ifo
BEITRÄGE
zur Wirtschaftsforschung

85
2019

Complex dimensions of climate policy: the role of political economy, capital markets, and urban form

Waldemar Marz

ifo INSTITUTE
Leibniz Institute for Economic Research
at the University of Munich

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation
in der Deutschen Nationalbibliografie; detaillierte bibliografische
Daten sind im Internet über
http://dnb.d-nb.de
abrufbar.

ISBN: 978-3-95942-062-4

Druck: ifo Institut, München

ifo Institut im Internet:
http://www.cesifo-group.de

ifo
BEITRÄGE
zur Wirtschaftsforschung

85
2019

Complex dimensions of climate policy: the role of political economy, capital markets, and urban form

Waldemar Marz

Herausgeber der Reihe: Clemens Fuest
Schriftleitung: Chang Woon Nam

ifo INSTITUTE
Leibniz Institute for Economic Research
at the University of Munich

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation
in der Deutschen Nationalbibliografie; detaillierte bibliografische
Daten sind im Internet über
http://dnb.d-nb.de
abrufbar.

ISBN: 978-3-95942-062-4

Druck: ifo Institut, München

ifo Institut im Internet:
http://www.cesifo-group.de

Preface

The most striking and challenging features of the problem of anthropogenic climate change are its complexity and multifaceted nature. It affects a great number of dimensions of (not only) human life and spreads across temporal, spatial, and disciplinary boundaries in complex ways. The potentially long period between cause (emissions) and effect (damages) makes it an intergenerational problem. The long time scale of the problem is caused, on the one hand, by many involved physical processes like the slow warming of the oceans, long-term changes in sea currents, and the persistence of accumulated carbon dioxide in the atmosphere. On the other hand, in the coming decades societies and economies are facing climate change related transformation processes in areas like agricultural production, economic growth, migration and fertility patterns. However, the time horizon of the political discourse and the length of politician's terms in office is much shorter – a few years or at most a few decades. The effects of political decisions can materialize up to an intermediate time scale of several decades, e.g. in the case of infrastructure decisions.

From the spatial perspective, the problem of climate change is global, but the actual consequences like flood damages must often be dealt with on a local or regional level. Also, the effects can be very heterogeneous among different regions. As a result the willingness to engage in climate policy varies largely across countries. The spatial complexity is also reflected in the different levels of climate governance, from international climate negotiations, over supranational (e.g., European Union) and national climate policy measures to regional and local initiatives.

A major challenge for research and policy making stems from the highly interdisciplinary nature of climate change related issues. A wide range of academic disciplines is involved: earth science, biology, physics and engineering, political science, economics, law, sociology, and philosophy are examples. Moreover, within the economic discipline, many subdisciplines are concerned like public finance, resource economics, economics of trade, political economics, urban economics, industrial organization, or growth economics. Disciplinary analyses in all these fields are without any doubt valuable and indispensable. But at the same time approaches which, at least partly, manage to bridge the gaps between the disciplines and subdisciplines and to integrate different dimensions of the analyzed phenomena can raise hopes of capturing additional aspects of the complex nature of the climate change problem.

This study, which has been submitted as a dissertation in economics (Dr. oec. publ.) at the Ludwig Maximilians University, Munich, in September 2018, follows the idea of bridging gaps between subfields within the economic discipline. It aims to better understand the complex effects of climate policy on different levels and to improve the basis for the development of effective climate policy instruments. Additional dimensions of complexity arise at every point of action which climate policy measures aim at. And such points and complexity dimensions are reflected in the different chapters.

Chapter 1 provides the basis for the analysis of Chapter 2. In Chapter 2 a carbon tax targets the supply side of a monopolistic market for fossil energy resources. An additional complexity dimension is considered there by taking into account the multiple interactions of the capital market and the resource market in the resulting general-equilibrium setup. Accounting for these interactions gives rise to a new view of a double role of exporters of non-renewable resources with market power as investors on the capital market and changes the supply behavior and the reaction to climate policy of the fossil resource exporter.

The climate policy measure in Chapter 3 aims at the demand side of the fossil energy market: fuel economy standards and fuel taxes are employed to reduce carbon emissions in the transportation sector. But the environmental policy measure over time also affects mobility patterns, location choice of households, and the real estate market on an urban economic dimension, which feeds back into driving and vehicle choice decisions. This complexity dimension is captured by connecting the transportation and environmental economic analysis with a spatial urban economic setting. This brings new channels of fuel economy standards and fuel taxes on welfare into the picture, together with a new potentially welfare-enhancing role of spatial urban constraints.

In Chapter 4 a national climate policy, apart from reducing carbon emissions, has distributional effects on households which are heterogeneous in income and in their degree of environmentalism and inequality aversion. The key element of the analysis in this chapter is that the distributional effects and the heterogeneity of households have a great influence on the evaluation of the policy platforms of political parties by the households and, thereby, on the very political process which determines the degree of climate policy. The integration of the environmental economic and the political economic perspective in a two-dimensional model of political competition opens up an own field of questions about how environmental policy interacts with redistributional policy in the political dynamics, how income inequality affects the degree of the resulting climate policy, and how climate policy measures like carbon taxation can be designed (for instance, with regard to their tax revenue recycling mechanism) to increase public support. Without accounting for this political-economic complexity dimension climate policy concepts which are otherwise well-designed might remain without effect.

In addition to a common theme of bridging subfields of economic analysis to account for relevant complex interactions, all four chapters share a common methodology. All chapters are theoretical studies with numerical simulations. The theoretical methodological perspective emphasizes the mechanisms behind the analyzed phenomena and is well suited to capture the connections between the different subdisciplinary dimensions of the problems which the described integrated approach addresses.

To obtain a better understanding of the mechanisms involved and of the role of model variables and parameters the analytical analyses have been combined with numerical simulations, graphical representations of the effects, and/or sensitivity analyses in all chapters. On the one hand, applying numerical methods allowed to surpass limits of analytic tractability: in all four chapters the complexity of the problems does not allow for closed-form solutions. On the other hand, the numerical simulation of the models with a basic calibration of the parameters facilitates a narrowing down of the magnitudes and the empirical and, finally, political relevance of the effects involved. This is more the case for chapters 2 and 3. For Chapter 4, which is the the most recent part of the dissertation, the calibration and getting closer to an empirical validation will be an important part of the preparation of the chapter for a journal publication.

Chapters 1 and 2 developed in close collaboration with Johannes Pfeiffer from the Ifo Institute. There are online working paper versions of both chapters available in the Ifo Working Paper Series (cf. Marz and Pfeiffer (2015b) and Marz and Pfeiffer (2015a)). Chapter 2 was submitted to the Journal of Environmental Economics and Management and received a "Revise & Resubmit" before submission of the dissertation. Chapters 3 and 4 are single-authored. In the following, a short overview over all chapters is given.

Chapter 1: Fossil Resource Market Power in General Equilibrium

In the first chapter we analyze monopoly power in a market for a scarce fossil resource like oil or rare earths which is complementary to the other factors of production (physical capital and labor) in a two country/two period model in general equilibrium with endogenous capital accumulation. The resource-rich country extracts and exports the resource in exchange for consumption goods, which are solely produced in the resource importing country. The analysis focuses on the complex interplay of the capital market and the resource market, and on the feedbacks of these effects into the resource monopolist's extraction decision. The general equilibrium feedback effects are the basis for additional supply motives of the resource monopolist which are not part of a conventional partial-equilibrium setting.

