\frac{F_{2Q}\mu W_{2K}}{\Xi}(1 - F_{2KK}SE)}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE}$$

The increase in the marginal productivity of capital invested in renewable energy generation from technological change is captured by the positive second term, which counteracts $\frac{dK_{2W}}{dR_2}$ given by (9.15) in appendix 9.2.2.2.

that the induced change in the final goods production capital stock, which is given by

$$\begin{aligned}\frac{dK_{2F}}{d\mu} &= \frac{dK_2}{d\mu} - \frac{dK_{2W}}{d\mu} \\ &= \frac{(1-\phi)W_2\left(\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}F_{2Q} + F_{2KQ}SE\right)}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE} \\ &\quad - \frac{\left.\frac{dK_{2W}}{d\mu}\right|_{K_2}(1 - F_{2KQ}\mu W_{2K})}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE} \gtrless 0\end{aligned} \tag{7.49}$$

is generally ambiguous, too. Even if technological change leads to a reallocation of capital from renewable energy generation to final goods production and K_2 decreases, K_{2F} still may increase if the simultaneous fall in K_{2W} is much stronger than the reduction in the aggregate capital stock K_2.

Unsurprisingly, given these ambiguous effects, the change in the energy supply from technological change is generally ambiguous, too. We have

$$\frac{dQ_2}{d\mu} = W_2 + \mu W_{2K}\frac{dK_{2W}}{d\mu} = \left.\frac{dQ_2}{d\mu}\right|_{K_2} + \mu W_{2K}\phi\frac{dK_2}{d\mu} \gtrless 0 \tag{7.50}$$

From (7.22) we can conclude that the ambiguity here solely arises from the adjustment in the overall capital stock K_2. If the aggregate capital stock increases with technological change, the energy supply, for a given resource supply, to the resource importing country will unambiguously increase, too. Otherwise, it may decrease as the renewable energy capacities shrink with the overall capital stock.

For the influence of technological change on the factor market prices, we again separate the direct from the indirect effect, which arises from the induced change in the overall capital stock according to (7.46). Analogue to (7.47), we first summarize the direct effects of technological change on the marginal productivity of energy. These arise from the (ceteris paribus) increase in energy supply due to the improved usability of existing generation capacities, and from the induced reallocation of capital between energy generation and final goods production captured in (7.21). Therefore, we have

$$\left.\frac{dp_2}{d\mu}\right|_{K_2} = F_{2QQ}W_2 + (F_{2QQ}\mu W_{2K} - F_{2KQ})\left.\frac{dK_{2W}}{d\mu}\right|_{K_2} < 0 \tag{7.51}$$

The negative sign holds true by definition (7.21). Intuitively, by improving the efficiency of the existing renewable generation capacities technological change increases the energy supply to the economy thereby lowering the marginal productivity of energy. This negative effect always dominates irrespective of whether technical change makes renewable energy generation to attract capital or not, i.e. irrespective of the sign in (7.21). Together with (7.32), we furthermore are able to decompose the influence of technical change increasing μ on the equilibrium market price of energy as

$$\frac{dp_2}{d\mu} = \left.\frac{dp_2}{d\mu}\right|_{K_2} + \left.\frac{dp_2}{dK_2}\right|_{R_2} \frac{dK_2}{d\mu} < 0 \tag{7.52}$$

The negative sign of this equilibrium relationship is derived in appendix 9.2.3.1. It implies that technical change always reduces the marginal productivity of energy, or the energy market price, irrespective of whether it increases or decreases the aggregate capital stock ((7.46)), or the overall energy supply to the economy ((7.50)), or the capital stock invested in renewable energy generation (7.48) and in final goods production ((7.49)). This conclusion is also in contrast to the effect of fossil resource supply on the energy market price (7.30): Resource supply does not necessarily reduce the marginal productivity of energy in the modified setting due to the reaction of the competitive renewable energy generation.

Analogously, by (7.47) and (7.26), we can decompose the equilibrium change in the market interest rate as

$$\frac{di_2}{d\mu} = \left.\frac{di_2}{d\mu}\right|_{K_2} + \left.\frac{di_2}{dK_2}\right|_{R_2} \frac{dK_2}{d\mu} \gtrless 0 \tag{7.53}$$

In contrast to the energy market price, we find in appendix 9.2.3.1 that the equilibrium interest rate generally may decrease or increase with technological change. This again reflects the ambiguity in the development of the capital stocks.

7.7.2 The Resource Supply Reaction

We now consider the implications of technical change for the resource supply path. To this end, we again resort to a comparative statics analysis building upon our observations and definitions from the previous section. Our focus in the following is on the differences to the effect of the renewable energy subsidy analyzed before.

7.7.2.1 Competitive Resource Market

To derive the intertemporal supply response in the competitive resource market, we totally differentiate Hotelling condition (2.3) with respect to the resource supply path

(R_1^c, R_2^c) and the state of the renewable energy technology μ. Since the equilibrium factor prices are functions of the technology parameter μ by (7.52) and (7.53), we get

$$\frac{dR_2^c}{d\mu} = \frac{-p_1 \frac{di_2}{d\mu} + (1-\tau)\frac{dp_2}{d\mu}}{\frac{di_2}{dR_2}p_1 - (1+i_2)\frac{\partial p_1}{\partial R_1} - (1-\tau)\frac{dp_2}{dR_2}} \tag{7.54}$$

As already discussed in section 7.6, the denominator of the comparative statics must be positive due to the second-order condition which has to hold for an optimal competitive market extraction path. In the numerator, we know from (7.52) that technological change will reduce the marginal productivity of energy and thereby the energy market price p_2. Due to the potential reallocation of capital to the energy sector, this holds true even though technical change does not necessarily increase the overall energy supply to the economy (see (7.50)). At the same time, according to (7.53) technological change generally increases or decreases the interest rate i_2. If the interest rate increases, the green paradox will necessarily arise, because both the rising interest rate as well as the falling energy market price create an incentive to accelerate extraction. If the increasing efficiency of capital in renewable energy generation leads to a strong reallocation of capital to final goods production, the interest rate may decrease and the incentive to accelerate extraction from the fall in the energy market price is counteracted. However, even though a fall in the interest rate establishes an incentive to slow down extraction, we proof in appendix 9.2.3.2 that the green paradox can never be reversed in the competitive resource market with symmetric preferences.

For a rather scarce fossil resource stock $\bar{R} = 1$, we already know that there is no interior solution in the competitive market case and thus no effect of future changes in the energy market on resource supply (see figure 7.1). The green paradox outcome for an interior equilibrium outcome is, however, illustrated for a resource stock of $\bar{R} = 10$ in figure 7.7. In our exemplary specification, technological progress leads to an increase in the market interest rate, which is reflected in the upward shift of the left hand side of Hotelling condition (2.3). Since inverse resource, or energy, demand in the second period is reduced at the same time, the green paradox unambiguously arises. Moreover, note that by ongoing technological improvements, capital is more and more effective in substituting the fossil resource in the second period. Hence, the economy again approaches the corner solution where it completely exploits the resource stock in the first period and entirely relies on renewable energies for energy generation in the second period.

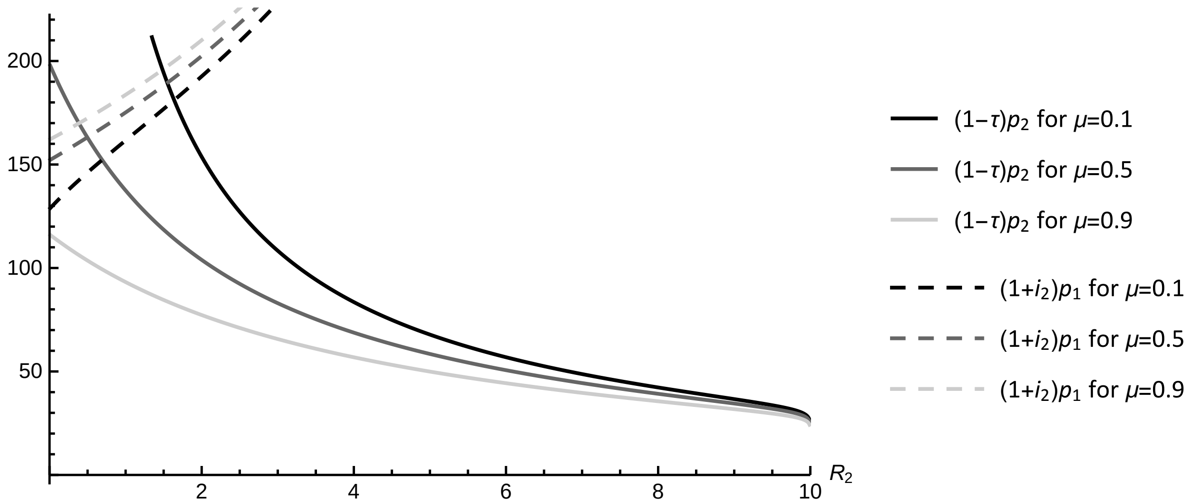

Figure 7.7: The influence of technological change on the competitive resource market equilibrium $\bar{R} = 10$;
assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\omega = 0$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 0.1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

7.7.2.2 Naive Sheikh

By totally differentiating Hotelling condition (5.4) with respect to resource supply and the state of technology the comparative statics for the naive sheikh can be derived as

$$\frac{dR_2^n}{d\mu} = \frac{-\frac{di_2}{d\mu}MR_1^n + \frac{dMR_2^n}{d\mu}}{\frac{di_2}{dR_2}MR_1^n - (1+i_2)\frac{dMR_1^n}{dR_1} - \frac{dMR_2^n}{dR_2}} \tag{7.55}$$

If we evaluate the comparative statics for an equilibrium supply path (R_1^n, R_2^n), the denominator must be of positive sign. For the proof, we again refer to our analogue discussion of the comparative statics in the standard framework in section 6.4.

The numerator captures the direct effects of technological change on the Hotelling condition. Analogue to (7.44), we simplify notation by defining the equilibrium influence of technological change on the marginal resource revenue MR_t^n from (7.33) as

$$\frac{dMR_2^n}{d\mu} = (1-\tau)\left[\frac{dp_2}{d\mu}\left(1 - \frac{1}{\epsilon_{R_2,p_2}^W}\right) + \frac{p_2}{\left(\epsilon_{R_2,p_2}^W\right)^2}\frac{d\epsilon_{R_2,p_2}^W}{d\mu}\right] \tag{7.56}$$

First, in contrast to the renewable subsidy, we know from (7.53) that the interest rate does not necessarily rise when capital becomes more productive in terms of energy actually usable in final goods production. If the interest rate decreases, the endogeneity of the interest rate in our framework at least tends to slow down extraction.

Second, in (7.56) we again separate the induced downward shift in resource demand (cf. (7.52)) given by the first component from the induced change in the price elasticity of residual resource demand ((7.34)). The latter can completely analogue to (7.44) be decomposed in the influence of technical change on the market share of fossil resources in the energy market, the price elasticity of energy demand, and on the additional weighting due to the reallocation of capital which higher resource supply induces when crowding out renewable energies in the energy market (see appendix 9.2.3.3). Analytically, the effect of the technological change on the price elasticity of resource demand is completely ambiguous, in general, even when assuming Cobb-Douglas production ($\sigma = 1$). We already have discussed the determinants of the price elasticity of resource demand in detail when we studied the effect of the renewable energy subsidy in section 7.6.3. At this point, we therefore focus on whether and where the effect of technical change differs from the effect of the renewable energy subsidy.

First, we generally do not know whether final goods production becomes more or less energy based with an increase in μ as both K_{2W} and K_{2W} may increase or decrease (see (7.48) and (7.49)). This also implies that the overall energy supply Q_2 does not necessarily rise with technological progress for a given resource supply path, and therefore that the market share of fossil resources needs not fall with an increase in μ. These ambiguities are in direct contrast to the effects of the renewable energy subsidy. In the end, they are on the one hand due to the endogenous adjustment of the aggregate capital stock K_2, which generally may increase or decrease with an increase in μ (see (7.46)) whereas it unambiguously rises with a higher subsidy for renewable energies.[31] On the other hand, the capital redistribution between final goods production and renewable energy generation which is induced by technological change is also generally ambiguous in contrast to the effect of the renewable energy subsidy (see (7.21)).

Second, the price elasticity of resource demand crucially depends on the crowding out of renewable energy generation and investments by fossil resource supply as we already pointed out in section 7.6.3. A higher subsidy changes the relation between the reduction in renewable energy supply and the amount of capital which is redis-

[31] Note that the aggregate capital stock does not necessarily fall with technological change, in contrast for example to Long and Stähler (2014a), because technological change, given that the renewable energy technology is capital intensive, also induces a substitution effect, which counteracts the savings disincentives from the additional future income if the interest rate ceteris paribus (i.e. for a constant capital stock K_2) increases with μ.

tributed to final goods production only insofar as the higher subsidy increases the investments in renewable energies and thereby lowers the marginal productivity of capital due to the concavity of the energy generation technology W_2. In contrast, technological change influences this relation even without any change in the capital investments since the effective marginal productivity of capital in energy generation μW_{2K} directly depends on the state of technology μ. In particular, technological progress, in contrast to the renewable subsidy, may even raise the effective marginal productivity of capital in energy generation. Using (7.48) we have

$$\begin{aligned} \frac{d\left[\mu W_{2K}\right]}{d\mu} &= W_{2K} + \mu W_{2KK} \frac{dK_{2W}}{d\mu} \\ &= \left.\frac{d\left[\mu W_{2K}\right]}{d\mu}\right|_{K_2} + \mu W_{2KK} \phi \frac{dK_2}{d\mu} \gtrless 0 \end{aligned} \tag{7.57}$$

Since the first term is positive by definition in (7.21) and independent of whether an increase in μ ceteris paribus reallocates physical capital to renewable energy generation or not, we observe that technological progress at least increases the effective marginal productivity of capital in energy generation as long as K_2 does not increase in μ.

What does an increase in the effective marginal productivity of capital in energy generation μW_{2K} imply for our more intuition based reasoning from section 7.6.3.1? Obviously, the crowding out of renewable energy by an increase in resource supply in the energy market then entails a lower reallocation of capital to final goods production. This tends to reduce the price elasticity of resource demand because the capital reallocation, by the complementarity of energy and capital in final goods production, fosters the marginal productivity of energy and thereby resources in production. However, if the production structure in the economy is such that especially the capital reallocation is required to restore the investment equilibrium (cf. (7.18)), technical change may still increase the price elasticity of resource demand. The reason is that in this case the necessary capital reallocation induces an even larger fall in renewable energy output after μW_{2K} has increased by technical change. This implies that fossil resource supply has a weaker influence on overall energy supply so that the negative own-price effect induced by an increase in resource supply is lower, and correspondingly that the price elasticity of resource demand is higher. Note that this line of reasoning for an increasing price elasticity of resource demand is completely contrary to the conditions for which a rising subsidy rate tends to increase the price elasticity of resource demand by crowding out of renewable energy and capital investments.

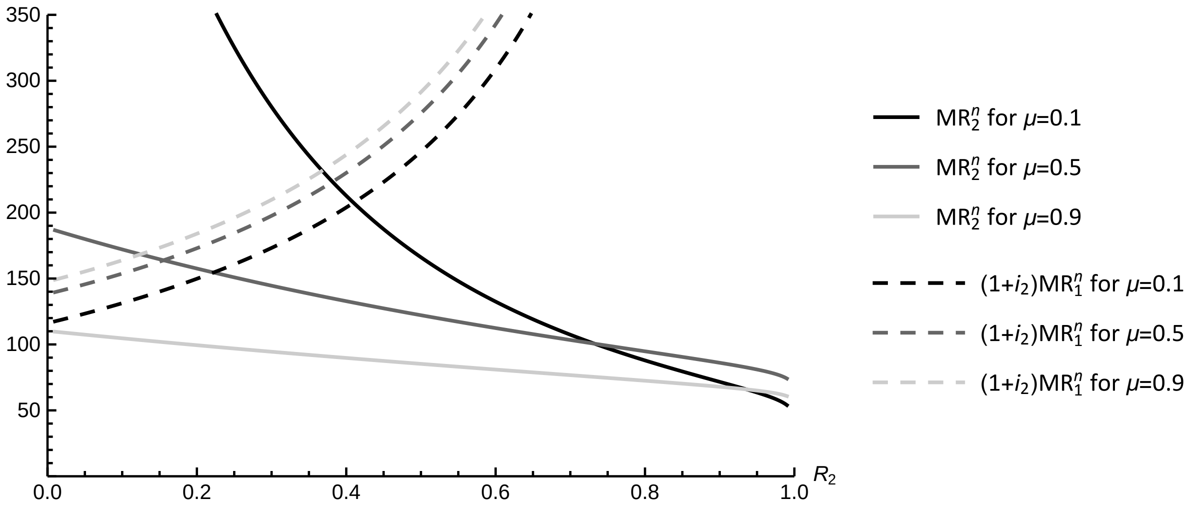

Figure 7.8: The naive sheikh's supply reaction to technical change with high resource scarcity: green paradox for $\bar{R} = 1$;
assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\omega = 0$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

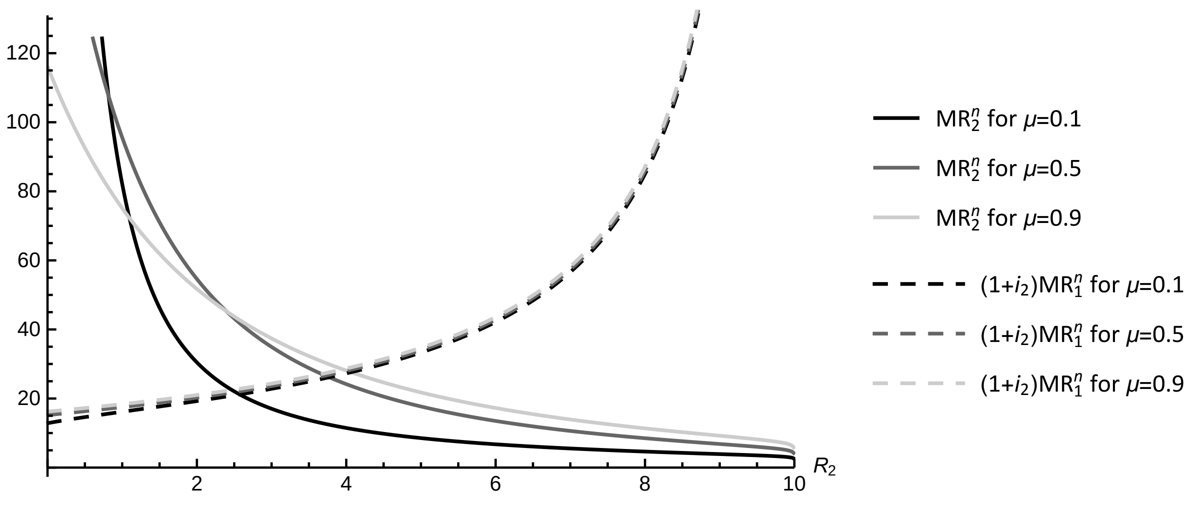

Figure 7.9: The naive sheikh's supply reaction to technical change with lower resource scarcity: green paradox for $\bar{R} = 10$;
assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\omega = 0$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

In contrast, if the effective marginal productivity of capital in renewable energy generation μW_{2K} decreases with technological progress, the price elasticity of resource demand may increase with technical progress for the same reasons as for the renewable subsidy. First, such a fall in the effective marginal productivity of capital is only possible for a non-linear renewable energy generation technology and a strong increase of investments in renewable energies K_{2W} due to a rising overall capital stock K_2. The reason is that the marginal productivity of capital always increases as long as K_2 is constant or decreases (see (7.57)). Second, as we already know, in this case the price elasticity of resource demand will tend to increase if the final goods production structure is such that a more or less constant renewable energy output reaction to a higher fossil resource supply is necessary to restore the renewable energy investment equilibrium. For higher μ and lower μW_{2K}, this necessary reduction in energy generation then entails a larger reallocation of capital to final goods production due to the decreasing marginal productivity of capital in energy generation and thereby leads to a stronger complementarity driven increase in energy demand (i.e. a lower negative own-price effect).

To verify that the green paradox may still be reversed if technological progress improves the usability of renewable energies in the system, we again must resort to the numerical simulation of (discrete) changes in the state of technology μ. For a low resource endowment $\bar{R} = 1$, market power yields an interior solution in contrast to the competitive case, but the naive sheikh is strongly induced to accelerate extraction and to approach the corner solution with full exploitation of the resource stock in the first period by technical change, as shown in figure 7.8. In contrast, with lower scarcity of the fossil resource, figure 7.9 demonstrates that the naive sheikh actually postpones resource extraction with an increasingly competitive capital-intensive renewable energy technology.

The green paradox is reversed even though technical change in this specification reduces the energy price and increases the interest rate as we know from figure 7.7, which both work towards an acceleration of extraction. All these effects, however, are overcompensated by a considerable increase in the price elasticity of residual resource demand. This can be observed from figure 7.10, which together with the accompanying figure 7.11 also illustrates the effects of technological change on the different components of the price elasticity of resource demand in (7.34). Note that the exemplary numerical specification exactly corresponds to the case for which technical change increases the effective marginal productivity of capital in renewable energy generation as can be observed from the first diagram in figure 7.11. The nu-

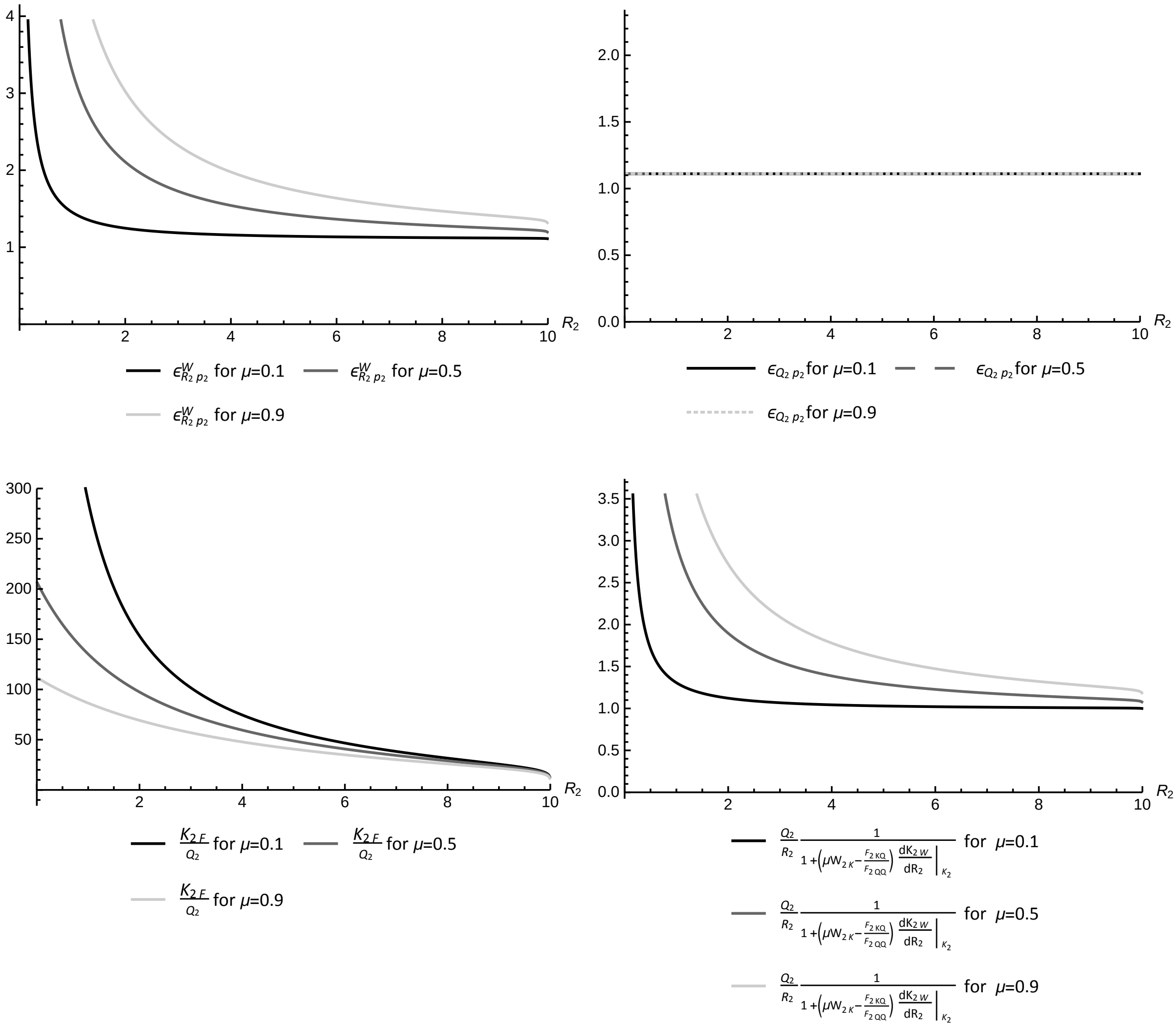

Figure 7.10: Decomposition 1: the influence of technological change on the price elasticity of (residual) resource demand;
assumptions: $\bar{R} = 10$, $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\omega = 0$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

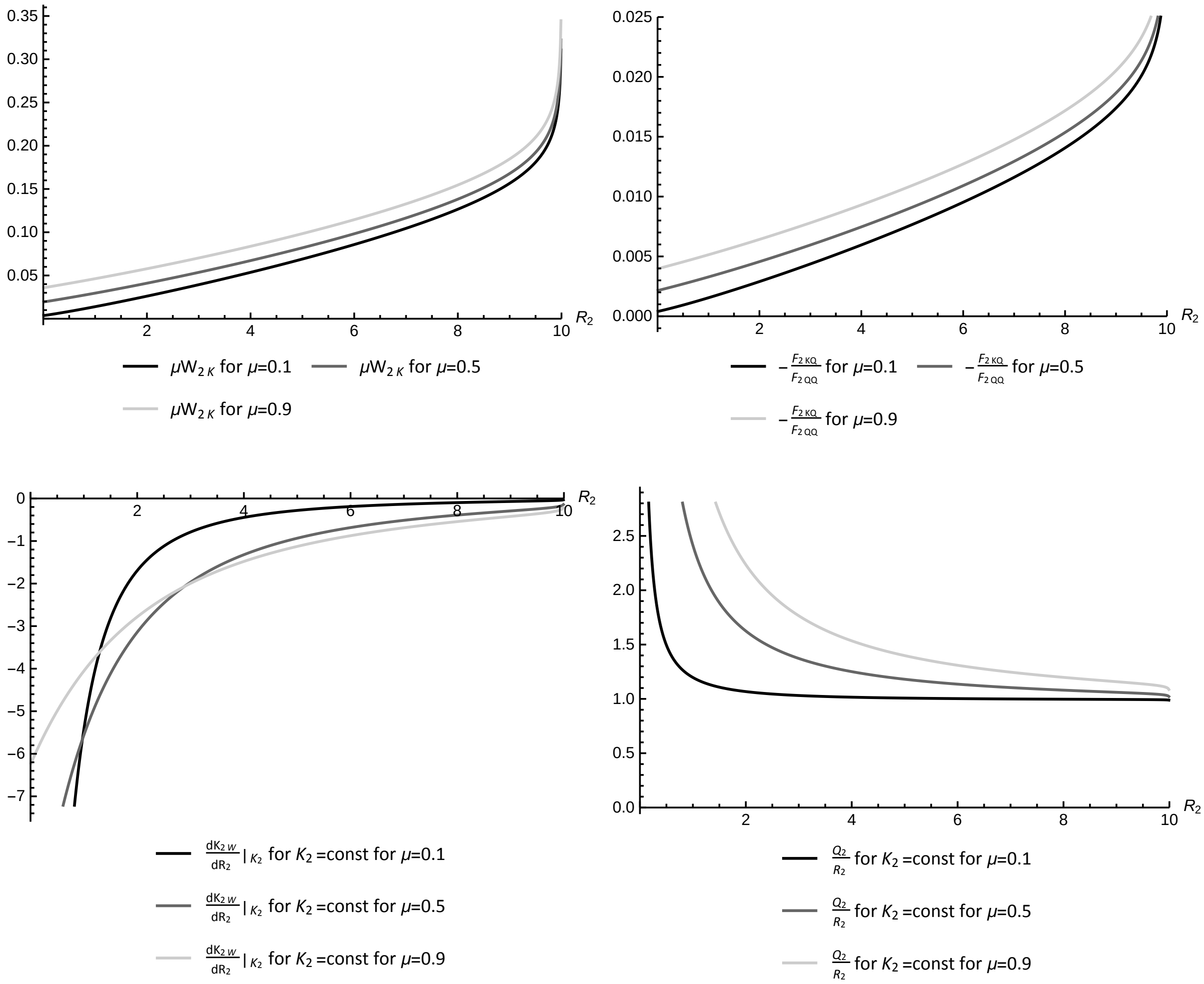

Figure 7.11: Decomposition 2: the influence of technological change on the price elasticity of (residual) resource demand;
assumptions: $\bar{R} = 10$, $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\omega = 0$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

merical results also illustrate the ambiguity of the influence of technical change. In fact, the ambiguity can be observed from the non-monotonous effect of technological change on the marginal resource revenue MR_2^n in figure 7.9. For example, for $R_2 = 2$, technological progress at first (from $\mu = 0.1$ to $\mu = 0.5$) substantially raises the marginal resource revenue whereas for further increases in μ (from $\mu = 0.5$ to $\mu = 0.9$) the marginal resource revenue falls again. Moreover, a similar ambiguity is shown in figure 7.11 for the influence of technical change on the renewable investments' reaction to resource supply.

7.8 Discussion and Conclusion

In this chapter, we have proposed an extension to our previous general equilibrium setting to consistently capture the effects of potentially carbon free energy technologies which are substitutive to fossil resources and accessible by the so far resource importing countries. The leading real-world example for the technologies we had in mind here are, of course, renewable energy technologies like wind and solar energy. To simplify the exposition we assumed that the renewable energy technology is only available in the future after an fossil fuel era in the first period.

The main contribution of the chapter to the literature is to highlight and investigate in a consistent framework an additional and new transmission channel of climate policies in general equilibrium, which in the context of the green paradox and the supply interests of fossil resource owners so far has only been briefly noted by Long (2015). This transmission channel arises from the widely recognized capital intensity and, correspondingly, from the capital demand of substutitive renewable energy technologies. The capital intensity of the substitutive energy technology establishes another interlinkage between the resource and the capital market as the new energy technology is not only a competitor to the fossil resource in the energy market but also attracts physical capital, which, if invested in final goods production, would be complementary to the fossil resource. In fact, the availability of the new energy technology in the second period effectively renders physical capital complementary and substitutive to fossil resources at the same time in our modified framework. Moreover, by generating additional demand for physical capital, the new energy technology directly influences the interest rate, which affects resource supply due to its intertemporal nature as long as there is an interior equilibrium with simultaneous use of both energy sources in the second period.