We find that, on the one hand, the monopolist not only considers the own-price effect of resource supply on the resource price, but also the influence of her resource supply on savings, capital accumulation, and the feedback effect on resource demand. The resulting "addiction motive" contributes to an acceleration of extraction as long as acceleration fuels capital accumulation. In a second supply motive, the "capital asset motive", the monopolist takes the influence of her resource supply on the returns on her own country's capital assets via factor complementarity into account. Considering this second income source in her dynamic optimization decision can lead to an acceleration, as well as a postponement of extraction. The net effect of the additional supply motives, which arise in the integrated analysis of resource market and capital market, on the resource extraction path can be postponement or acceleration relative to a conventional monopolist with a partial-equilibrium reasoning (cf. Stiglitz (1976) and Dasgupta and Heal (1979)). The conservationist bias, which has inspired the phrase of the monopolist being "the conservationist's friend" (Solow, 1974) can be reinforced, dampened or reversed by the additional supply motives.

Chapter 2: Petrodollar Recycling, Oil Monopoly, and Carbon Taxes

Chapter 2 is based on the same framework as Chapter 1 and is devoted to the analysis of climate policy in this setting, while the scarce fossil resource is considered to be oil. The complex interaction of capital market and oil market and the internalized influence of the oil monopolist on her country's capital assets ("capital asset motive") lead to a new general equilibrium transmission channel of climate policy on oil extraction. The capturing of oil rents via a carbon tax on oil imports and their redistribution to the importing country leads to an increase in savings and future capital assets by the households of the exporting country. This creates an additional incentive for the monopolist to postpone extraction in order to boost the returns on the increased future capital asset stock of her country. In the numerical simulation postponement of extraction occurs under a wide range of reasonable parameter settings: present extraction can drop considerably for a moderately high carbon tax. We also show that (even) an over time increasing carbon tax can be a viable policy option in contrast to conventional partial equilibrium analyses of climate policy instruments.

One recommendation in the literature on undesired effects of climate policy like an acceleration of extraction is a capital income tax (cf. Sinn (2008)). However, our analysis shows that, due to the crucial role of capital assets of the oil exporting country, a capital income tax is no longer immune against an undesired acceleration of extraction. In an extension we endogenize cumulative extraction by introducing investments into exploration. In this case it appears that capital accumulation depends on the exploration investment decision due to the interaction of the capital market and the resource market in general equilibrium. As a result, the monopolist, who internalizes this relationship, can choose to reduce cumulative extraction and still reduce first-period extraction at the same time. This contrasts with the literature on supply-side effects of climate policy which neglects these capital market implications. Overall, concerns about carbon taxes arising from impeding climate-damaging supply reactions are alleviated, while taxing asset returns may induce acceleration of extraction.

Chapter 3: CAFE in the City - A Spatial Analysis of Fuel Economy Standards

The goal of Chapter 3 is to investigate fuel economy standards for passenger cars and carbon taxes on gasoline as climate policy instruments in the transportation sector. This approach integrates the environmental and transportation economic analysis with a spatial urban model to incorporate the complex long-term interaction between the climate policy measures, mobility patterns, household vehicle and location choice, and the real estate market. The policies lead not only the choice of more fuel efficient vehicles, but also to a long-term adjustment of the urban form: an expansion of the city for fuel economy standards, which implies a commute-related rebound effect, and a contraction for fuel taxes. Long-term decarbonization scenarios are run to analyze the accruing welfare effects in two steps: first, in a partial-equilibrium reaction of the vehicle market to the policy shock while housing prices are kept constant and, second, in a general-equilibrium adjustment of the housing market, the urban form, and, again, vehicle choice at the new locations. This goes beyond more short-term empirical analyses of the rebound effect in driving.

The increase in fuel efficiency causes additional costs and decreases welfare, but additional housing due to the expansion increases welfare. Nevertheless, the net effect of urban adjustment on welfare is negative. The reason is the distortion in the vehicle market which is caused by the fuel economy standard and the resulting cross-subsidy from dirty to clean cars. The additional welfare costs of urban adjustment have a significant magnitude and have not been accounted for in the previous literature on welfare costs of fuel economy standards. These expansion-related welfare costs can be reduced roughly by one half through the combination of fuel economy standards with an urban growth boundary. Fuel taxes, in turn, lead to an urban contraction and additional welfare gains from a reduction of the vehicle market distortion. A sensitivity analysis sheds light on the role of the different model parameters.

Chapter 4: Climate Policy and Inequality in Two-Dimensional Political Competition

Chapter 4 combines an interdisciplinary model of two-dimensional political competition with a model of economic and distributional effects of climate policy and a key role for income inequality and redistribution in order to investigate the conditions for the formation of climate policy in a national political arena. This approach allows to shed light on the important political, social, and economic preconditions for the realization of environmental policy measures. Voters in the model are heterogeneous in their skill level, which determines income (log-normally distributed between zero and infinity) and in their level of "collective orientation" (uniformly distributed between zero and one). The latter indicates voters’ environmentalism and desired degree of redistribution, which accounts not only for the income tax rate, but also for the redistributional implication of the carbon tax. Political competition between two parties is two-dimensional over the carbon tax and a proportional income tax with lump-sum revenue recycling. The model of two-dimensional political competition is built on the concept of *party-unanimity Nash equilibrium* (PUNE) as described in Roemer (2006) and adapted to environmental policy and redistribution for the first time.

When political competition is one-dimensional over the carbon tax only, then a higher degree of pre-tax inequality in this setting leads to higher (lower) equilibrium carbon tax proposals when the carbon tax recycling mechanism is progressive (regressive) by assumption. When political competition turns two-dimensional over the carbon tax and the income tax, then an increase in inequality of pre-tax income is compensated by a higher redistribution via the income tax. But the average carbon tax proposal remains largely unaffected, independently of the progressivity of carbon tax recycling. However, changes in pre-income-tax inequality and in the salience of the political discourse on redistribution affect the polarization of the parties' carbon tax proposals. The implied change in policy uncertainty can play an important role for investments in green technologies. If voters are, in contrast, myopic with respect to the implications of the carbon tax proposals for the overall distribution of income, then changes in pre-exiting income inequality and in the progressivity of carbon tax recycling do significantly affect the carbon tax proposals. This shows how important communication of the involved effects in the political debate is.

Keywords: Hotelling rule, sovereign wealth funds, monopoly, fossil energy resources, general equilibrium, capital market, climate policy, fuel economy standards, fuel tax, monocentric city, rebound effect, inequality, political economy, multidimensional political competition

JEL-No: D42, D58, D90, H20, H23, L90, P16, Q30, Q31, Q38, Q48, Q52, Q54, R40

Acknowledgement

Research is a collective effort and I am very grateful to all the great people who supported me in many ways over the last five years as a PhD student. First of all, of course, I would like to thank my supervisor Karen Pittel for her invaluable support and advice on research issues, but also on the academic world in general. I learned a great deal from her over the course of these five years in spontaneous chats or discussions lasting for hours (or the former turning into the latter). Also, I always felt a great degree of confidence and encouragement from her side from the early stages of my research ideas until the submission of finished work.

I would also like to thank my fantastic co-author, colleague, and office mate at the Ifo Institute Johannes Pfeiffer for his company, eye for detail, commitment, and all those years of extensive discussions on research, the world, and everything else. My particular thanks go to Frank Götzke for introducing me into the world of urban and spatial economics and for many hours of econ and academia-related discussions and great conversation about the rest. Especially the urban economic chapter benefited a lot from the chats with Frank.

I sincerely thank our Ifo department's research director and frequent guest at Ifo Christian Traeger for his interest in my work, research advice, enthusiasm, encouragement, and support in the recent years. I am also highly indebted to all my colleagues at the Ifo Center for Energy, Climate, and Resources for their companionship, advice on research and academia, lunch breaks, proof-reading, support and humor: Suphi Sen, Niko Jaakkola, Marie von Schickfus, Markus Zimmer, Anna Ciesielski, Ana Montoya, Jana Lippelt, Christoph Weissbart, Christina Littlejohn, Mathias Mier, and Hans Wackerbauer. And I also thank the frequent visitors at Ifo who contribute a great deal to the vibrant academic atmosphere and who I have the pleasure to meet quite regularly, for their openness to discussions and exchanging ideas: Ngo Van Long, Ralph Winkler, Cees Withagen, Rick van der Ploeg, Michael Rauscher, and many others.

My special thanks go to Ken Gillingham for his openness and interest in my work and for the invitation to my research visit during the fall semester in 2017 at the Yale School of Forestry & Environmental Studies. I really appreciate his advice, comments, and encouragement. I am also very grateful to all the great people I met at the environmental economics seminar at Yale and beyond for their comments and ideas: Matt Kotchen, Eli Fenichel, Stefano Carattini, Paige

Weber, Mani Rouhi Rad, John E. Roemer, Jan K. Brueckner who was a visiting researcher at Yale at the same time, and everybody else. It was a great time.

I am very grateful to the Friedrich Ebert Foundation for the doctoral scholarship over the course of four years and the program for doctoral students. It helped a lot to be able to focus on my research and reconcile quick progress with having a family at the same time. I also thank the German Federal Ministry of Education and Research for funding the research project "Assessing the Green Paradox" (project no. 01LA1120A). Chapters 1 and 2 of this thesis developed as a part of this project.

But most of all I would like to thank my family for their constant support, encouragement, and understanding. I thank my dear wife Annika for her love and patience during all these years and for her great share in the whole PhD project. I thank our beautiful children Elias, Jan, and Mathilda for their endurance and inspiring curiosity. I thank my parents and my brother Alex for their steadfast confidence and encouragement. And I thank both my parents and my parents-in-law Robert and Petra for their providing the indispensable infrastructure for academic advance: child care, food, and sleep. As I said, it is a collective effort.

Complex Dimensions of Climate Policy: The Role of Political Economy, Capital Markets, and Urban Form

1. Inaugural-Dissertation

Zur Erlangung des Grades
Doctor oeconomicae publicae (Dr. oec. publ.)

eingereicht an der
Ludwig-Maximilians-Universität München
2019

vorgelegt von

Waldemar Marz

Referent: Prof. Dr. Karen Pittel
Korreferent: Prof. Kenneth Gillingham, PhD
Promotionsabschlussberatung: 30.01.2019

Contents

List of Figures

List of Tables

1 Fossil Resource Market Power in General Equilibrium

1.1 Introduction

Since the industrial revolution and up until today the use of crucial fossil resources like oil is playing a key role in the production of goods and driving economic growth in industrialized countries, as well as in emerging economies. From an economic perspective, the degree of complementarity between fossil resources and other production factors, in particular capital and labor, at the macro level, is still enormous. This is especially true for oil. But also other non-renewable resources like rare earths are rising in importance for the global economy with their increasing role in energy storage or electronic devices. The use of these important resources increases the productivity of the other production factors and, thus, e.g. the returns on capital.[1] Also, fossil resources play an important role for capital accumulation and the long-term growth path.[2] In turn, a steep growth path, e.g. recently by emerging economies, fuels additional demand for scarce fossil resources and resulting price increases.[3] Even today, the substitutability of oil in the transportation sector, especially with regard to freight and air transport, or of rare earth metals in the production of many goods like permanent magnets for generators and electric motors remains limited, in spite of technological advancements. Overall, these particular key fossil resources have widespread effects on incomes, prices and expected returns in the world economy.

At the same time, deposits of these non-renewable resources are geographically quite concentrated and their markets exhibit a great degree of supply-side market power.[4] In the present study we combine both aspects to investigate what the special role of these resources means for the market power of the exporting countries and for the economies involved: the widespread economic effects of the fossil resource are captured and endogenized in a two-period

---

[1] Cf. Hamilton (1983, 2013), Kang et al. (2014), Cunado and Perez de Gracia (2014), Kilian (2009).

[2] Cf. Berk and Yetkiner (2014) and Stern and Kander (2012) (empirical) and Stiglitz (1974) (theoretical).

[3] Cf. Kilian and Hicks (2013) and Fouquet (2014).

[4] The market share of OPEC was 43.5% in 2017 (Statista, 2018) and 48% in 2040 under the 450ppm carbon scenario (OECD 2014, p. 115, table 3.5). China's market share in rare earth metals was around 85% in 2016 (cf. Zhou et al. (2017)). But the long-term development of Chinese market power seems less clear because of possible alternative sources (cf. Massari and Ruberti (2013), Packey and Kingsnorth (2016), Pothen (2018)).

general equilibrium framework with a single resource-exporting country E with market power and a resource importing country I, where final good production is taking place, and endogenous accumulation of physical capital. In addition, we examine the implications of the fossil resource monopolist's[5] being aware of the complementarity-driven feedback effects between the resource market and the capital market and accounting for them in her intertemporal extraction decision in our model. This gives rise to additional supply motives which go beyond a conventional partial-equilibrium reasoning. We identify these motives and analyze their mechanisms and their role for the extraction behavior of a resource monopolist in general equilibrium.

Apart from considering the conventional own-price effect of resource supply on the resource price, one additional motive that our monopolist takes into account is how her resource supply affects income streams, savings behavior with resulting capital accumulation, and the feedback effect on resource demand. By fostering capital accumulation via resource supply the monopolist can raise the importing country's resource "addiction" in the future. This "addiction motive" contributes to an acceleration of extraction as long as it fosters capital accumulation.

As a second additional supply motive, the monopolist considers the influence of her resource supply on the return on capital assets via the complementarity of the two factors in production. In contrast to Hillman and Long (1985), this influence runs only via resource market power and explicitly not by assuming that the resource monopolist has additionally capital market power. This "capital asset motive", as we call it, is especially important because the monopolist considers not only resource revenues when maximizing country E's utility, but also capital asset holdings of her country, which provide a second simultaneous income source. These capital holdings can represent sovereign wealth funds, as well as privately held assets.[6] Depending on the development of the resource exporting country's capital holdings over time, accounting for this effect on country E's capital asset returns can provide an incentive to accelerate or postpone extraction. On top of that, accounting for how resource-driven capital

---

[5] For simplification – but of course in contrast to the real world oil market – we consider a resource monopolist instead of an oligopolistic (or competitive fringe) market structure.