We investigated the implications of this additional dimension of the interrelationship between the resource and the capital market for the effects of climate policies and technological change. This also gave us additional insights into the role of resource market power in the context of the green paradox. To this end, we slightly modified the notion of the "naive" sheikh from section 5.2.2.1 by assuming that the sheikh, albeit still being naive with respect to her influence on the interest rate and capital accumulation, is aware of the reaction of her competitive fringe in the resource market. Due to the capital intensity of the renewable energy generation, the latter, however, does not only include the reaction in renewable energy output but also the (ceteris paribus) reallocation of capital to final goods production which necessarily comes along with the crowding out of the renewable energy in the energy market. This may arguably be seen as some inconsistency in the modified notion of the naive sheikh, but otherwise the naive sheikh would even fail to correctly account for the market reaction in the energy market. Similar to Hillman and Long (1982), we found that at least for iso-elastic energy demand the simultaneous use of the renewable energy technology in the second period establishes an incentive for the naive sheikh to not follow the competitive but a more conservative extraction path. The reason is that by taking into account the market reaction of the competitive fringe residual resource demand is effectively no longer iso-elastic and always more price-elastic than energy demand.

In particular, and in contrast to Hillman and Long (1982), we considered the implications of the new transmission channel for the effect of climate policy interventions and technological change. The second best carbon tax, which is only levied or raised in the second period, is still just of pure rent-redistributive effect. It therefore still unambiguously gives rise to a green paradox outcome for symmetric countries in the competitive resource market as well as for the naive sheikh, just as in the standard setting from chapter 6. In contrast, a renewable energy subsidy, which we introduced as an ad-valorem subsidy on capital costs and which is typically seen as a second best climate policy prone to give rise to a green paradox outcome, directly affects the equilibrium of investments in final goods production and in renewable energy generation if there is an interior equilibrium with simultaneous use of fossil and renewable energy. Thus, the subsidy does not only induce an increase in renewable energy generation by fostering the competitiveness of the new technology compared to fossil resources, but is also not neutral with respect to the overall capital market equilibrium. In fact, supporting the wider deployment of the new technology makes renewable energy generation attract capital so that the subsidy effectively "creates" additional capital demand in the economy. This leads to an increase in capital accumulation and in the interest rate. Both, the induced capital reallocation to renewable energy generation by the complementarity of capital and resources in final goods production and the increase in the interest rate, thereby strengthen the incentive of competitive resource owners to accelerate extraction. Hence, with competitive resource supply the green paradox necessarily arises and is likely to be amplified compared to a setting where the support of a resource substitute is neutral with respect to capital investments and the interest rate.

For the naive sheikh, in contrast, this does not necessarily hold true. In fact, we demonstrated that even the naive sheikh may have an incentive to postpone extraction. The reason is that a higher subsidy level does not only improve the competitiveness of the renewable energy technology, but may also, by directly altering the investment equilibrium, increase the sensitivity of renewable energy generation to fossil resource supply, both in terms of energy output as well as in terms of capital reallocated from its substitutive to its complementary use in final goods production, and thereby the price elasticity of (residual) resource demand. While analytically intractable, we provided at least some intuition for why and when more strongly subsidizing renewable energy generation can increase the price elasticity of residual resource demand. Moreover, we could numerically show that for a sufficiently strong increase in the price elasticity of (residual) resource demand the green paradox actually can be reversed. Since the reversal is excluded in the competitive market, this result again illustrates that resource market power may in fact play a more prominent role for the arising of the green paradox than often assumed in the literature so far. In line with our previous conclusions, we also observed from the numerical simulations that the green paradox is more likely to be reversed by the additional effects of climate policies in this modified general equilibrium setting the less scarce the fossil resource stock is.

In addition to the renewable subsidy, we also studied the effect of exogenous technical change, which improves the “usability” of renewable energy output in the economy and thereby the effective energy output from capital investments in the energy sector. However, to large extent the effects of technical change are completely ambiguous, in general. The reason is in particular that this form of technical change, by improving the efficiency of the installed generation capacities, does not necessarily make the energy sector attract capital, in contrast to a subsidy reducing the capital costs to renewable energy producers. Still, we were able to show that technical change in an interior equilibrium with simultaneous use of both energy sources in the second period always leads to an acceleration of extraction as long as the resource market is competitive. This holds true even though the interest rate and second period energy supply in the resource importing economies may fall with technical change. For the naive sheikh, however, we again could demonstrate by relying on numerical simulations that technical change may overall also increase the price elasticity of residual resource demand so strongly that the naive sheikh is contrary to the green paradox induced to postpone resource extraction. Moreover, and as intuitively expected, the simulations again illustrated that this form of technical change crucially influences the degree of fossil resource scarcity in the economy. In fact, the higher the effective energy output from capital investments in renewable energy generation, the stronger is the incentive for the monopolist (and competitive resource suppliers) to fully exploit the resource stock already in the first period, i.e. the less binding the constraint by the resource stock underground becomes.

For the moment, we left particularly two issues for future research. First, similar to the standard framework we assumed away extraction costs and therefore especially did not endogenize overall resource extraction. Given the relevance of cumulative emissions for the climate problem, this is admittedly an important gap. Moreover, not least the discussion in section 3.2.4 revealed that resource extraction and exploration are capital intensive, too. This establishes an additional interrelationship between the resource and the capital market, which so far has not been studied, too. Even more interestingly, capital costs of resource extraction or exploration introduce an additional channel through which, for example, a subsidy scheme for the capital intensive renewable energy technology can affect resource supply. In fact, by attracting capital from the rest of the world economy, the renewable energy generation then does not only reduce the capital stock in production, which is at the expense of resource profits as capital is complementary to resources in production, but also reduces the availability of capital in extraction and exploration. This may imply that a renewable energy subsidy is even more successful in limiting cumulative extraction than in more standard settings without capital intensive backstop technologies and capital costs of extraction or exploration.

Second, we restricted the analysis of the imperfect competition case to the naive sheikh, and particularly did not consider a resource sheikh who pursues the asset motive. We know from our discussion in the previous chapters 5 and 6 that the asset motive, and thereby also the reversal mechanism via the carbon tax induced adjustment in the asset holdings, crucially depends on the positive influence of resource supply on capital return. The availability and simultaneous use of the renewable energy technology in the second period does not resolve or even change the complementarity between fossil resources and physical capital in production. However, the induced energy output and capital investment reaction of renewable energy generators reduce or even reverse the influence of resource supply on capital return in the second period (see (7.29)). A lower influence on capital return implies that the future asset motive and, regarding the effect of the carbon tax, the effect of the carbon tax induced savings increase on the extraction decision of the (non-naive) sheikh is weaker. Hence, a reversal of the green paradox is less likely. Obviously, if the influence of resource supply on capital return is even reversed in the second period, the effect of the future period's asset motive on the extraction decision is reversed, too. The carbon tax induced increase in asset holdings then can no longer lead to a postponement but always induces an acceleration of extraction. A more detailed analysis of the interaction between the capital intensive energy technology, the asset motive, and the reversal mechanism via the carbon tax induced savings reaction as well as of the influence of the renewable energy subsidy and technical change on the asset motive is, however, beyond the scope of this concluding discussion.

Finally, the capital intensity of renewable energy technologies in the end introduces a second investment option to final goods production, which, however, is not complementary but substitutive to fossil resources. This may give the savings and investments of the resource-rich country an additional strategic role for the strength of the competition in the energy market. To this end, the investments from the resource-rich country in contrast to our setting so far would have to be of significant influence on overall capital supply, and the resource-rich country would have to be able to direct its savings to either of both investment options.

8 Conclusion

The use of fossil resources is at the core of the problem of climate change. Decarbonizing the economy and thereby mitigating climate change, therefore, is inevitably in conflict with the economic interests of resource owners in the exploitation of their resource deposits underground. That understanding and accounting for the supply interests of resource owners can be key for the effectiveness of climate mitigation policies has in particular been demonstrated by the possibility of so called green paradox outcomes. Due to the intertemporal nature of fossil resource supply, which arises from the exhaustibility of resource stocks, climate policies, which are supposed to successively reduce resource demand over time, may give rise to supply reactions of resource owners that are completely contrary to the actual good intentions of policy makers.

The predominantly partial equilibrium literature has already yielded important insights about the possibilities and implications of such resource supply reactions and unintended policy outcomes, which we reviewed in the beginning of this study. However, our work intended to show that there are additional transmission channels and feedback effects which arise from the even closer interrelationship between the resource and the capital market than that typically captured in partial equilibrium settings, therein in particular from the asymmetric international distribution of resource stocks, and from the capital investments of resource owners. The central line of reasoning of this study therefore was that the supply interests of fossil resource owners and the interest conflict with climate change mitigation can only be comprehensively understood within a general equilibrium setting that adequately represents the interrelationship between the resource and the capital market.

Following this view, our study provided an overview discussion of the potential influence of climate policies on the capital market, pointed out why these effects may be important for the exploitation of fossil resources, and surveyed the so far existing literature on general equilibrium effects of climate policies for resource extraction. The specific contributions of our work to the literature on the green paradox and to the more comprehensive understanding of the supply interests of fossil resource owners build upon three observations. First, markets for fossil resources, and oil in particular, are widely recognized as not being truly competitive, which is already evident from the geographical concentration of resource stocks. Second, resource-rich countries heavily invest in the international capital market. And third, substitutive technologies to fossil resources are mostly capital intensive.

Resource market power as well as the asset holdings of resource-rich countries so far have been seen to be only of minor or even no relevance for the effect of climate policies on the extraction decisions. Within a rather conventional general equilibrium framework of resource extraction and endogenous capital formation, however, we were able to demonstrate that the interplay of both can fundamentally alter the effect of climate policies compared to a competitive resource market. This is due to the newly identified asset motive, which arises primarily from the complementarity driven influence of resource supply on capital return. The asset motive directly links the resource supply decision of a utility maximizing resource owner with at least some influence in the resource market to the holding of assets in the capital market. Moreover, since climate policies do not only deteriorate future sales prospects in the resource market but, due to their large redistributive effects between resource-rich and -poor countries, also induce adjustments in savings and investments, the asset motive establishes an additional transmission channel even if climate policies on an aggregate level are completely neutral in the international capital market. In particular, with a standard consumption smoothing, or alternatively a precautionary savings, argument resource-rich countries are induced to save more. By the asset motive, this increase in savings then can lead to a reversal of the green paradox.

By extending the general equilibrium framework, this study also for the first time in the literature consistently captures the capital intensity of substitutive carbon-free technologies like wind and solar energy in an analytical framework. The need of capital of these technologies introduces an additional transmission channel for climate policies via the demand side of the capital market, which is new to the literature as well. In fact, an increasing deployment of these capital intensive substitutive energy technologies does not only lead to stronger competition for fossil resources in the energy market, but also to stronger capital demand and to some extent to a reallocation of capital from its use in final goods production, where it is complementary to fossil resources, to the substitutive (renewable) energy generation. We investigated the implications of this additional dimension of the interrelationship between the resource and the capital market by studying the effects of (second best) climate policies and technological change. Focusing on a market equilibrium with simultaneous use of fossil and renewable energy, this illustrated again that resource market power can be of greater relevance for the effect of climate policies than often assumed in the literature: While excluded under competition, the green paradox can be reversed with market power even without accounting for the asset motive. The reversal of the green paradox in this case derives from the influence of the new energy technology on residual resource demand, and more specifically on the price elasticity of residual resource demand.

Overall, our findings give new relevance to the aforementioned real world observations for the effect of climate policies and for the impending intertemporal resource supply responses. By contributing to the more comprehensive understanding of the supply (and investment) interests of resource owners, we believe our work can provide important insights for the design of climate policies and also for negotiations strategies which may be relevant, for example, in future rounds of mitigation pledges under the climate policy architecture of the Paris Agreement.

9 Appendix

9.1 Standard Framework

9.1.1 Capital Supply

To derive (4.17), we first note that aggregate capital supply can be written as

$$K_2^s = K_2^s(y_{1E}, \pi_{2E}^\tau, y_{1I}, \pi_{2I}^\tau, i_2)$$

with

$$dK_2^s = \frac{\partial s_{1E}}{\partial y_{1E}} dy_{1E} + \frac{\partial s_{1E}}{\partial \pi_{2E}^\tau} d\pi_{2E}^\tau + \frac{\partial s_{1I}}{\partial y_{1I}} dy_{1I} + \frac{\partial s_{1I}}{\partial y_{1I}} d\pi_{2I}^\tau + \left(\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} \right) di_2$$

We can further decompose the changes in the period income streams by differentiating with respect to changes in the factor market prices, the resource supply path, and the carbon tax. This yields

$$dy_{1E} = R_1 dp_1 + p_1 dR_1 + s_{0E} di_1$$
$$d\pi_{2E}^\tau = (1-\tau) R_2 dp_2 + (1-\tau) p_2 dR_2 - p_2 R_2 d\tau$$

for country E. Using the first-order conditions for the optimal factor input choice of competitive final goods producers ($F_{tK} = i_t$, $F_{tR} = p_t$), the decomposition of the induced changes in the period income streams of the representative household in country I is given by

$$dy_{1I} = -R_1 dp_1 + (-K_1 + s_{0I}) di_1 = -R_1 dp_1 - s_{0E} di_1$$
$$d\pi_{2I}^\tau = \tau p_2 dR_2 - (1-\tau) R_2 dp_2 + p_2 R_2 d\tau - K_2 di_2$$

For simplicity, we do not consider changes in the capital endowments here. Furthermore, since we are particularly interested in scenarios of resource scarcity, we assume that the resource constraint (4.3) binds, which implies that changes in period resource consumption always correspond to shifts in the resource supply path and therefore $dR_1 = -dR_2$. Aggregating and simplifying by use of our definitions of income redistribution effects in (4.19) and (4.20) and the aggregate substitution effect SE in (4.18) we finally arrive at (4.17).

Side Note: Interest Rate Changes and their Effect on Aggregate Savings

From the total derivative in (4.17) we know that capital supply will increase with the interest rate so that the substitution effect dominates the income effect, or, given the international redistribution of income from higher capital income, the net effect from distributing labour income to the resource exporting country E on aggregate capital supply will be positive if

$$SE + ID_2 s_{1E} > 0$$

Obviously, this will always hold true for $ID_2 \geq 0$, i.e. for symmetric countries or for the resource exporting country E being more patient, which is reflected by $\beta_E \geq \beta_I$.

Since the resource importing country I suffers a loss in second period income due to the redistribution of labour income to country E – for the resource importing country I, an increase in the interest rate leads to a negative income effect whenever country E holds some share in the capital stock K_2 – the substitution and income effect in country I both work towards higher savings s_{1I}. Hence, aggregate savings must also rise with the interest rate even for $ID_2 < 0$ if the substitution effect dominates the income effect in country E. This can be observed upon rearranging using definitions (4.20), (4.18), and (4.11)[1] so that

$$SE + ID_2 s_{1E} = \frac{\frac{1}{\eta}\left[c_{2E} + c_{2I} + \frac{c_{2I}}{c_{1I}}\frac{\pi_{2E}^{\tau}+(1-\eta)(1+i_2)s_{1E}}{1+i_2} + \frac{c_{2E}}{c_{1E}}\frac{\pi_{2I}^{\tau}+(1+i_2)s_{1I}+\eta(1+i_2)s_{1E}}{1+i_2}\right]}{\left[1+i_2+(\beta_E(1+i_2))^{\frac{1}{\eta}}\right]\left[1+i_2+(\beta_I(1+i_2))^{\frac{1}{\eta}}\right]}$$

All the terms in the numerator are unambiguously positive but the second, which by (4.14) is only positive as long as the substitution effect dominates the income effect in country E. The latter will be the case if the intertemporal elasticity of substitution exceeds the share of capital income in total second period income of the representative household in country E

$$\frac{1}{\eta} > \frac{(1+i_2)s_{1E}}{\pi_{2E}^{\tau} + (1+i_2)s_{1E}} = \frac{(1+i_2)s_{1E}}{c_{2E}}$$

[1] We substitute $\frac{c_{2m}}{c_{1m}}$ for $(\beta_m(1+i_2))^{\frac{1}{\eta}}$, which has to hold by the Euler equation (cf. (4.11)) as households optimally save in market equilibrium.

Note that the right side is lower than unity (but only since we have a positive second period income apart from savings).

Due to the unambiguous positive savings reaction in country I, this, however, is only a sufficient condition for the numerator to be positive for $ID_2 < 0$. By further rearranging the numerator[2] and isolating the intertemporal elasticity of substitution, we derive the necessary condition for a positive relationship between aggregate savings and the interest rate

$$\begin{aligned}\frac{1}{\eta} >&(1+i_2)s_{1E}\frac{\left(\frac{c_{2I}}{c_{1I}}-\frac{c_{2E}}{c_{1E}}\right)c_{1E}c_{1I}}{(1+i_2)c_{1E}c_{1I}(c_{2E}+c_{2I})+c_{2E}c_{2I}(c_{1E}+c_{1I})}\\ &=(1+i_2)s_{1E}\frac{c_{2I}c_{1E}-c_{2E}c_{1I}}{(1+i_2)c_{1E}c_{1I}(c_{2E}+c_{2I})+c_{2E}c_{2I}(c_{1E}+c_{1I})}\end{aligned}$$

For $ID_2 \geq 0$, the right side is non-positive as we have $\frac{c_{2I}}{c_{1I}} - \frac{c_{2E}}{c_{1E}} > 0$ by the Euler equation (4.11) so that the inequality always holds as $\eta > 0$ (see (4.1)).

Thus, again, $ID_2 \geq 0$ is sufficient for the aggregate substitution effect to dominate. Intuitively, for $ID_2 > 0$ the resource exporting country E is more patient and therefore reduces its savings upon an increase in second period income by less than the resource importing country I increases its savings due to its loss in labour income from the increase in the interest rate. This implies that the net effect of the induced income redistribution is positive and thus adding to the still positive aggregate substitution effect.

For $ID_2 < 0$, the right side is positive but lower than $\frac{(1+i_2)s_{1E}}{c_{2E}}$, which confirms that the substitution effect dominating the income effect in country E is a sufficient but not a necessary condition for an overall positive relationship between the interest rate and aggregate savings for $ID_2 < 0$.[3]

[2] Note that by the Euler equation (4.11) we have for the numerator of ID_2

$$(1+i_2)^{\frac{1}{\eta}}\left(\beta_E^{\frac{1}{\eta}}-\beta_I^{\frac{1}{\eta}}\right)=\frac{c_{2E}}{c_{1E}}-\frac{c_{2I}}{c_{1I}}$$

[3] Indeed, we can show that

$$\frac{1}{\eta} > \frac{c_{2I}c_{1E}-c_{2E}c_{1I}}{(1+i_2)c_{1E}c_{1I}(c_{2E}+c_{2I})+c_{2E}c_{2I}(c_{1E}+c_{1I})}$$

9.1.2 Conditional Market Equilibrium: Derivation of the Comparative Statics

For the second period comparative statics, we totally differentiate the resource and capital market equilibrium conditions from (4.22) and (4.24). We substitute for dp_1 and di_1 from (4.26) and (4.27) and take into account our previous results about the total derivatives of the aggregate capital supply (4.17) as well as capital and resource demand from (4.6), and (4.7).

Solving for the change in the second period interest rate yields

$$di_2 = \left\{ \frac{F_{2KR} + F_{2KK}\left[\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right]}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2 F_{2KR}(1-\tau)R_2} + \frac{F_{2KK}\left[-ID_1\left(F_{1RR}R_1 + F_{1KR}s_{0E}\right) + \Gamma_2 ID_2(1-\tau)R_2\right]}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2 F_{2KR}(1-\tau)R_2} \right\} dR_2 - \frac{ID_2 p_2 R_2}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2 F_{2KR}(1-\tau)R_2} d\tau$$

Using this in (4.6) we derive the total derivative of the second period resource price as

$$dp_2 = \left\{ \frac{F_{2RR} - \Gamma_2\left(SE + ID_2 s_{1E}\right) + F_{2KR}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right)}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2 F_{2KR}(1-\tau)R_2} - \frac{F_{2KR}\left[ID_1\left(F_{1RR}R_1 + F_{1KR}s_{0E}\right) + ID_2 \tau p_2\right]}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2 F_{2KR}(1-\tau)R_2} \right\} dR_2 - \frac{ID_2 F_{2KR} p_2 R_2}{1 - F_{2KK}\left(SE + ID_2 s_{1E}\right) - ID_2 F_{2KR}(1-\tau)R_2} d\tau$$

which then allows us to derive from (4.17) the total derivative of the equilibrium second period capital stock as

$$dK_2 = \left[\frac{\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 - ID_2 \tau p_2\right) + \frac{\partial i_2}{\partial R_2}\left(SE + ID_2 s_{1E}\right)}{1 - \frac{\partial i_2}{\partial K_2}\left(SE + ID_2 s_{1E}\right) - ID_2(1-\tau)\frac{\partial p_2}{\partial K_2} R_2} - \frac{ID_1\left(\frac{\partial p_1}{\partial R_1} R_1 + \frac{\partial i_1}{\partial R_1} s_{0E}\right) - ID_2(1-\tau)\frac{\partial p_2}{\partial R_2} R_2}{1 - \frac{\partial i_2}{\partial K_2}\left(SE + ID_2 s_{1E}\right) - ID_2(1-\tau)\frac{\partial p_2}{\partial K_2} R_2} \right] dR_2 - \frac{ID_2 p_2 R_2}{1 - \frac{\partial i_2}{\partial K_2}\left(SE + ID_2 s_{1E}\right) - ID_2(1-\tau)\frac{\partial p_2}{\partial K_2} R_2} d\tau \tag{9.1}$$

Positive Sign of the Denominator

Although there are generally counteracting terms, we show in the following that the denominator of the comparative statics in (9.1) must be of positive sign in market equilibrium. To this end, we refer back to the households' savings decision, which are made as to maximize life-time utility given rational expectations. Considering country E, for example,[4] for a utility maximizing savings decision not only the first-order condition represented by the Euler equation (4.11) but also the second-order condition for a utility maximum

$$\begin{aligned}\frac{d^2U}{(ds_{1E})^2} &= u''(c_{1E}) + \beta_E(1+i_2)^2u''(c_{2E}) + \beta_E\frac{\partial i_2}{\partial K_2}u'(c_{2E})\frac{dK_2}{ds_{1E}} \\ &\quad + \beta_E(1+i_2)u''(c_{2E})\left((1-\tau)\frac{\partial p_2}{\partial K_2}R_2 + \frac{\partial i_2}{\partial K_2}s_{1E}\right)\frac{dK_2}{ds_{1E}} \\ &< 0\end{aligned} \tag{9.2}$$

has to hold. Whereas the first-order condition reflects the price-taking behavior of the representative household with rational expectation, for the second-order condition we have to account for the influence of the savings s_{1E} in the economic system, in particular for its influence on the aggregate second period capital stock, which is given by

$$\frac{dK_2}{ds_{1E}} = 1 + \frac{ds_{1I}}{ds_{1E}}$$

This is to guarantee that the savings decision actually constitutes a utility maximum within the given economic system. By totally differentiating the Euler equation (4.11) for country I with respect to changes in savings from country E and using the definitions of the savings reactions in (4.13) and (4.14),[5] we compute the equilibrium savings reaction of country I to a change in the savings from country E as

$$\frac{ds_{1I}}{ds_{1E}} = \left[\frac{\partial i_2}{\partial K_2}\left(-\frac{\partial s_{1I}}{\partial i_2} + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau}}K_2\right) + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau}}(1-\tau)\frac{\partial p_2}{\partial K_2}R_2\right]\frac{dK_2}{ds_{1E}}$$

---

[4] The following reasoning applies to the savings decision of country I completely analogue.

[5] This gives

$$\begin{aligned}&\left[-u''(c_{1I}) - \beta_I(1+i_2)^2u''(c_{2I})\right]ds_{1I} = \\ &\beta_I\left[\frac{\partial i_2}{\partial K_2}u'(c_{2I}) + (1+i_2)u''(c_{2I})\left(F_{2K} - (1-\tau)\frac{\partial p_2}{\partial K_2}R_2 i_2 - \frac{\partial i_2}{\partial K_2}K_2 + \frac{\partial i_2}{\partial K_2}s_{1I}\right)\right]\frac{dK_2}{ds_{1E}}ds_{1E}\end{aligned}$$

where $F_{2K} = i_2$ in market equilibrium with competitive final goods production.

Finally, using this together with the definitions in (4.13) and (4.14), we can simplify the second-order condition (9.2) to

$$1+\frac{\partial i_2}{\partial K_2}\left(\frac{\partial s_{1E}}{\partial i_2}+\frac{\partial s_{1I}}{\partial i_2}-\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau}}K_2\right)-(1-\tau)\frac{\partial p_2}{\partial K_2}R_2\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}-\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau}}\right)>0$$

which by the definitions of the income distribution effect ID_2 in (4.20) and of the aggregate substitution effect SE in (4.18) is completely equivalent to the denominator in the total derivative. Thus, in market equilibrium the denominator must be of positive sign due to the second-order condition ensuring that the individual household's savings decision constitutes a utility maximum.

Derivation of Sufficiency Condition (4.29)

From the definition of the savings propensities in (4.13) and the aggregate substitution effect SE in (4.18) follows by setting $c_{2E}+c_{2I}=F_2+K_2$ from the budget constraints (4.9) and (4.10) and $F_{2R}=p_2$ and $F_{2K}=i_2$ in market equilibrium that

$$\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}p_2-\frac{\partial s_{1E}}{\partial y_{1E}}p_1+F_{2KR}SE=\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}p_2\left[1-\frac{1}{\sigma\eta}\frac{i_2+\theta_{2K}}{1+i_2}\right]-\frac{\partial s_{1E}}{\partial y_{1E}}p_1$$

where we also use $F_{2KR}=\frac{1}{\sigma}\frac{F_{2R}F_{2K}}{F_2}$ by the standard properties of the CES production technology (4.4). Since $\theta_{2K}<1$ by definition, the term in curly brackets will be positive if $\frac{1}{\sigma\eta}\leq 1<\frac{1+i_2}{\theta_{2K}+i_2}$. This shows that (4.29) is a sufficient condition for the savings effect from the intertemporal income shift dominating the substitution effect.

The necessary condition for this to hold is

$$\frac{1}{\sigma\eta}<\frac{1+i_2}{\theta_{2K}+i_2}\left[1+(\beta_E(1+i_2))^{\frac{1}{\eta}}\frac{p_1}{p_2}\right]$$

where the right side is greater than unity by definition.

9.1.3 Resource Supply in General Equilibrium

9.1.3.1 Marginal Resource Revenue and Value as Functions of the Resource Supply Path

In the following, we assume without loss of generality that $\tau_2=\tau=0$ in addition to $\tau_1=0$. The marginal resource revenue MR_t^n from (5.5) is ceteris paribus decreasing in resource supply as by the concavity of the production function and $\frac{\partial p_t}{\partial R_t}=F_{tRR}$

$$\left.\frac{\partial MR_t^n}{\partial R_t}\right|_{K_t}=(1-\tau)\frac{2-\sigma}{\sigma}\left[\theta_{tR}-\frac{1-\sigma}{2-\sigma}\right]\frac{\partial p_t}{\partial R_t}<0\quad\text{for all }\sigma>0 \tag{9.3}$$

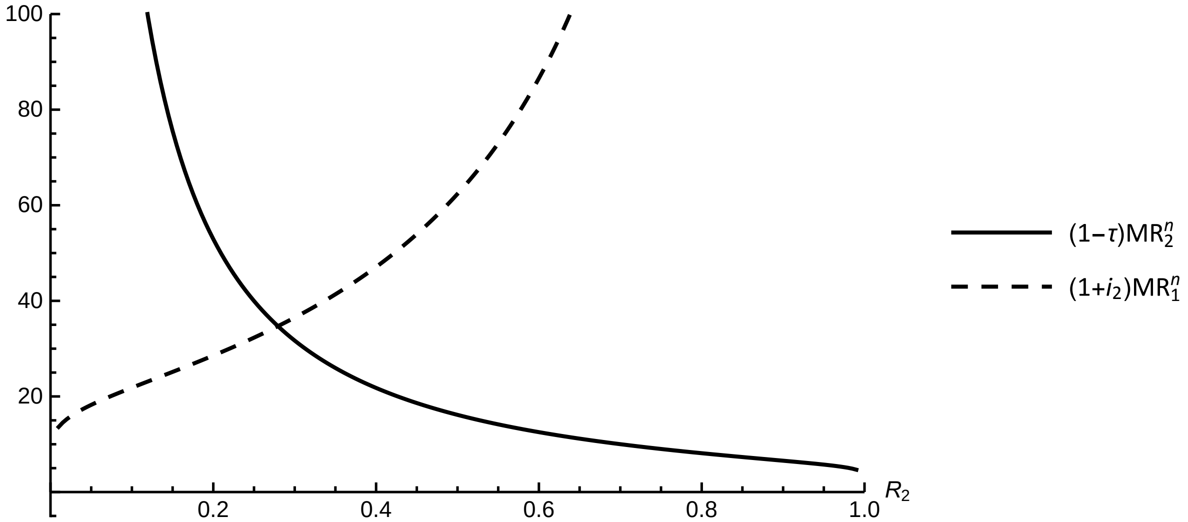

Figure 9.1: Graphical representation of the naive sheikh's extraction decision; assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, $\tau = 0$, total productivity factor $A = 300$

as long as $MR_t^n > 0$, which again is a reasonable restriction at least for the naive sheikh. Otherwise, the fossil resource would not be (economically) scarce anymore (see also (5.7)).

Together with $\frac{di_2}{dR_2} > 0$ from (4.31) for symmetric preferences, we therefore have

$$\frac{d[1+i_2]MR_1^n}{dR_2} = \frac{di_2}{dR_2}MR_1^n - (1+i_2)\left.\frac{\partial MR_1^n}{\partial R_1}\right|_{K_1} \tag{9.4}$$

Thus, the left side of the naive sheikh's Hotelling condition (5.4) is unambiguously falling in R_1, or equivalently for a binding resource constraint is unambiguously increasing in R_2, even though the interest rate endogenously adjust with shifting more and more resources to the second period. Moreover, as long as $\frac{di_2}{dR_2} > 0$, we can conclude that the left side of the Hotelling condition increases more strongly in R_2 in general than in partial equilibrium where $\frac{di_2}{dR_2} = 0$.

For the right side of Hotelling condition (5.4) we have to account for the endogeneity of the second period capital stock K_2. We already know from (5.7) that the marginal resource revenue MR_t^n is ceteris paribus rising with a higher capital stock for all $\sigma > 0$. Using this result we can analogue to (4.30) and (4.31) decompose the overall influence of second period resource supply on the future period marginal resource revenue by separating the direct from the indirect effect of resource supply via the capital dynamics as

$$\begin{aligned}\frac{dMR_2^n}{dR_2} &= \left.\frac{\partial MR_2^n}{\partial R_2}\right|_{K_2} + \left.\frac{\partial MR_2^n}{\partial K_2}\right|_{R_2} \frac{dK_2}{dR_2} \\ &= (1-\tau)\frac{2-\sigma}{\sigma}\left(\theta_{2R} - \frac{1-\sigma}{2-\sigma}\right)\frac{dp_2}{dR_2} < 0 \quad \text{for all } \sigma > 0\end{aligned} \tag{9.5}$$

Again, the negative sign holds definitely true as long as $MR_2^n > 0$ for all $\sigma > 0$. Moreover, this result is independent of $\frac{dK_2}{dR_2}$ from (4.28), because we have $\frac{dp_2}{dR_2} < 0$ for symmetric homothetic preferences (see (4.30)).