[6] Real exporting countries of fossil energy resources often dispose of considerable sovereign wealth funds. The funds of the United Arab Emirates ($ 1,078.5 billion) and Saudi Arabia ($ 757 billion) are the two biggest such sovereign asset stocks among OPEC countries (SWFI 2016). Beyond official sovereign wealth funds, all other kinds of petrodollar bank deposits are invested in some manner in the capital market, very often in the industrialized countries.

stock dynamics also affect the interest rate strengthens the second period's asset motive and contributes to postponement of extraction as long as this postponement decreases capital accumulation.

The net effect of all the additional supply motives which arise in general equilibrium on the resource extraction path can be postponement or acceleration relative to a conventional monopolist with a partial-equilibrium reasoning (cf. Stiglitz (1976) and Dasgupta and Heal (1979)). The conservationist bias, which has inspired the phrase of the monopolist being "the conservationist's friend" (Solow, 1974) can be reinforced, dampened or reversed by the additional supply motives. Moreover, even for an iso-elastic resource demand (i.e. elasticity of substitution between capital and resource $\sigma = 1$) the extraction shift to the present may persist and the resulting extraction paths of monopoly and competitive case cease to be identical, in contrast to the usual partial equilibrium setup.

On the one hand, the asset motive and the addiction motive can be interpreted as extensions of conventional resource market power, because the monopolist has an influence on additional aspects. On the other hand, the dependency of capital returns and long-term capital accumulation and resulting resource demand on the availability of resources constrains the resource exporter when she tries to exert market power in the resource market. The often discussed dependency of the oil importers on the "good-will" of key resource exporting countries therefore may not be as unilateral as often perceived, but in fact mutual once the cross-market effects between the capital and the resource market are considered.

For our analysis we build upon previous steps in the literature from partial equilibrium to general equilibrium analysis of exhaustible resource extraction under market power. While Hoel (1981) introduced an influence of a resource monopolist's decision on the interest rate, this influence was still postulated in an otherwise partial equilibrium model and unspecified, disregarding the associated capital stock dynamics. Hassler et al. (2010) also incorporate an influence of the resource supplier on the capital returns, but lack the intertemporal optimization of supply. Hillman and Long (1985) bring forward a general equilibrium model, where the interest rate is chosen by a resource exporter with market power on both, the resource and the capital market. However, given the size of the capital market, the assumption of capital market power seems rather strong. Also, their model lacks the impact channel from resource extraction on the interest rate directly over the physical production function, as well as the corresponding effect of the capital stock dynamics on the interest rate over the production function and all resulting repercussions. Thus, they leave this aspect of complementarity between oil and physical capital in production out of the picture. Moreover, it's exactly their exporter's choice of the interest rate as an additional independent variable that excludes the effects of resource supply behavior on the capital market (and the corresponding consequences), that naturally arise in our general equilibrium framework and that we are interested in, from their model. Moussavian and Samuelson (1984) incorporate an exhaustible resource monopolist's influence on the capital accumulation in their model. Our analysis of the "addiction motive" is consistent with this study and yields, in contrast to Moussavian and Samuelson (1984), unambiguous effects on extraction due to our finite time horizon. Besides the studies mentioned above, however, a resource monopoly is usually, from Stiglitz (1976) to Fischer and Laxminarayan (2005), analyzed with an exogenous and constant interest rate and capital stock. We, therefore, provide a comprehensive account of a resource monopolist's reasoning and extraction behavior in general equilibrium by connecting separate aspects from the previous literature over the special complementarity-driven role of the resource.

Gaitan et al. (2006) also see the necessity for dynamic general equilibrium models and propose an own such contribution. But they focus on the case of iso-elastic resource demand in a competitive resource market instead of, more generally, resource demand and monopoly power. With Long and Stähler (2014) and van der Meijden et al. (2015) there are recent papers with a focus on unintended consequences of climate policy which also address general equilibrium aspects. But they feature perfectly competitive resource markets and, therefore, do not concentrate on implications for the supply behavior. Building on the framework and the analysis in the present chapter, we analyze the effects of climate policy by the industrialized countries on the extraction behavior of an oil supplier with market power in Chapter 2.

We start by introducing the model and by deriving equilibrium relationships conditional on the chosen resource supply path in section 1.2. In section 1.3, we analyze the optimal supply decision of the resource monopolist and the contained general-equilibrium supply motives. We do this by first establishing as a benchmark a "naive" monopolist who neglects the general-equilibrium feedbacks. Then we gradually add different supply motives to the monopolist's reasoning and compare them to the benchmark to carve out their effects on extraction. We present a numerical illustrative example a briefly discuss the limits of our line of argument in Section 1.4. Section 1.5 concludes.

1.2 Model

The model derived and described in this Section is the basis for the analysis of a fossil resource monopoly in general equilibrium in this Chapter and also for its application to the global oil market and climate policy in Chapter 2. For the analysis of monopolistic supply motives in the present Chapter 1 the resource import tax is not of any interest and is, therefore, set to zero. In Chapter 2, in contrast, the resource import tax plays a crucial role as the tool to implement climate policy. The only model related difference in Chapter 2 compared to Chapter 1, thus, is that the resource import tax is non-zero.

We consider a general equilibrium model with two countries (indexed by $m \in \{E, I\}$) and a finite time horizon of two periods: $t \in 1, 2$. The entire global resource stock $\bar{S}$ is located in the resource exporting country E. Consumption goods are produced competitively with the factors resource, physical capital, and labor in the resource importing country I only. Country E exports the resource as a monopolist to country I in exchange for consumption goods. In each country, households derive utility from consuming the numeraire final good.

1.2.1 Firms

1.2.1.1 Resource Extraction

Extraction costs are zero.[7] In country E, a government or state-owned company extracts the resource and benevolently distributes the resource revenues

$$\pi_{tE}^{\tau} = \tilde{p}_t R_t \tag{1.1}$$

to the households of country E, where R_t denotes resource supply and $\tilde{p}_t$ the producer price for the resource net of the resource import tax τ_t levied by country I. For simplicity, we assume throughout Chapters 1 and 2 $\tau_1 = 0$. We also assume the resource to be scarce such that the intertemporal resource constraint with the initial resource stock $\bar{S}$ is binding

$$R_1 + R_2 = \bar{S} \tag{1.2}$$

---

[7] Later on, in Section 2.6 of Chapter 2 we introduce exploration costs.

The resource is extracted in both periods ($R_1, R_2 > 0$). The monopolist's optimal extraction path is determined in an intertemporal arbitrage consideration according to the Hotelling rule and will be described and discussed in detail in Section 1.3.