Altogether, we can conclude from these observations that at least for symmetric preferences the left and the right side of Hotelling condition (5.4) are decreasing in the resource supply of the respective period over the relevant range of extraction paths. This ensures that there must be a unique equilibrium extraction path if the resource stock is sufficiently small so that the Hotelling condition holds for $MR_t^n >$. This conclusion is graphically illustrated by figure 9.1.

The figure presents the left and the right side of Hotelling condition (5.4), which are computed from an exemplary numerical simulation of the conditional market equilibrium for feasible extraction paths within the given resource stock. The width of the diagram is defined by the available resource stock $\bar{R}$ so that going from the left to the right implies an increase in second period resource supply and correspondingly a decrease in first period resource supply. Owing to this construction, we can include both periods into one figure. Since the conditional market equilibrium holds along these curves, the endogeneity of factor market prices and the second period capital stock is directly included into the figure by construction. Obviously, the optimal extraction decision is defined by the point of intersection of both graphs.

We now consider the extraction decision of the omniscient sheikh. By (5.3), (5.10), and (5.18) we know that

$$MR_1^o = MR_1^{na} \qquad \text{and} \qquad MR_2^o = MR_2^{na} + \Psi\frac{dK_2}{dR_2}$$

The marginal resource value MR_t^{na} without the feedback effects from the capital dynamics from (5.10) is falling in resource supply just as MR_t^n if we hold the capital stock and the assets/savings constant and if $MR_t^{na} > 0$[6]

$$\left.\frac{\partial MR_t^{na}}{\partial R_t}\right|_{K_t, s_{(t-1)E}} = \frac{1}{\sigma}\frac{\partial p_t}{\partial R_t}\left[\theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t}(1-\theta_{tR}) - (1-\sigma)(1-\theta_{tR})\right] < 0 \quad (9.6)$$

The negative sign holds because $\theta_{1R} > \theta_{1R}(1-\theta_{1R})$ by construction so that the term in curly brackets must be positive whenever $MR_t^{na} > 0$, or equivalently $\theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t} - (1-\sigma) > 0$ by (5.10).

Thus, if the interest rate positively depends on second period resource supply so that $\frac{di_2}{dR_2} > 0$, the left side of Hotelling condition (5.2) will be falling in R_1, or equivalently rising in R_2, i.e.

$$\frac{d[(1+i_2)MR_1^o]}{dR_2} = -(1+i_2)\frac{\partial MR_1^o}{\partial R_1} + \frac{di_2}{dR_2}MR_1^o > 0 \quad (9.7)$$

over the relevant range of extraction paths for which $MR_1^{na} = MR_1^o > 0$.

For the right side of Hotelling condition (5.2), we again have to account for the induced change in the capital stock but also for the endogeneity of savings s_{1E}. Considering MR_2^{na} first we can again separate the direct from the indirect effects of resource supply as before and write

$$\frac{dMR_2^{na}}{dR_2} = \left.\frac{\partial MR_2^{na}}{\partial R_2}\right|_{K_2, s_{1E}} + \left.\frac{\partial MR_2^{na}}{\partial K_2}\right|_{R_2, s_{1E}}\frac{dK_2}{dR_2} + \left.\frac{\partial MR_2^{na}}{\partial s_{1E}}\right|_{K_2, R_2}\frac{ds_{1E}}{dR_2}$$

[6] The derivative with respect to first period resource supply can then be derived as follows (for $\tau_1 = \tau_2 = 0$):

$$\begin{aligned}
\frac{\partial MR_t^{na}}{\partial R_t} &= \frac{1}{\sigma}\frac{\partial p_t}{\partial R_t}\left(\sigma - 1 + \theta_{tR} + \theta_{tK}\frac{s_{0E}}{K_t}\right) + \frac{p_t}{\sigma}\left(\frac{\partial\theta_{tR}}{\partial R_t} + \frac{\partial\theta_{tK}}{\partial R_t}\frac{s_{0E}}{K_t}\right)\\
&= \frac{1}{\sigma}\frac{\partial p_t}{\partial R_t}\left(\sigma - 1 + \theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t}\right)\\
&\quad + \frac{p_1}{\sigma F_t}\left(p_t + \frac{\partial p_t}{\partial R_t}R_t - p_t\theta_{tR} + \frac{\partial i_t}{\partial R_t}s_{(t-1)E} - p_t\theta_{tK}\frac{s_{(t-1)E}}{K_t}\right)\\
&= \frac{1}{\sigma}\frac{\partial p_t}{\partial R_t}\left(\sigma - 1 + \theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t}\right)\\
&\quad + \frac{p_t}{\sigma F_t}\left(p_t(1-\theta_{tR}) + \frac{\partial p_t}{\partial R_t}R_t + \frac{1}{\sigma}p_t\theta_{tK}\frac{s_{(t-1)E}}{K_t} - p_t\theta_{tK}\frac{s_{(t-1)E}}{K_t}\right)\\
&= \frac{1}{\sigma}\frac{\partial p_t}{\partial R_t}\left(\sigma - 1 + \theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t}\right) - \frac{\partial p_t}{\partial R_t}\theta_{tR} + \frac{1}{\sigma}\frac{\partial p_t}{\partial R_t}\theta_{tR} - \frac{\theta_{tR}\theta_{tK}}{\sigma}\frac{\partial p_t}{\partial R_t}\frac{s_{(t-1)E}}{K_t}
\end{aligned}$$

We know from (9.6) that the first term is negative, at least as long as $MR_2^{na} > 0$.[7] The second term corresponds to[8]

$$\left.\frac{\partial MR_t^{na}}{\partial K_t}\right|_{K_t, s_{(t-1)E}} = \frac{1}{\sigma}\frac{\partial p_t}{\partial K_t}\left[(2-\sigma)\left(\theta_{tR} + \theta_{tK}\frac{s_{(t-1)E}}{K_t} - \frac{1-\sigma}{2-\sigma}\right) - \frac{s_{(t-1)E}}{K_t}\right] \tag{9.8}$$

This is generally of ambiguous sign even for $MR_t^{na} > 0$ which only ensures that the first element in curly brackets is positive. The ambiguity is in contrast to (5.7) for MR_t^n but due to the ambiguous effect of capital on the complementarity effect of resource supply on the marginal productivity of capital and therefore on the asset component of MR_t^{na}. For the CES production function we have[9]

$$\frac{\partial F_{tKR}}{\partial K_t} = \frac{1}{\sigma}\frac{F_{tKR}}{K_t}\left[(2-\sigma)\theta_{tK} - 1\right]$$

where $\theta_{tK} = \frac{i_t K_t}{F_t} < 1$ may or may not be greater than $\frac{1}{2-\sigma}$ for $\sigma < 2$. For $\sigma \geq 2$, we always have $\frac{\partial F_{tKR}}{\partial K_t} < 0$. The influence of the capital stock is also demonstrated by figure 9.2, which plots for the exemplary numerical simulation the cross derivative F_{2KR} as a function of the resource supply path. The blue curve includes the endogenous adjustment of the overall capital stock K_2 whereas the green curve represents the relationship for the capital stock held fixed at the level which corresponds to the minimal R_2 assumed in the numerical simulation ($R_2 = 0.01$), i.e. both curves start at the same point on the left side of the diagram. Since condition (4.29) holds in our exemplary numerical simulation, the capital stock monotonously falls with shifting resources to the second period, i.e. along the blue curve. In the numerical simulation, this simultaneous fall in the capital stock obviously has a positive effect on the cross derivative/complementarity measure F_{2KR} as the apparently negative influence of resource supply is weaker with the endogenous than with constant capital stock.

7 Note that the restriction $MR_2^{na} > 0$ only holds true for the sheikh pursuing just the asset motive. For the omniscient sheikh, however, we cannot infer $MR_2^{na} > 0$ from the binding resource constraint. The reason is that the binding resource constraint only implies $MR_2^o > 0$ which may hold even for $MR_2^{na} < 0$ if the additional terms from the internalization of the capital dynamics positively contribute to the marginal resource value (see (5.3)).

8 For the second period and positive resource tax, we have

$$\left.\frac{\partial MR_2^{na}}{\partial K_2}\right|_{K_2, s_{1E}} = \frac{1}{\sigma}\frac{\partial p_2}{\partial K_2}\left[(2-\sigma)\left((1-\tau)\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{1-\sigma}{2-\sigma}\right) - \frac{s_{1E}}{K_2}\right]$$

9 Similarly, we have

$$\frac{\partial F_{tKR}}{\partial R_t} = \frac{1}{\sigma}\frac{F_{tKR}}{R_t}\left[(2-\sigma)\theta_{tR} - 1\right] \gtrless 0$$

Moreover, the sharp decrease in the capital stock for very high R_2, which we can observe from figure 9.3, even causes the cross derivative to increase at the right end of the diagram. Thus, whereas the decrease in the capital stock reduces ceteris paribus the marginal resource revenue MR_2^n according to (5.7), there is a counteracting effect of the decrease in the capital stock on the asset component in MR_2^{na}.

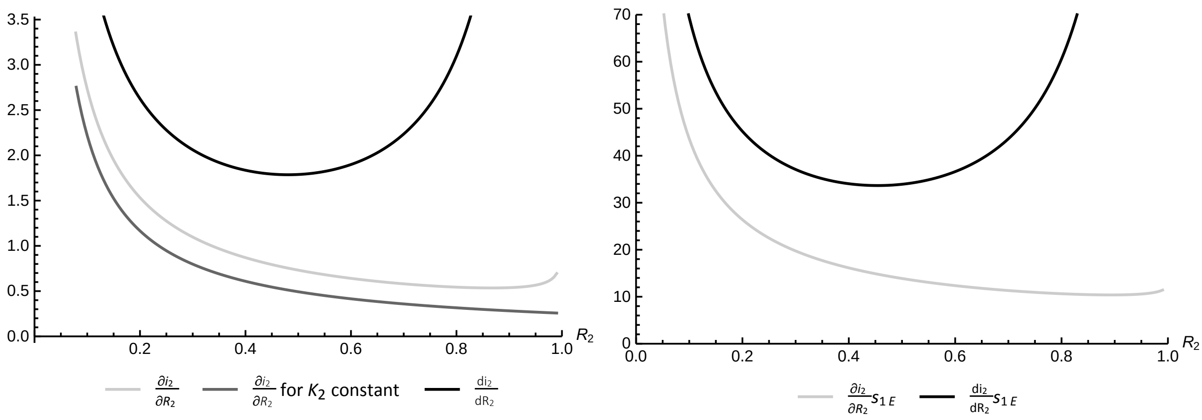

Figure 9.2: The complementarity effect of second period resource supply on the marginal productivity of capital;
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, $\tau = 0$, total productivity factor $A = 300$

The savings of country E generally may also decrease or increase with a postponement of resource extraction which can be observed from decomposing the influence of the extraction path by use of the savings reactions in (4.13) and (4.14) as

$$\begin{aligned}\frac{ds_{1E}}{dR_2} &= -\frac{\partial s_{1E}}{\partial y_{1E}}\frac{\partial y_{1E}}{\partial R_1} + \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\frac{d\pi_{2E}^{\tau}}{dR_2} + \frac{\partial s_{1E}}{\partial i_2}\frac{di_2}{dR_2} \\ &= -\frac{\partial s_{1E}}{\partial y_{1E}} MR_1^{na} + \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}(1-\tau)\left(p_2 + \frac{dp_2}{dR_2}R_2\right) + \frac{\partial s_{1E}}{\partial i_2}\frac{di_2}{dR_2}\end{aligned}$$

with $\frac{dp_2}{dR_2} < 0$ from (4.30) and $\frac{di_2}{dR_2} > 0$ from (4.31) for symmetric preferences. The ambiguity is also illustrated by figure 9.3, which represents the savings of country E as a function second period resource supply for our exemplary numerical simulation.

All these ambiguous analytical results imply that the marginal resource value MR_t^{na} to the sheikh may increase with future resource supply even if the sheikh is not omniscient but only pursues the asset motive but does not internalize the capital dynamics.

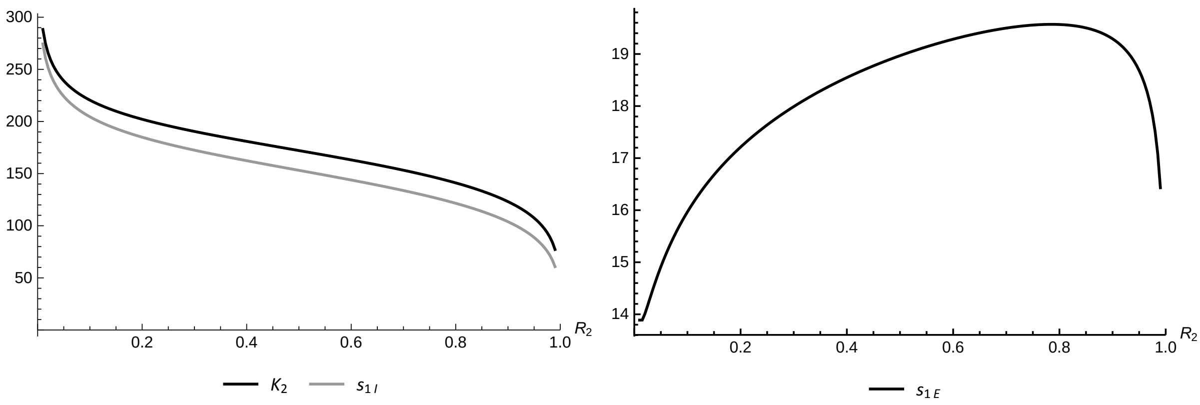

Figure 9.3: The second period capital stock and savings of both countries as functions of the extraction path in the conditional market equilibrium; parameter assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, $\tau = 0$, total productivity factor $A = 300$

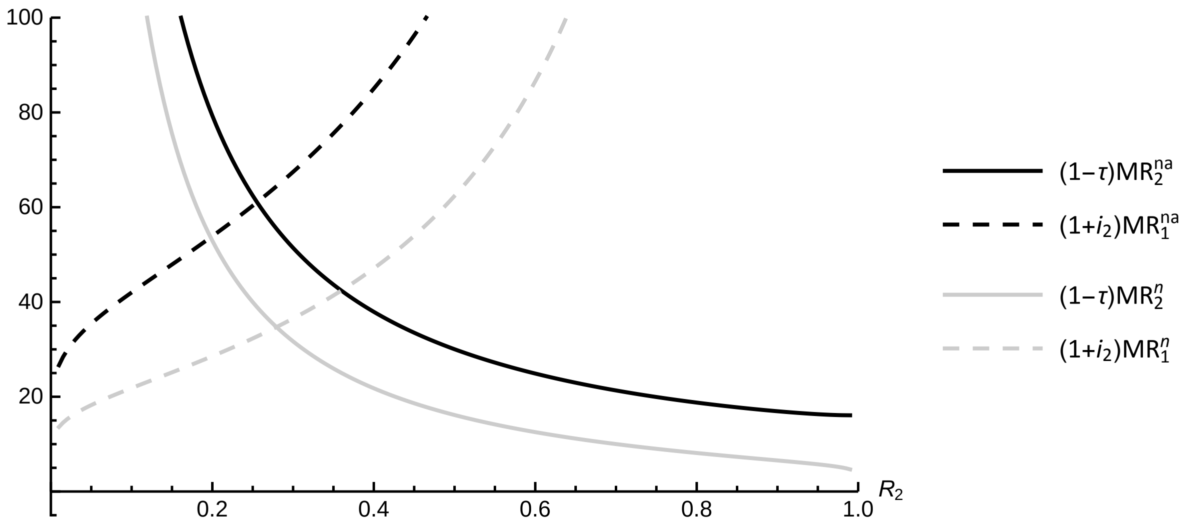

Figure 9.4: The extraction decision of the asset motive pursuing sheikh; assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, $\tau = 0$, total productivity factor $A = 300$, $L = 1$

While this is not the case in figure 5.1 for a resource stock $\bar{R} = 1$, we observe exactly such an increasing part of MR_2^{na} for very conservative extraction paths to the right end of the diagram for a larger resource stock $\bar{R} = 10$ in figure 9.4. From our previous discussion we can conclude that the reason for this is the influence of the capital stock on the cross derivative F_{2KR} and thereby on the asset motive component of MR_2^{na}, which overcompensates also the reduction in the asset holdings of country E (see figure 9.3). Since sufficiency condition (4.29) holds in our numerical simulations irrespective of the resource stock, note that the capital stock K_2 monotonously decreases with raising R_2. This tends to reduce the marginal resource revenue MR_2^n additionally according to (5.7). For the comparison between the completely naive and the asset motive pursuing sheikh we have also included the marginal revenue curves from figure 9.1. Obviously, for the exemplary specification with $\bar{R} = 10$, the asset motive introduces an incentive to accelerate extraction here.

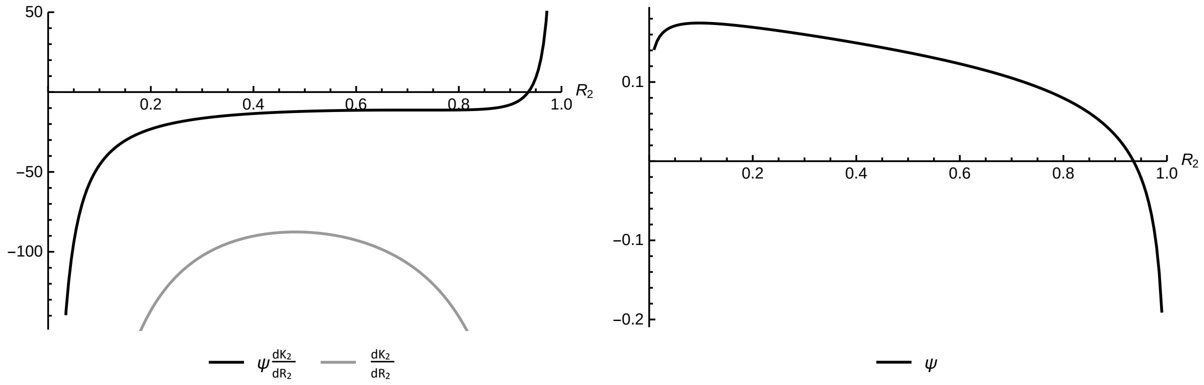

Figure 9.5: The relationship between the future capital stock and resource supply and the contribution of the capital dynamics to the marginal resource value; assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 20$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, $\tau = 0$, total productivity factor $A = 300$

The right side of Hotelling condition (5.2) also includes the feedback effects from the capital dynamics. The overall influence of the extraction path is therefore given by the decomposition

$$\frac{dMR_2^o}{dR_2} = \frac{dMR_2^{na}}{dR_2} + \frac{d\Psi}{dR_2}\frac{dK_2}{dR_2} + \Psi\frac{d^2K_2}{(dR_2)^2} \tag{9.9}$$

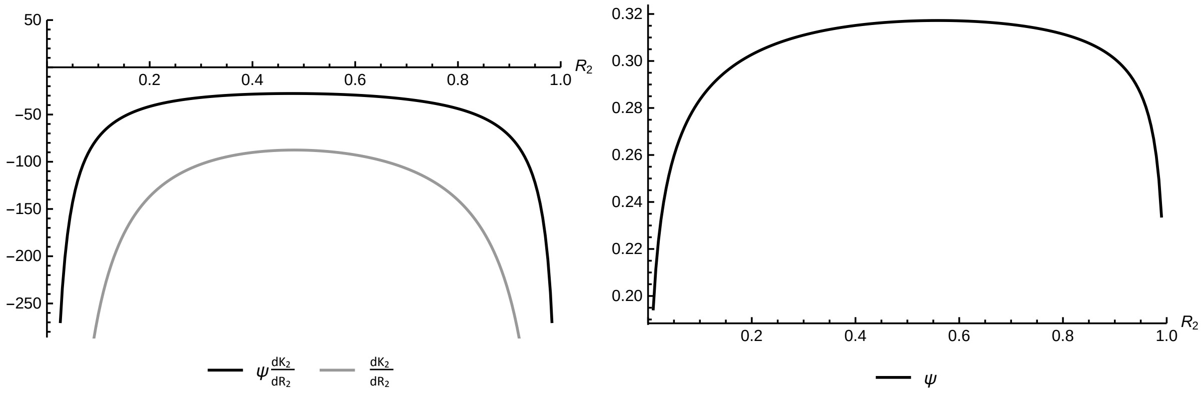

Figure 9.6: The relationship between the future capital stock and resource supply and Ψ for $s_{0E} = 0$;
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 0$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, $\tau = 0$, total productivity factor $A = 300$

We already know that the first term is ambiguous, in general. The same holds true for $\frac{dK_2}{dR_2}$ from (4.28), for Ψ from (5.18), and for[10]

$$\frac{d\Psi}{dR_2} = \left.\frac{\partial \Psi}{\partial R_2}\right|_{K_2, s_{1E}} + \left.\frac{\partial \Psi}{\partial K_2}\right|_{R_2, s_{1E}} \frac{dK_2}{dR_2} + \left.\frac{\partial \Psi}{\partial s_{1E}}\right|_{K_2, R_2} \frac{ds_{1E}}{dR_2}$$

Even without considering the virtually intractable term $\frac{d^2 K_2}{(dR_2)^2}$, all these analytical results suggest that (9.9) may not monotonously fall with R_2. This conclusion is supported by our exemplary numerical simulation, which is represented in figure 5.1: at the right end of the diagram for $R_2 \to \bar{R}$ MR_2^o is strongly upward sloping whereas MR_2^{na} is not. This difference must be due to the feedback effects on the asset motive and the negative own-price effect from the capital dynamics, which only the omniscient sheikh explicitly takes into account. In fact, figure 9.5 illustrates that Ψ (5.18) is ambiguous, but that these feedback effects from the endogeneity of capital accumulation strongly add to the marginal resource value for $R_2 \to \bar{R}$.

[10] We have

$$\begin{aligned}\left.\frac{\partial \Psi}{\partial R_2}\right|_{K_2, s_{1E}} &= \frac{1}{\sigma} F_{2KR} \left[(2-\sigma)\left((1-\tau)\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2}\right) - (1-\sigma)(1-\tau)\right] \\ \left.\frac{\partial \Psi}{\partial K_2}\right|_{R_2, s_{1E}} &= \frac{1}{\sigma}\left[\left(\frac{1}{\sigma}\theta_{2K} - 1\right)\left((1-\tau)\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2}\right) + (1-\theta_{2K})\frac{s_{1E}}{K_2}\right]\end{aligned}$$

which are ambiguous, in general, due to the ambiguity of $\Psi = \frac{i_2}{\sigma}\left((1-\tau)\theta_{2R} + \theta_{2K}\frac{s_{1E}}{K_2} - \frac{s_{1E}}{K_2}\right)$.

Recall that by redistributing capital endowments away from country E we can reduce the savings of country E without influencing the overall conditional market equilibrium for any given extraction path with symmetric homothetic preferences (see section 5.2.2.2). Since Ψ negatively depends on the second period capital assets s_{1E}, this implies that whether we observe an upward sloping part of MR_2^o or not also depends on the distribution of capital endowments between both countries and tends to be more likely the more capital endowment country E holds. In turn, redistributing capital endowments from country E to country I shifts Ψ upwards so that it turns negative only for even more conservative extraction paths than before. This is illustrated in figures 9.6 and 9.7 where we redistribute all the capital endowment s_{0E} to the resource importing countries I. In fact, in this case we have $\Psi > 0$ for all feasible extraction paths, and the feedback effects from the endogeneity of capital accumulation therefore negatively contribute to the marginal resource value throughout.

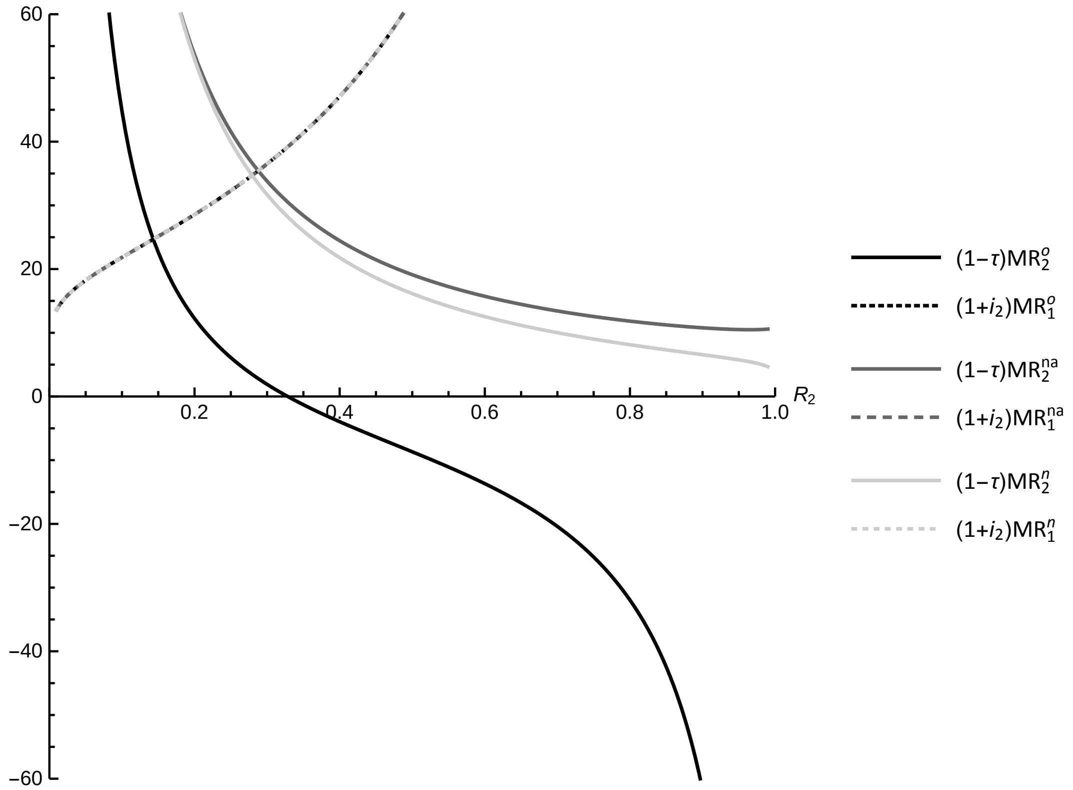

Figure 9.7: The extraction decision of the omniscient sheikh without first period asset holdings;
assumptions: $\bar{R} = 1$, $K_1 = 200$, $s_{0E} = 0$, $L = 1$, $\sigma = 0.91$, $\lambda = 0.1$, $\gamma = 0.4$, $\tau = 0$, total productivity factor $A = 300$

9.1.3.2 Derivation of the Second-Order Conditions

Omniscient Sheikh

The first-order condition to the optimization problem of the omniscient sheikh (5.1) reads

$$\begin{aligned}\frac{dU}{dR_2} &= -u'(c_{1E})\left[\underbrace{\left(p_1 + \frac{\partial p_1}{\partial R_1}R_1 + \frac{\partial i_1}{\partial R_1}s_{0E}\right)}_{MR_1^o}\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right] \\ &\quad + \beta_E u'(c_{2E})\left[\underbrace{p_2 + \frac{dp_2}{dR_2}R_2 + \frac{di_2}{dR_2}s_{1E}}_{MR_2^o} + (1+i_2)\frac{ds_{1E}}{dR_2}\right] \\ &\overset{!}{=} 0\end{aligned} \tag{9.10}$$

where we set $u'(c_{tE}) = \frac{\partial u}{\partial c_{tE}}$ and $\frac{dR_1}{dR_2} = -1$ due to the binding resource constraint. Note that the omniscient sheikh accounts for the entire influence of the resource supply decision. For the extraction path (R_1^o, R_2^o) maximizing the life-time utility of the representative household in country E, the second-order condition is

$$\begin{aligned}\frac{d^2U}{(dR_2)^2} &= u''(c_{1E})\left[MR_1^o\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right]^2 \\ &\quad + u'(c_{1E})\left[\frac{\partial MR_1^o}{\partial R_1}\left(\frac{dR_1}{dR_2}\right)^2 - \frac{d^2 s_{1E}}{(dR_2)^2}\right] \\ &\quad + \beta_E u''(c_{2E})\left[MR_2^o + (1+i_2)\frac{ds_{1E}}{dR_2}\right]^2 \\ &\quad + \beta_E u'(c_{2E})\left[\frac{dMR_2^o}{dR_2} + \frac{di_2}{dR_2}\frac{ds_{1E}}{dR_2} + (1+i_2)\frac{d^2 s_{1E}}{(dR_2)^2}\right] \\ &< 0\end{aligned} \tag{9.11}$$

At the same time, as we have already laid out in section 4.1.3.1, the representative household makes a saving decision with rational expectations regarding its period incomes y_{1E} and π_{2E}^{τ} and the interest rate i_2, and therefore given the conditional market equilibrium. This allows us to conclude that the Euler equation (4.11) holds for any resource extraction policy the sheikh chooses. On the one hand, we therefore can reduce the first-order condition (9.10) to Hotelling rule (5.2) as we argued in section 5.2.2. On the other hand, we can totally differentiate the Euler equation with respect to R_2 and savings, which gives us

$$\begin{aligned}&-\left[u''(c_{1E}) + \beta_E(1+i_2)^2 u''(c_{2E})\right]\frac{ds_{1E}}{dR_2} = \\ &\qquad u''(c_{1E})MR_1^o + \beta_E(1+i_2)u''(c_{2E})MR_2^o + \beta_E u'(c_{2E})\frac{di_2}{dR_2}\end{aligned} \tag{9.12}$$

where we set by the budget constraints (4.10)

$$\left.\frac{dc_{1E}}{dR_1}\right|_{s_{1E}} = p_1 + \frac{\partial p_1}{\partial R_1}R_1 + \frac{\partial i_1}{\partial R_1}s_{0E} = MR_1^o$$
$$\left.\frac{dc_{2E}}{dR_2}\right|_{s_{1E}} = (1-\tau)\left(p_2 + \frac{dp_2}{dR_2}R_2\right) + \frac{di_2}{dR_2}s_{1E} = MR_2^o$$

Substituting the total derivative (9.12) in the second-order condition, and additionally using Hotelling condition (5.2) as we are interested in equilibrium extraction paths, we can rearrange and simplify the second-order condition to become

$$\begin{aligned}\frac{d^2U}{(\partial R_2)^2} &= \beta_E u'(c_{2E})\frac{di_2}{dR_2}\left[MR_1^o\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right] \\ &\quad + \beta_E(1+i_2)u''(c_{2E})\left(MR_2^o + (1+i_2)\frac{ds_{1E}}{dR_2}\right)MR_1^o\frac{dR_1}{dR_2} \\ &\quad - \beta_E(1+i_2)u''(c_{2E})\left(MR_2^o + (1+i_2)\frac{ds_{1E}}{dR_2}\right)\frac{ds_{1E}}{dR_2} \\ &\quad + \beta_E u'(c_{2E})\left[(1+i_2)\frac{\partial MR_1^o}{\partial R_1}\left(\frac{dR_1}{dR_2}\right)^2\frac{dMR_2^o}{dR_2}\right] \\ &\quad + \beta_E u'(c_{2E})\frac{di_2}{dR_2}\frac{ds_{1E}}{dR_2} + \beta_E u''(c_{2E})\left[MR_2^o + (1+i_2)\frac{ds_{1E}}{dR_2}\right]^2 \\ &= \beta_E u'(c_{2E})\left[(1+i_2)\frac{\partial MR_1^o}{\partial R_1} + MR_1^o\frac{dR_1}{dR_2}\frac{di_2}{dR_2} + \frac{dMR_2^o}{dR_2}\right] < 0\end{aligned}$$

Finally, since $\beta_E u'(c_{2E}) > 0$, this demonstrates that condition (5.22) must hold by the second-order condition.