1.2.1.2 Final Goods Production

In country I final goods are produced competitively using physical capital K_t, resource R_t, and labor L_t as input factors and CES technology

$$F_t = F(K_t, R_t) = A\left[\gamma K_t^{\frac{\sigma-1}{\sigma}} + \lambda R_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma-\lambda)L^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{1.3}$$

with total factor productivity $A > 0$ and constant elasticity of substitution σ. Labor is supplied inelastically and constant over time ($L_t = L$).[8] The CES technology has overall constant returns to scale but decreasing returns to scale with respect to capital and the resource. With profit-maximizing competitive final goods producers, the first-order conditions for optimal factor use (implicitly) define resource demand R_t^d[9]

$$\frac{\partial F_t}{\partial R_t} = F_{tR}(K_t, R_t^d) = p_t \tag{1.4}$$

with the consumer resource price p_t and capital demand K_t^d

$$\frac{\partial F_t}{\partial K_t} = F_{tK}(K_t^d, R_t) = i_t \tag{1.5}$$

with the capital rent i_t. The representative household in country I receives the residual profits π_{tI} after remuneration of capital and the resource as labor income: $\pi_{tI} = F_t - p_t R_t - i_t K_t$.

---

[8] We assume flexible wages under full employment here.

[9] The superscript "s" indicates *supply*, while superscript "d" means *demand*.

1.2.2 Households

1.2.2.1 Preferences

Households in countries I and E have symmetric homothetic preferences represented by the life-time utility function

$$U(c_{1m}, c_{2m}) = u(c_{1m}) + \beta u(c_{2m}) = \begin{cases} \dfrac{c_{1m}^{1-\eta} - 1}{1-\eta} + \beta \dfrac{c_{2m}^{1-\eta} - 1}{1-\eta} & \text{for} \quad \eta \neq 1, \eta > 0 \\ \ln c_{1m} + \beta \ln c_{2m} & \text{for} \quad \eta = 1 \end{cases} \tag{1.6}$$

where $1/\eta$ equals the constant elasticity of intertemporal substitution and $\beta < 1$ denotes the utility discount factor for the respective country $m \in \{E, I\}$.

1.2.2.2 Capital Supply

For the first period, there is an exogenously given capital endowment to households in both countries resulting from the savings s_{0m} in the previous period: $K_1 = s_{0E} + s_{0I}$. Second-period capital supply derives from the aggregated endogenous savings of households in both countries. The existing capital stock is available for consumption (and savings) at the end of each period without depreciation. Positive capital accumulation therefore implies that $s_{1E} + s_{1I} > K_1$. The respective household has rational expectations and chooses savings so as to maximize its life-time utility (1.6) subject to country-specific budget constraints.

In country I, the household takes current and future labor income, market interest rates i_1 and i_2, and tax revenue T_2 (for a constant population size of one) as given. The tax revenue is collected through an ad valorem resource tax τ_2 in the second period and distributed to the households of country I in a lump-sum fashion. Therefore, the budget constraints for country I households in periods 1 and 2 are

$$c_{1I} + s_{1I} = \pi_{1I} + (1 + i_1)s_{0I} \tag{1.7}$$

$$c_{2I} = \pi_{2I}^{\tau} + (1 + i_2)s_{1I} \tag{1.8}$$

with $\pi_{2I}^{\tau} = \pi_{2I} + T_2$. In Chapter 2, we concentrate on the case of an ad-valorem tax, but point out when a unit resource tax would have different implications. For the most part, the unit resource tax case is a complete analogue.

The representative household in country E receives income from the capital endowment and from resource revenue so that the budget constraints for both periods are given by

$$c_{1E} + s_{1E} = \pi_{1E} + (1 + i_1)s_{0E} \tag{1.9}$$

$$c_{2E} = \pi^{\tau}_{2E} + (1 + i_2)s_{1E} \tag{1.10}$$

where π^{τ}_{2E} denotes the resource revenue net of taxes from (1.1).

Households maximize intertemporal utility given the budget constraints taking their income streams and the interest rate i_2 as given. This yields the respective Euler equation

$$\frac{u'(c_{1m})}{\beta u'(c_{2m})} = 1 + i_2 \tag{1.11}$$

From the total derivative of the Euler equation with respect to changes in period incomes and the interest rate, we derive the savings reactions (cf. Appendix A.1.1)

$$\frac{\partial s_{1m}}{\partial y_{1m}} > 0, \quad \frac{\partial s_{1m}}{\partial \pi^{\tau}_{2m}} < 0, \quad \frac{\partial s_{1m}}{\partial i_2} \gtrless 0 \tag{1.12}$$

Since we assume homothetic consumption preferences, the marginal savings reactions with respect to changes in period incomes are independent of the household's income level. They are determined only by the discount factor β, the intertemporal elasticity of substitution $\frac{1}{\eta}$, and the market interest rate i_2. As will be shown in Section 1.2.3, the market interest rate is independent of the resource tax in the symmetric country case, that is, the case where both discount factors are the same for both countries. Thus, in this case, the marginal saving propensities with respect to changes in period incomes are also independent of the resource tax and therefore completely equivalent to the no-tax case. Given that the resource constraint holds, second-period capital supply K^s_2 from aggregated savings can be represented as a function of only the resource supply path and the interest rate i_2 for homothetic preferences (as we show in Appendix A.1.2):

$$K^s_2 = K^s_2(R_2, i_2) \tag{1.13}$$

A shift of resource extraction to the future period implies a transfer of final goods production and thereby aggregate (world) income from the first to the second period, ceteris paribus. Given the savings propensities in (1.12), this redistribution of income creates a disincentive to save. Moreover, aggregate savings unambiguously increase with a rise in the interest rate i_2, ceteris paribus, because the income effect of a change in the interest rate only has a redistributive effect and cancels out for symmetric homothetic preferences. Similarly, aggregate capital supply does not depend on the future period's resource tax levied in country I. By increasing the second-period resource tax, country I is, ceteris paribus, able to capture a larger share of the resource rents from country E. With symmetric homothetic preferences, these income effects from the redistribution of the resource rents, however, exactly cancel out.

1.2.3 Conditional Market Equilibrium

1.2.3.1 General Equilibrium Conditions

In the following, we characterize the market equilibrium in all three markets – the resource market, the capital market, and the market for final goods – conditional on the resource supply path, that is, given *any* allocation of resources to both periods that fulfills the binding resource constraint. We analyze the comparative statics of this conditional market equilibrium with respect to changes in the resource supply path. This will give us the (general equilibrium) market reaction to the supply decision, which the resource monopolist will take into account (see Section 1.3).

Resource Market

The resource market equilibrium is characterized by the market-clearing condition

$$R_t^d(p_t, i_t) = R_t^s \quad \text{for both periods } t = 1, 2 \tag{1.14}$$

for resource demand derived from competitive final goods production (cf. Equations (1.4) and (1.5)) and in conjunction with the binding resource constraint (1.2).

Capital Market

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

$$K_1^d(p_1, i_1) = K_1 = s_{0E} + s_{0I} \tag{1.15}$$

with capital demand from Equations (1.4) and (1.5). In the second period, the capital market equilibrium is again characterized by the market-clearing condition

$$K_2^d(p_2, i_2) = K_2^s(R_2, i_2) \tag{1.16}$$

where capital supply is a function of the resource supply path and the interest rate only in case of symmetric and homothetic consumption preferences according to Equation (1.13).