Naive Sheikh

The first-order condition from the utility maximization problem of the naive sheikh reads

$$\frac{dU}{dR_2} = -u'(c_{1E})MR_1^n + \beta_E u'(c_{2E})MR_2^n \overset{!}{=} 0 \tag{9.13}$$

Whereas the first-order condition is clearly directly dependent on the sheikh's limited level of information, the second-order condition must include the actual equilibrium relationships between the choice variable, i.e. the resource extraction path, and the overall economy given in the conditional market equilibrium to guarantee that the extraction policy characterizes a (local) utility maximum. We therefore have

$$\begin{aligned}\frac{d^2U}{(dR_2)^2} &= u''(c_{1E})MR_1^n\left(MR_1^o + \frac{ds_{1E}}{dR_2}\right) + u'(c_{1E})\frac{dMR_1^n}{dR_1} \\ &\quad + \beta_E u''(c_{2E})MR_2^n\left[MR_2^o + (1+i_2)\frac{ds_{1E}}{dR_2}\right] + \beta_E u'(c_{2E})\frac{dMR_2^n}{dR_2} < 0\end{aligned} \tag{9.14}$$

Following the same reasoning as for the omnisient sheikh, we can show by use of the Euler equation, its total derivative (9.12), and Hotelling condition (5.4), which all have to hold along the naive sheikh's equilibrium extraction path (R_1^n, R_2^n), that by second-order condition ensures (5.21) must hold.

Asset Motive Pursuing Sheikh

To ensure that extraction policy (R_1^{na}, R_2^{na}) solves the utility maximization problem of the asset motive pursuing sheikh, the second-order condition again has to include the actual general equilibrium relationships even though the sheikh in this case only accounts for the direct complementarity driven influence on the interest rate (F_{2KR}). Thus, the second-order condition in this case reads

$$\begin{aligned}\frac{d^2U}{(dR_2)^2} &= u'(c_{1E})\frac{dMR_1^{na}}{dR_2} + u''(c_{1E})\left[(MR_1^{na})^2 + \frac{ds_{1E}}{dR_2}\right] \\ &\quad + \beta_E u'(c_{2E})\frac{dMR_2^{na}}{dR_2} + \beta_E u''(c_{2E})MR_2^{na}\left[MR_2^o + (1+i_2)\frac{ds_{1E}}{dR_2}\right]\end{aligned}$$

Along the equilibrium extraction path (R_1^{na}, R_2^{na}) for which Hotelling condition (5.9) holds this can be simplified to

$$\begin{aligned}\frac{d^2U}{(dR_2)^2} &= \beta_E u'(c_{2E})\left[(1+i_2)\frac{dMR_1^{na}}{dR_2} + \frac{dMR_2^{na}}{dR_2}\right] \\ &\quad + MR_1^{na}\left[u''(c_{1E})MR_1^o + \beta_E(1+i_2)u''(c_{2E})MR_2^o\right] \\ &\quad + MR_1^{na}\left[u''(c_{1E}) + \beta_E(1+i_2)^2u''(c_{2E})\right]\frac{ds_{1E}}{dR_2} < 0\end{aligned}$$

Analogue to the derivation for the omniscient sheikh, by use of the Euler equation (4.11) and its total derivative (9.12) this can further be simplified to

$$\beta_E u'(c_{2E})\left[(1+i_2)\frac{dMR_1^{na}}{dR_2} + \frac{dMR_2^{na}}{dR_2} - \frac{di_2}{dR_2}MR_1^{na}\right] < 0$$

which again demonstrates that the negative sign in (5.23) holds true by the second-order condition along the optimal extraction policy (R_1^{na}, R_2^{na}).

9.1.4 Revisiting the Green Paradox in General Equilibrium: Competitive Market

We use (6.1), (6.2), and (6.3) as well as (4.18) and (2.3) along the competitive equilibrium extraction path to rearrange the numerator of the comparative statics (6.5) along the following lines:

$$-p_2 + (1-\tau)\frac{dp_2}{d\tau} - \frac{di_2}{d\tau}p_1 > 0$$

$$F_{2KK}\frac{dK_2}{d\tau}\left(\frac{1-\tau}{p_1}\frac{F_{2KR}}{F_{2KK}} - 1\right) > \frac{p_2}{p_1}$$

$$ID_2\left[p_2 R_2 F_{2KK}\frac{F_2 + K_2}{F_2 - i_2 K_2} + \frac{1-\tau}{p_1}F_{2KR}p_2 R_2 + \frac{p_2}{p_1}F_{2KK}s_{1E}\right] > \frac{p_2}{p_1}\left(1 - F_{2KK}SE\right)$$

$$ID_2 F_{2KK}\left(p_2 R_2 + \frac{p_2}{p_1}s_{1E}\right) > \frac{p_2}{p_1}\left(1 - F_{2KK}SE\right)$$

$$\frac{p_2}{p_1}\frac{F_{2KK}}{\eta(1+i_2)}\left[ID_2(\eta - 1)c_{2E} - \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau}}\left(c_{2E} + c_{2I}\right)\right] > \frac{p_2}{p_1}$$

Note that we set $\frac{\partial p_2}{\partial K_2} = F_{2KR} = \frac{1}{\sigma}\frac{p_2 i_2}{F_2}$, $\frac{\partial i_2}{\partial K_2} = F_{2KK} = \frac{1}{\sigma}\frac{i_2}{K_2}\left(\theta_{2K} - 1\right)$ by (4.30) and (4.31) in market equilibrium.

9.2 Capital Intensive Renewable Energy

9.2.1 Capital Supply With Renewable Energies

To decompose aggregate capital supply, we totally differentiate the budget constraints of each country. For country E, this gives by (4.10)

$$dy_{1E} = p_1 dR_1 + R_1 dp_1 + s_{0E} di_1 \qquad \text{and}$$
$$d\pi_{2E}^{\tau} = (1-\tau)p_2 dR_2 + (1-\tau)R_2 dp_2 - p_2 R_2 d\tau$$

and for country I

$$dy_{1I} = -R_1 dp_1 - s_{0E} di_1 \qquad \text{and}$$
$$d\pi_{2I}^{\tau} = \tau p_2 dR_2 - (1-\tau)R_2 dp_2 - K_2 di_2 + F_{2Q} W_2 d\mu + p_2 R_2 d\tau$$

Using these total derivatives together with the savings reactions from (4.13) and (4.14), we can decompose the determinants of the aggregate capital supply function. Summarizing terms and using our definitions of the net effects of income redistribution in (4.19) and (4.20) as well as the definition of the aggregate substitution effect SE from (4.18) we get

$$\begin{aligned} dK_2^s = & \left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + ID_2 \tau p_2\right) dR_2 + ID_1 R_1 dp_1 + ID_1 s_{0E} di_1 \\ & + ID_2(1-\tau)R_2 dp_2 + \left(\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} K_2\right) di_2 \\ & + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2Q} W_2 d\mu - ID_2 p_2 R_2 d\tau \end{aligned}$$

By definition, we can set $\frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} K_2 = SE + ID_2 s_{1E}$.

For symmetric consumption preferences, we have $ID_1 = ID_2 = 0$ so that (7.14) arises.

9.2.2 Comparative Statics of the Conditional Market Equilibrium

9.2.2.1 Derivation

To derive the comparative statics for the second period we proceed completely analogue to our analysis of the conditional equilibrium without renewable energies in section 4.2.2.2.

Totally differentiating the future period resource market equilibrium condition (7.16) and solving for dp_2 gives

$$\begin{aligned}
dp_2 = & \frac{\Gamma_2 F_{2Q}\mu W_{2KK}}{F_{2KK}F_{2Q}\mu W_{2KK} + \Gamma_2\left(\mu W_{2K}\right)^2} dR_2 \\
& + \frac{F_{KQ}F_{2Q}\mu W_{2KK} + (1-\omega)\Gamma_2\mu W_{2K}}{F_{2KK}F_{2Q}\mu W_{2KK} + \Gamma_2\left(\mu W_{2K}\right)^2} di_2 \\
& - \frac{\Gamma_2 F_{2Q}\mu W_{2KK}}{F_{2KK}F_{2Q}\mu W_{2KK} + \Gamma_2\left(\mu W_{2K}\right)^2} \frac{W_{2K}^2 - W_{2KK}W_{2K}}{W_{2KK}} d\mu \\
& - \frac{i_2\Gamma_2\mu W_{2K}}{F_{2KK}F_{2Q}\mu W_{2KK} + \Gamma_2\left(\mu W_{2K}\right)^2} d\omega
\end{aligned}$$

Substituting for dp_2 in the total derivative of the capital market equilibrium condition (7.17) and solving for di_2 then yields

$$\begin{aligned}
di_2 = & \left\{ \frac{F_{2KQ} + \left(F_{2KQ}\mu W_{2K} - F_{2KK}\right) \left.\frac{dK_{2W}}{dR_2}\right|_{K_2}}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} \right. \\
& \left. + \frac{\left[(1-\phi)F_{2KK} + \phi F_{2QK}\mu W_{2K}\right]\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right)}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} \right\} dR_2 \\
& + \left\{ \frac{\left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2Q}W_2}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} \right. \\
& - \frac{\frac{F_{2Q}W_{2K}\left(F_{2KQ}\mu W_{2K} - F_{2KK}\right)}{\Xi}}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} \\
& \left. + \frac{W_2\left[F_{2KQ} + \left(F_{2KQ}\mu W_{2K} - F_{2KK}\right)\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}\right]}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} \right\} d\mu \\
& - \frac{i_2\left(F_{2KQ}\mu W_{2K} - F_{2KK}\right)}{\Xi\left[1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE\right]} d\omega
\end{aligned}$$

Finally, by substituting for di_2 in (7.14) we derive the comparative statics of capital accumulation, i.e. the equilibrium relationship between the second period capital stock K_2 and the resource supply path, technological status and the renewable energy subsidy as

$$dK_2 = \left\{ \frac{\left(\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right) +}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} + \frac{\left[F_{2KQ} + (F_{2KQ}\mu W_{2K} - F_{2KK}) \left.\frac{dK_{2W}}{dR_2}\right|_{K_2}\right] SE}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} \right\} dR_2$$
$$+ \frac{\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} F_{2Q} W_2 + \left[F_{2KQ} W_2 + (F_{2KQ}\mu W_{2K} - F_{2KK}) \left.\frac{dK_{2W}}{d\mu}\right|_{K_2}\right] SE}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} d\mu$$
$$+ \frac{(F_{2KQ}\mu W_{2K} - F_{2KK}) \left.\frac{dK_{2W}}{d\omega}\right|_{K_2} SE}{1 - \left[(1-\phi)F_{2KK} + \phi F_{2KQ}\mu W_{2K}\right] SE} d\omega$$

which holds instead of (9.1) for symmetric preferences if $\mu > 0$ and if there is simultaneous use of both, fossil resources and the renewable energy technology in the second period. With symmetric homothetic consumption preferences, the resource tax again does not have any separate (or "direct") effect on the conditional market equilibrium, or the capital market equilibrium in particular.

9.2.2.2 Equilibrium Influence of the Resource Extraction Path on Capital Investments and Energy Supply

In this section, we provide more details on the equilibrium influence of the resource extraction path. Based on (7.25) we can derive the induced change in the capital stock invested in renewable energy generation K_{2W}. On the one hand, we know that fossil resources crowd out renewable energies so that capital is redistributed to final goods production (see (7.19)). On the other hand, a share ϕ of the induced change in the aggregate capital stock K_2 translates into renewable energy investments so that we get for the overall relationship

$$\begin{aligned} \frac{dK_{2W}}{dR_2} &= \left.\frac{dK_{2W}}{dR_2}\right|_{K_2} + \phi \frac{dK_2}{dR_2} \\ &= \frac{(1 - F_{2KK} SE) \left.\frac{dK_{2W}}{dR_2}\right|_{K_2} + \phi \left(\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KQ} SE\right)}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE} \\ &< 0 \end{aligned} \tag{9.15}$$

The negative sign holds true as long as we assume $\sigma > \frac{1}{\eta}$. In this case, the capital stock invested in renewable energy generation decreases due to both, the induced capital reallocation to final goods production as well as the falling aggregate capital stock K_2. However, even if the aggregate capital stock did not shrink, we might have lower investments in renewable energies as renewable energies are squeezed out of the energy energy market by fossil resources.

Using (7.25) and (9.15), we derive the relationship between postponing resource extraction and the capital stock invested in final goods production as

$$\begin{aligned}\frac{dK_{2F}}{dR_2} &= \frac{dK_2}{dR_2} - \frac{dK_{2W}}{dR_2} \\ &= \frac{(1-\phi)\left(\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KQ} SE\right)}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE} \\ &\quad - \frac{(1 - F_{2KQ}\mu W_{2K} SE) \left.\frac{dK_{2W}}{dR_2}\right|_{K_2}}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE}\end{aligned} \tag{9.16}$$

In contrast to the renewable energy capital stock, the production capital reaction generally may increase or decrease with a higher second period resource supply.[11] Note that this holds true even for $\sigma > \frac{1}{\eta}$, for which the first term in the numerator is negative. This ambiguity result is also in contrast to the standard case without renewable energies where the capital stock invested in production decreases with higher future resource supply for $\sigma > \frac{1}{\eta}$. This is due to the reallocation of physical capital by the crowding out of renewable energies with higher fossil resource supply. Obviously, the larger the fall in renewable energy investments according to (9.15) the more likely the capital stock invested in final goods production rises with higher resource supply R_2 even if the aggregate physical capital stock shrinks.

The induced reallocation of capital away from the renewable energy generation also implies that overall energy supply to the economy does not necessarily rise with higher resource supply in the second period. By $Q_2 = R_2 + \mu W_2$ from (7.2) we have

$$\begin{aligned}\frac{dQ_2}{dR_2} &= 1 + \mu W_{2K} \frac{dK_{2W}}{dR_2} \\ &= 1 + \mu W_{2K} \left.\frac{dK_{2W}}{dR_2}\right|_{K_2} + \mu W_{2K} \phi \frac{dK_2}{dR_2} \gtrless 0\end{aligned} \tag{9.17}$$

[11] In the competitive resource market equilibrium, the second term, however, positively adds to the first.