Final Goods Market

In equilibrium, aggregate consumption (and savings) has to equal aggregate consumption possibilities, which are given from production and the capital stock in both periods:

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

If the resource market and the capital market are in equilibrium, then, according to Walras' law, the market for final goods must be in equilibrium, too.

1.2.3.2 Comparative Statics of the Conditional Market Equilibrium

We now focus on the conditional market equilibrium's dependency on the chosen resource supply path. In other words: how do the equilibrium market prices for the resource, p_t, and for capital, i_t, as well as the second-period capital stock K_2, react to changes in the resource supply path (given a binding resource constraint (1.2))?

For period 1 we totally differentiate Equations (1.14) and (1.15) while taking into account Equations (1.4) and (1.5). Solving the two resulting equations together, we observe that

$$\frac{dp_1}{dR_1} = \frac{\partial p_1}{\partial R_1} = F_{1RR} < 0 \tag{1.17}$$

holds due to the concavity of the production technology. Moreover, we know by the complementarity of capital and resources in production:

$$\frac{di_1}{dR_1} = \frac{\partial i_1}{\partial R_1} = F_{1KR} > 0 \tag{1.18}$$

In period 2, factor price reactions to changes in the extraction path are more complex compared to (1.17) and (1.18) due to the endogenous adjustment of the capital stock. By totally differentiating Equations (1.13), (1.14), and (1.16) while taking into account Equations (1.2), (1.4), and (1.5) and solving the resulting equations together (cf. Appendix A.1.3), the equilibrium market price reactions in period 2 can be decomposed according to

$$\frac{dp_2}{dR_2} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} = F_{2RR} + F_{2RK}\frac{dK_2}{dR_2} < 0 \tag{1.19}$$

$$\frac{di_2}{dR_2} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2} = F_{2KR} + F_{2KK}\frac{dK_2}{dR_2} > 0 \tag{1.20}$$

The overall reaction of the period 2 capital stock to, e.g., a postponement of extraction $\frac{dK_2}{dR_2}$ is determined by two counteracting effects, and is generally ambiguous (cf. Equation (A.3) in Appendix A.1.3): on the one hand, a shift in resource extraction causes an according change in output, aggregate income, and savings incentives. If resource extraction is postponed, then future income increases, while present income decreases. This income effect reduces the incentive to save (cf. (1.12)). On the other hand, postponement of extraction also increases the productivity of capital in period 2, that is, the interest rate i_2. Even though the income effect of the interest rate change cancels out for symmetric homothetic preferences (cf. Appendix A.1.2), the increase in the future interest rate induces a substitution effect which contributes to an increase in savings.

The signs of (1.19) and (1.20) are unambiguous irrespectively of the sign of $\frac{dK_2}{dR_2}$ as long as preferences are symmetric. This implies that the direct effects of resource supply on resource price and interest rate if the capital stock was kept constant ($\frac{\partial p_2}{\partial R_2}$ and $\frac{\partial i_2}{\partial R_2}$) always outweigh the respective indirect price effects from the endogeneity of capital accumulation.

1.3 The Resource Monopolist’s Optimal Extraction Path

In the present general equilibrium setting the resource monopolist faces a number of cross-market effects between the resource and the capital market which have an impact on both sources of income of country E: resource revenues and capital asset returns. To better understand the interactions between the different feedback effects and their implications for the monopolist’s extraction behavior, we build up the analysis in several steps: first, we derive the extraction behavior of the monopolist who takes all relevant general equilibrium effects into account (Section 1.3.1). To prepare the analysis of the different supply motives, we then examine the behavior of a "naive" monopolist, who only considers the conventional own-price effect of resource supply on the resource price while neglecting all the additional general equilibrium aspects, as a benchmark case (Section 1.3.2). This setup is contained in the full omniscient monopolist's reasoning and corresponds to a partial-equilibrium monopolist. In Section 1.3.3, we investigate how the impact of resource supply on future capital accumulation changes country I's resource demand and affects the monopolist's resource supply path, which we call "addiction motive". Section 1.3.4 analyzes how the monopolist internalizes the influence of her resource supply on country E's capital asset income, how this affects her extraction policy ("capital asset motive"), and how accounting for endogenous capital stock dynamics impacts this supply motive. The extraction behavior of the monopolists in Sections 1.3.3 and 1.3.4 is compared to the naive monopolist and to the outcome of a competitive resource market, respectively. Finally, in Section 1.3.5 we examine the omniscient monopolist again and how the different supply motives interact in her extraction policy.

In the whole analysis of this chapter the resource import tax τ_t is suppressed because it does not add to the understanding of the role of the resource supply motives. Chapter 2, in contrast, applies the model to the oil market and climate policy, where the resource import tax plays a central role.

1.3.1 Optimal Resource Supply: Full General Equilibrium

Our omniscient monopolist is benevolent and seeks to maximize the utility of households in country E, given the conditional market equilibrium:

$$\max_{R_1,R_2} u(c_{1E}) + \beta u(c_{2E}) \tag{1.21}$$

subject to the resource constraint (1.2), the budget constraints (1.9) and (1.10) and the conditional market equilibrium represented by Equations (1.14), (1.15), and (1.16) and the corresponding equilibrium relationships between second-period resource supply and factor market prices (Equations (1.19) and (1.20)). Due to the binding resource constraint, the monopolist's optimization problem is one-dimensional ($R_2 = \bar{S} - R_1$). Moreover, the representative household in country E makes optimal saving decisions for any set of resource income streams and interest rates taking them as given. Therefore, the Euler equation (1.11) holds for any resource supply path chosen by the omniscient monopolist.

Thus, substituting the marginal rate of substitution from the Euler equation (1.11) into the first-order condition and simplifying the first-order condition for the optimal resource supply path gives the modified Hotelling rule

$$(1+i_2)\left[p_1+\frac{\partial p_1}{\partial R_1}R_1+\frac{\partial i_1}{\partial R_1}s_{0E}\right]=p_2+\frac{dp_2}{dR_2}R_2+\frac{di_2}{dR_2}s_{1E} \tag{1.22}$$

Interestingly, there appears no derivative of the market discount factor $(1+i_2)$ in the modified Hotelling rule (1.22), although the resource monopolist accounts for her influence on the capital return i_2. This is due to the fact that the discount factor $(1+i_2)$ derives from the separate savings decision of the households (cf. Euler equation (1.11)) which act as price takers on the capital market. In benevolently maximizing household utility in country E the monopolist takes the households' Euler equation (1.11) as given.

From the monopolist's perspective, the overall marginal resource value consists of the marginal resource revenue and the marginal capital income effect of resource supply:

$$MV_t=p_t+\frac{dp_t}{dR_t}R_t+\frac{di_t}{dR_t}s_{(t-1)E}=MR_t+\frac{di_t}{dR_t}s_{(t-1)E} \tag{1.23}$$

with $\frac{dp_1}{dR_1}$ from (1.17), $\frac{di_1}{dR_1}$ from (1.18), $\frac{dp_2}{dR_2}$ from (1.19), $\frac{di_2}{dR_2}$ from (1.20), and the marginal resource revenue MR_t.