By (7.27) we know that the ambiguity arises due to the induced change in the aggregate physical capital stock.[12]

9.2.3 The Effect of Technical Change

9.2.3.1 Comparative Statics of the Conditional Market Equilibrium with respect to Technical Change

The negative sign of (7.52) can only be observed from rewriting the comparative statics effect. In fact, using the definitions in (7.46), (7.51), and (7.32) we have

$$\frac{dp_2}{d\mu} = \frac{F_{2Q}\mu W_{2KK}W_2\left(F_{2QQ} - \Gamma_W SE + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2KQ}F_{2Q}\right)}{\Xi\left(1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE\right)} + \frac{F_{2Q}W_{2K}\left(\Gamma_W SE\mu W_{2K} + F_{2KQ} - F_{2QQ}\mu W_{2K}\right)}{\Xi\left(1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE\right)} + \frac{(1-\omega)\Gamma_W W_2\left(1 + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}(1-\omega)F_{2K}\right)}{\Xi\left(1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE\right)} < 0$$

All elements are positive by definition and since $|\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}(1-\omega)F_{2K}| < 1$ by (4.13) but $\Xi < 0$ by (7.20).

[12] However, we can show that in the competitive resource market equilibrium defined by the Hotelling condition (2.3) overall energy supply Q_2 must always rise with a higher supply of fossil resources. Upon rearranging we have

$$\frac{dQ_2}{dR_2} = \frac{\frac{F_{2Q}\mu W_{2KK}}{\Xi}(1 - F_{2KK}SE) + \phi\left[1 + \mu W_{2K}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}p_2 - \frac{\partial s_{1E}}{\partial y_{1E}}p_1\right)\right]}{1 - \left.\frac{di_2}{dK_2}\right|_{R_2} SE}$$

which is positive in the competitive equilibrium because in this case $1+\mu W_{2K}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}p_2 - \frac{\partial s_{1E}}{\partial y_{1E}}p_1\right) > 0$. For the naive monopolist, in contrast, this does not necessarily hold true.

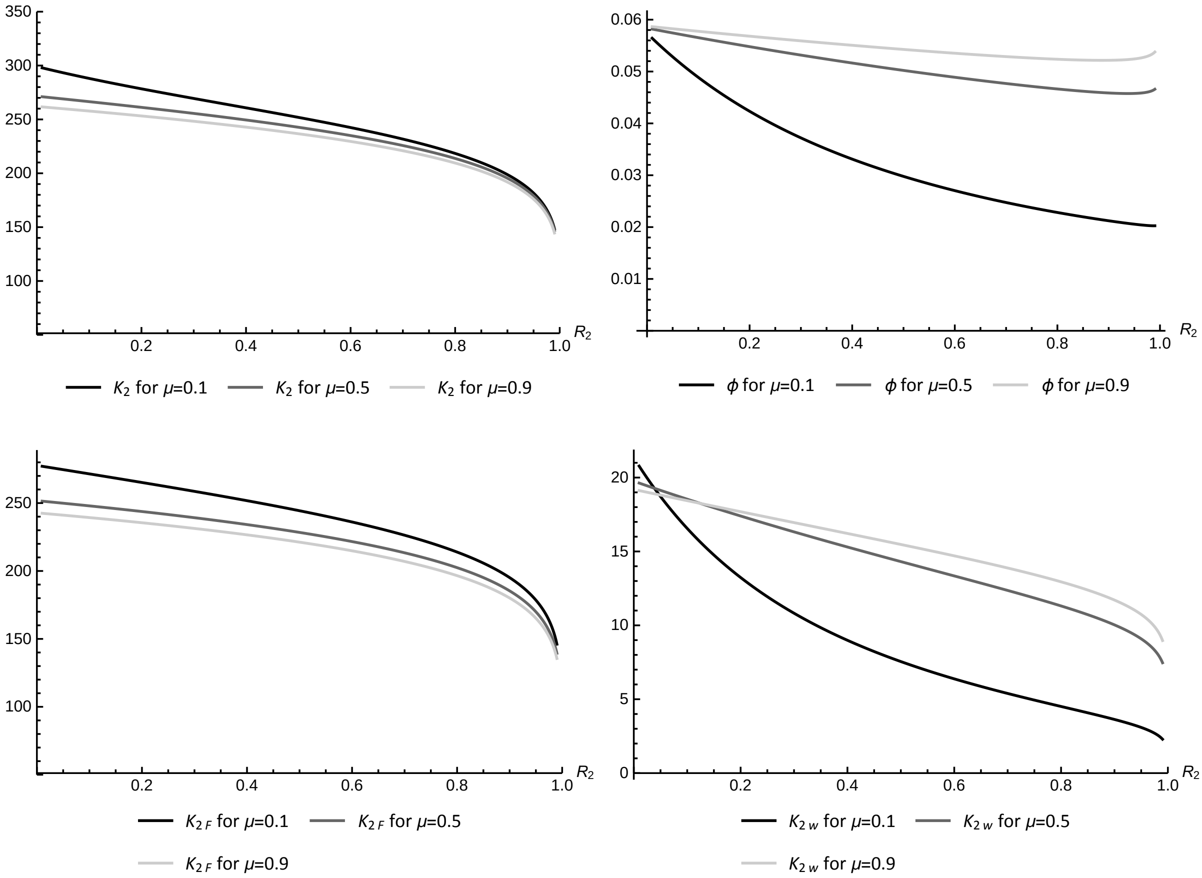

Figure 9.8: The influence of the state of the renewable energy technology on the capital stock invested in final goods production and in energy generation for $\bar{R} = 1$;
assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\omega = 0$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

As for the energy market price, we can rewrite the comparative statics effect in (7.53) by use of the definitions in (7.47), (7.26), and (7.46) to get

$$\frac{di_2}{d\mu} = \frac{F_{2Q}\mu W_{2KK}W_2\left(F_{2KQ} + F_{2KK}\frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}F_{2Q}\right)}{\Xi\left(1 - \frac{di_2}{dK_2}\Big|_{K_2} SE\right)} + \frac{F_{2Q}W_{2K}\left(F_{2KK} - F_{2KQ}\mu W_{2K}\right)}{\Xi\left(1 - \frac{di_2}{dK_2}\Big|_{K_2} SE\right)} + \frac{\Gamma_W \mu W_{2K} W_2\left(1 + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}F_{2Q}\mu W_{2K}\right)}{\Xi\left(1 - \frac{di_2}{dK_2}\Big|_{K_2} SE\right)} \gtrless 0$$

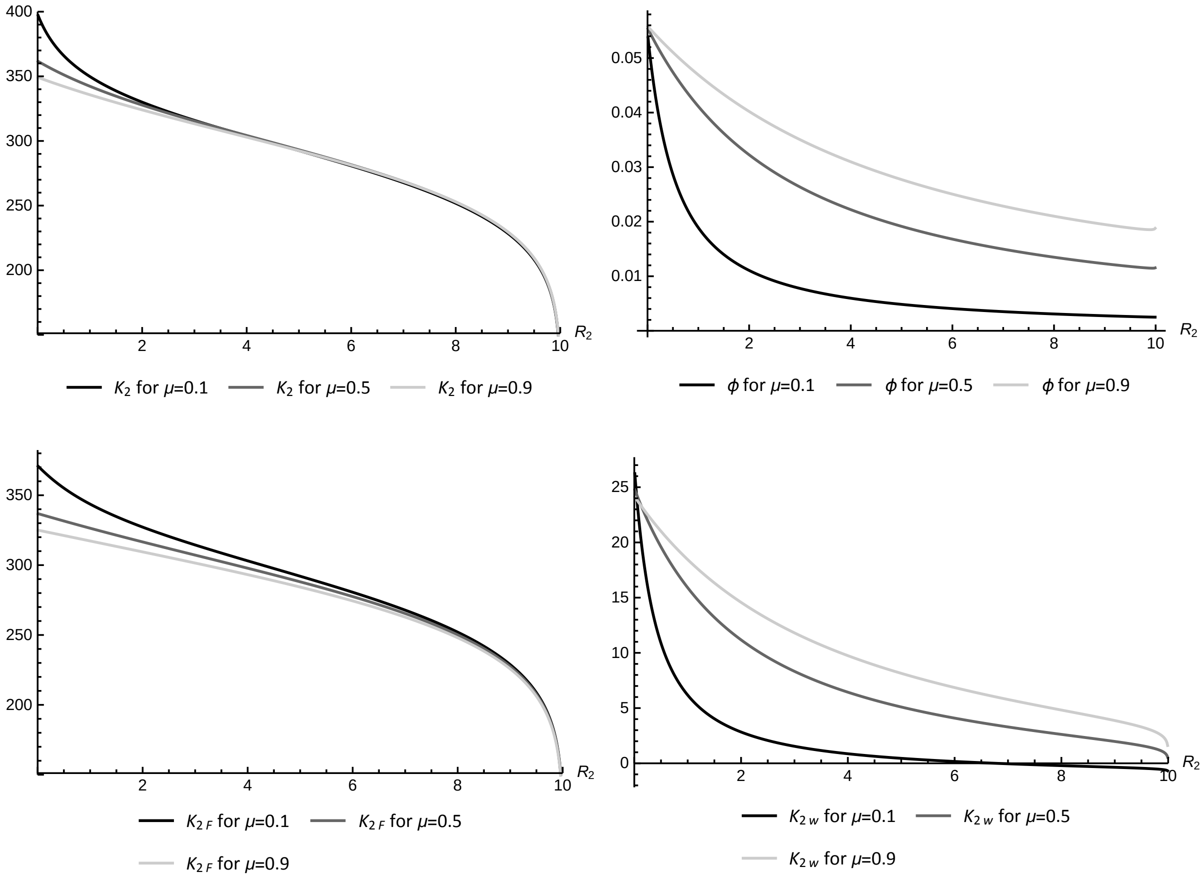

Figure 9.9: The influence of the state of the renewable energy technology on the capital stock invested in final goods production and in energy generation $\bar{R} = 10$;
assumptions: $K_1 = 200$, $s_{0E} = 10$, $L = 1$, $\beta_E = \beta_I = 0.3$, $\eta = 2$, $\tau = 0$, $\omega = 0$, $\lambda = 0.1$, $\gamma = 0.4$, $\sigma = 1$, $A = 300$, $W_2 = \ln(1 + K_{2W})$

The ambiguity is due to the fact that the first fraction is negative whereas the second is positive because we have by (7.18) and (4.13) $1 + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2Q}\mu W_{2K} = 1 - \frac{(1-\omega)i_2}{1+i_2+[\beta_I(1+i_2)]^{\frac{1}{\eta}}} > 0$.

Figures 9.8 and 9.9 provide an overview over the influence of technical change on the equilibrium relationship between the capital stocks K_{2F} and K_{2W} and future resource use for our exemplary numerical simulations.

9.2.3.2 Resource Supply Response to Technical Change: Competitive Market

To show that the green paradox can never be reversed under competitive resource supply even if technical change induces a fall in the interest rate, we manipulate the numerator of the comparative statics (7.54) by use of (7.52) and (7.53) as follows

$$
\begin{aligned}
&p_1 \frac{di_2}{d\mu} - (1-\tau)\frac{dp_2}{d\mu} = \\
&\frac{F_{2Q}\mu W_{2KK}W_2}{\Xi\left(1 - \frac{di_2}{dK_2}\Big|_{K_2} SE\right)}\left\{p_1 F_{2KQ} + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2Q}\left[p_1 F_{2KK} - (1-\tau)F_{2KQ}\right]\right. \\
&\qquad \left. -(1-\tau)\left(F_{2QQ} - \Gamma_W SE\right)\right\} \\
&+ \frac{\Gamma_W W_2 \left(1 + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2Q}\mu W_{2K}\right)}{\Xi\left(1 - \frac{di_2}{dK_2}\Big|_{K_2} SE\right)}\left[p_1 \mu W_{2K} - (1-\tau)(1-\omega)\right] \\
&+ \frac{F_{2Q}W_{2K}}{\Xi\left(1 - \frac{di_2}{dK_2}\Big|_{K_2} SE\right)}\left[p_1\left(F_{2KK} - F_{2KQ}\mu W_{2K}\right)\right. \\
&\qquad \left. -(1-\tau)\left(\Gamma_W \mu W_{2K} SE + F_{2KQ} - F_{2QQ}\mu W_{2K}\right)\right]
\end{aligned}
$$

On the right hand side, all the elements but the second are unambiguously positive due to (4.13), (7.10), (7.20), (7.26), and due to the concavity of the renewable energy generation technology and the final goods production technology. Since we evaluate the comparative statics (7.54) for the competitive market equilibrium, we know that the first-order conditions (7.5), (7.7), and (7.6) as well as the Hotelling condition (2.3) characterizing the optimal extraction path have to hold. This implies on the one hand that

$$
\begin{aligned}
1 + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}} F_{2Q}\mu W_{2K} &= 1 + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau,\omega}}(1-\omega)F_{2K} \\
&= 1 - \frac{(1-\omega)F_{2K}}{1 + i_2 + \left[\beta_I(1+i_2)\right]^{\frac{1}{\eta}}} > 0
\end{aligned}
$$

by (4.13) and $i_2 = F_{2K}$ in the conditional market equilibrium, and on the other hand that

$$
\begin{aligned}
p_1\mu W_{2K} - (1-\tau)(1-\omega) &= p_1\mu W_{2K} - (1-\tau)\frac{F_{2Q}\mu W_{2K}}{F_{2K}} \\
&= \mu W_{2K}\left(p_1 - \frac{1+i_2}{i_2}p_1\right) < 0
\end{aligned}
$$

Thus, we can conclude that the second element must be of positive sign, too. Overall, this implies that the numerator in the comparative statics (7.54) must be of negative sign along the competitive resource extraction path so that a green paradox necessarily arises from an increase in μ.

9.2.3.3 Resource Supply Response to Technical Change: Naive Sheikh

The decomposition of the influence of technical change on the price elasticity of residual resource demand is analogue to (7.45) given by

$$
\begin{aligned}
\frac{d\epsilon^W_{R_2,p_2}}{d\mu} = & \frac{\epsilon^W_{R_2,p_2}}{1+\left(\mu W_{2K} - \frac{F_{2KQ}}{F_{2QQ}}\right)\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}} \left\{ \frac{\epsilon_{Q_2,p_2}}{R_2}\left(W_2 + \mu W_{2K}\frac{dK_{2W}}{d\mu}\right) \right. \\
& + \frac{\frac{Q_2}{R_2}}{\epsilon^W_{R_2,p_2}}\left[\frac{\partial \epsilon_{Q_2,p_2}}{\partial Q_2}\left(W_2 + \mu W_{2K}\frac{dK_{2W}}{d\mu}\right) + \frac{\partial \epsilon_{Q_2,p_2}}{\partial K_{2F}}\frac{dK_{2F}}{d\mu}\right] \\
& - \frac{\partial\left[\left(\mu W_{2K} - \frac{F_{2KQ}}{F_{2QQ}}\right)\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}\right]}{\partial K_{2W}}\frac{dK_{2W}}{d\mu} \\
& - \frac{\partial\left[\left(\mu W_{2K} - \frac{F_{2KQ}}{F_{2QQ}}\right)\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}\right]}{\partial K_{2F}}\frac{dK_{2F}}{d\mu} \\
& \left. - \frac{\partial\left[\left(\mu W_{2K} - \frac{F_{2KQ}}{F_{2QQ}}\right)\left.\frac{dK_{2W}}{dR_2}\right|_{K_2}\right]}{\partial \mu} \right\}
\end{aligned}
$$

where again $\frac{\partial \epsilon_{Q_2,p_2}}{\partial Q_2}$ and $\frac{\partial \epsilon_{Q_2,p_2}}{\partial K_{2F}}$ depend on the elasticity of substitution according to (5.6) and (5.8).

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