1.3.2 Benchmark: A 'Naive' Monopolist

We adapt the terminology of Moussavian and Samuelson (1984) and refer to the naive monopolist (superscript "N") as the monopolist who ignores all the additional cross-market effects in our general equilibrium setting and just internalizes the negative own-price effect from resource supply on the resource market price. Thus, all the additional components in (1.22) drop out, and the naive monopolist follows the Hotelling condition

$$(1+i_2)MR_1^N=MR_2^N \tag{1.24}$$

with the marginal resource revenue

$$MR_t^N=p_t+\frac{\partial p_t}{\partial R_t}R_t=\frac{p_t}{\sigma}\left[\theta_{tR}-(1-\sigma)\right] \tag{1.25}$$

Here, the share of total output which is captured as remuneration in period t by production factor f is denoted by "θ_{tf}". This formulation of marginal resource revenue is identical to a partial equilibrium setting. Only here inverse resource demand is derived from the marginal productivity of the resource for the CES production technology (1.3). We denote the extraction decision of the naive monopolist by ($R_1^N; R_2^N$). The price elasticity of demand is given by

$$\epsilon_{R_t,p_t} = \frac{\sigma}{1-\theta_{tR}} \quad \text{with} \quad \frac{\partial \epsilon_{R_t,p_t}}{\partial R_t} = \frac{\sigma-1}{1-\theta_{2R}} \frac{p_t}{F_t} \gtreqless 0 \quad \text{for} \quad \sigma \gtreqless 1 \tag{1.26}$$

Given our general equilibrium setting, we have to take into account that the second period capital stock K_2 is very likely to deviate from the first period capital stock K_1. Having the growth path of the world economy since the industrial revolution in mind, we focus on positive accumulation of physical capital over time ($K_1 < K_2$), although $K_1 > K_2$ cannot generally be excluded. For $K_1 < K_2$, (inverse) resource demand in period 2 shifts upward relative to period 1 due to the complementarity of fossil resources and capital. In the following, the role of capital accumulation for the supply decision of the naive monopolist is assessed.

First, the complementarity driven upward shift in resource demand leads to an increase in marginal resource revenue (for a CES resource demand schedule):[10]

$$\left.\frac{\partial MR_t^N}{\partial K_t}\right|_{R_t} = \frac{2-\sigma}{\sigma}\left(\theta_{tR} - \frac{1-\sigma}{2-\sigma}\right) F_{tRK} > 0 \quad \text{for all } \sigma > 0 \tag{1.27}$$

The positive sign holds true as long as $MR_t^N > 0$, which is the case for a binding resource constraint (1.2).[11] Thus, capital accumulation induces the naive monopolist generally to supply more resources in the second period compared to a 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 (cf. Stiglitz, 1976), which we denote by $(R_1^C; R_2^C)$, as summarized in the first Proposition.

---

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

[11] Note that the restriction $MR_t^N > 0$ ensures that $\theta_{tR} > 1-\sigma$, and therefore that

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

which confirms that the sign of (1.27) does not depend on the elasticity of substitution $\sigma > 0$.

Proposition 1.1. *With positive capital accumulation ($K_1 < K_2$), naive monopoly power leads to a more "conservationist" extraction path relative to the competitive equilibrium if $R_1^C > R_2^C$ and $\sigma < 1$. However, if $K_1 < K_2$ leads to $R_1^C < R_2^C$ or if $K_1 > K_2$, then the monopolistic bias is ambiguous.*

The 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 (1.26), and not on the capital stock. Like in partial equilibrium, the naive monopolist in general equilibrium will choose a more conservative extraction policy (irrespective of the development of the capital stock over time) if the competitive supply path is falling over time and the price elasticity of resource demand is falling in resource consumption. With a CES demand schedule, the latter is the case for $\sigma < 1$ according to (1.26). This has inspired the phrase of the monopolist being "conservationist's friend" (Solow, 1974).

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

$$\begin{aligned}\left.\frac{\partial \epsilon_{R_t,p_t}}{\partial K_t}\right|_{R_t} &= -\frac{\sigma}{(1-\theta_{tR})^2}\frac{\partial \theta_{tR}}{\partial K_t} \\ &= (\sigma-1)\frac{\theta_{tR}}{(1-\theta_{tR})^2}\frac{F_{tK}}{F_t} \gtreqless 0 \quad for \quad \sigma \gtreqless 1. \end{aligned} \tag{1.28}$$

Like resource consumption (cf. (1.26)), the capital stock increases the price elasticity for $\sigma > 1$, and decreases the price elasticity for $\sigma < 1$. For iso-elastic demand and $\sigma = 1$, both have no influence at all. Considering the case $\sigma < 1$, these results suggest at first glance that capital accumulation exacerbates the conservationist bias relative to a constant capital stock. But for a full quantitative comparison we must also take into account that with capital accumulation the resource is extracted more conservatively in the competitive market, too. Since closed-form analytical solutions for the extraction path are excluded even in the competitive case, general conclusions about the magnitude of the monopolistic extraction bias with and without capital accumulation are not possible. However, as the price elasticity of resource demand changes with capital accumulation according to (1.28), we can conclude that the naive monopolist will deviate from the competitive market solution for $\sigma \neq 1$ even if $R_1^C = R_2^C$ due to the increase in the future resource market price from capital accumulation.

If $K_1 < K_2$ leads to $R_1^C < R_2^C$, or if $K_1 > K_2$ with $R_1^C > R_2^C$, by (1.26) and (1.28) 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 naive monopolist's extraction bias relative to the competitive outcome is, in general, ambiguous in these cases.[12]

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 (1.26) and (1.28) the naive monopolist's and the competitive extraction path then coincide with and without capital dynamics.

1.3.3 The Endogeneity of the Future Resource Demand Curve and the Addiction Motive

We assume here that the monopolist realizes that her resource supply decision affects the second period capital stock ($\frac{dK_2}{dR_2}$) and (via the complementarity of production factors) leads to a shift second period inverse resource demand ($\frac{\partial p_2}{\partial K_2}$).[13] This is in contrast to the naive monopolist who is just confronted with different resource demand functions over time due to different capital stocks K_1 and K_2.

At the same time, the monopolist neglects the influence of her supply decision on the market interest rate, neither from the direct complementarity effect ($\frac{\partial i_t}{\partial R_t}$) nor from the indirect effect by the endogeneity of the capital stock ($\frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2}$). In this case, the monopolist extracts the resource stock according to the Hotelling rule

$$(1+i_2)\left(p_1 + \frac{\partial p_1}{\partial R_1} R_1\right) = p_2 + \left(\frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2}\right) R_2 \tag{1.29}$$

To investigate how the internalization of the endogeneity of capital accumulation affects the monopolist's supply decision, we contrast the modified Hotelling rule (1.29) with the naive monopolist's supply path determined by (1.24). Since the capital dynamics only affect the second period marginal resource value MV_2, we can restrict the analysis to the second period. In particular, no additional intertemporal trade-off is introduced.

---

[12] A scenario $K_1 > K_2$ with $R_1^C < R_2^C$ cannot occur because with $K_1 > K_2$ the necessary growth in the marginal resource rent for Hotelling condition (1.24) to hold requires $R_1^C > R_2^C$.

[13] This setup corresponds the non-naive monopolist which Moussavian and Samuelson (1984) consider.

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 (postponing) extraction always increases (decreases) the future capital stock without depreciation. In our framework, in contrast, savings are a function of first and second period income and the interest rate (cf. (A.1) in Appendix A.1.1), so that $\frac{dK_2}{dR_2}$ may, in general, be positive or negative, leading to the following proposition.

Proposition 1.2. *Taking into account the feedback of capital dynamics on inverse resource demand leads to an accelerated (postponed) extraction relative to the naive monopolist if* $\frac{dK_2}{dR_2} < 0$ *(*$\frac{dK_2}{dR_2} > 0$*).*

From (1.19) we know that $\frac{dp_2}{dR_2} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} < 0$ for symmetric homothetic preferences, irrespective of the sign of $\frac{dK_2}{dR_2}$. However, if the future capital stock negatively depends on future resource supply ($\frac{dK_2}{dR_2} < 0$, as in Moussavian and Samuelson (1984)), then the negative own-price effect that the non-naive monopolist considers is even stronger than for the naive monopolist, and vice versa. This is reflected by the effective price elasticity of resource demand, which includes the feedback effect from the capital dynamics:

$$e_{R_2,p_2} = -\frac{1}{\frac{dp_2}{dR_2}\frac{R_2}{p_2}} = \frac{\sigma}{1-\theta_{2R}-\theta_{2K}\frac{dK_2}{dR_2}} \gtrless \frac{\sigma}{1-\theta_{2R}} = -\frac{1}{\frac{\partial p_2}{\partial R_2}\frac{R_2}{p_2}} = \epsilon_{R_2,p_2} \qquad (1.30)$$

$$for \quad \frac{dK_2}{dR_2} \gtrless 0$$

By taking into account the stronger resource price reaction the monopolist realizes that future resource demand is less price-elastic and unambiguously accelerates extraction. By doing so, she boosts production and savings and takes advantage of the increase in resource demand in period 2. The indirect feedback via the endogeneity of capital accumulation enables the monopolist not only to exploit but even to manipulate the dependency or “addiction” of the resource importing countries on fossil resources and introduces what we may call an “addiction motive”. 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. In that case, the monopolist would have an incentive to postpone extraction relative to her naive counterpart.

The effective price elasticity of resource demand in (1.30) also directly implies that the monopolistic and the competitive extraction path do not coincide anymore for iso-elastic resource demand ($\sigma = 1$).

Proposition 1.3. *The monopolist's extraction path is less (more) conservationist than under perfect competition 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 monopolist's supply schedule only coincides with the competitive extraction path if, by chance, the elasticity of the second period capital stock with respect to future resource supply is[14]

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

where

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

is the cross price elasticity of resource demand. For $(R_1^C > R_2^C)$, the right side in the above equality condition is negative (positive) if $\sigma < 1$ ($\sigma > 1$), this is, if the price elasticity of resource demand is falling (increasing) in resource consumption (cf. (1.26)). In this case, the naive monopolist extracts more slowly than the competitive market. If $\frac{dK_2}{dR_2}$ is negative (positive), then accounting for the endogenous capital dynamics counteracts (strengthens) the conservationist extraction bias of the naive monopolist. To which extent the standard monopolistic extraction bias is counteracted (or even reversed) depends on the strength of the additional feedback effect from the capital dynamics, 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 (cf. Section 1.3.4), the effect of the endogeneity of capital accumulation is not affected by a redistribution of capital endowments. Again, this is due to the assumption of symmetric homothetic preferences which ensures that aggregate savings

---

[14] The equality condition follows from setting $1 - \frac{1}{e_{R_2,p_2}} = 1 - \frac{1}{\epsilon_{R_1,p_1}}$ which implies by the Hotelling conditions $(1 + i_2)p_1 = p_2$ for perfect competition and (1.29) for the non-naive monopolist in this section that the monopolist will follow the competitive extraction path.

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 of $\frac{dK_2}{dR_2}$, 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).[15]

1.3.4 The Capital Asset Motive

1.3.4.1 Introduction of the Capital Asset Motive

In addition to the own-price effect (cf. Section 1.3.2), now the benevolent monopolist recognizes that additional resource supply in either period increases the marginal productivity of capital and, thereby, generates a higher return on the investments which her constituency holds in the capital market (but neglects the capital market feedback on resource demand from Section 1.3.3). In the following we call this capital income component in the benevolent monopolist's supply decision the "asset motive". The according equilibrium extraction path is characterized by the condition

$$(1+i_2)\left(p_1+\frac{\partial p_1}{\partial R_1}R_1+\frac{\partial i_1}{\partial R_1}s_{0E}\right)=p2+\frac{\partial p_2}{\partial R_2}R2+\frac{\partial i_2}{\partial R_2}s_{1E} \tag{1.31}$$

The asset motive adds to the standard marginal resource revenue MR_t and, thus, increases the total marginal resource value MV_t from the monopolist's perspective as long as her constituency has positive capital holdings abroad $s_{(t-1)E}>0$. For future reference we define this extended marginal resource value (using standards properties of CES production) as

$$MV_t^{NA}=p_t+\frac{\partial p_t}{\partial R_t}R_t+\frac{\partial i_t}{\partial R_t}s_{(t-1)E}=\frac{p_t}{\sigma}\left(\theta_{tR}+\theta_{tK}\frac{s_{(t-1)E}}{K_t}-(1-\sigma)\right)$$

The superscript "NA" stands for "naive monopolist with asset motive" since the monopolist here is still naive with respect to the capital dynamics.

---

[15] With an infinite time horizon in Moussavian and Samuelson (1984), a shift in the extraction path does not only trigger a change the subsequent period's capital stock but in all future periods. Due to rising marginal resource productivity over time, a postponement of extraction might lead to more, but also later, capital accumulation in the future. 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.

From a static perspective, the asset motive creates an incentive to increase period resource supply.[16] Of course, with a binding resource constraint increasing resource supply in both periods is not feasible. The asset motive, therefore, introduces an additional intertemporal trade-off to the monopolist's supply decision and provides a new perspective[17] on the role of by now significant capital holdings of resource rich countries.[18]

For a naive monopolist (cf. Section 1.3.2) maximizing household life-time utility and maximizing the sum of discounted resource profits by a private resource firm is equivalent, because households smooth consumption in a separate savings decision (see also the corresponding discussion in Hoel (1981)). With accounting for the asset motive, however, the equivalency of both approaches breaks down. The reason is that the utility maximizing monopolist, apart from resource income, also considers capital income of her constituency (thus pursuing a twofold strategy), but does not account for the influence of resource supply on the market discount factor $(1 + i_2)$ in (1.31). The market discount factor derives from the separate saving decision of households which take the interest rate as given. In contrast, a profit maximizing monopolistic firm which recognizes the complementarity-based influence on the interest rate directly takes into account that postponing extraction increases the opportunity costs of leaving resources underground, this is, the interest rate i_2, but neglects her influence on households' capital income.[19]

With no closed-form solution for the optimal extraction path, we take the naive monopolist's extraction decision as a benchmark and study if and under which conditions the asset motive

---

[16] This has also been noted by Calvo and Findlay (1978) and Hassler et al. (2010) for positive capital holdings.

[17] A relationship between the capital asset holdings and the (dynamic or intertemporal) supply decision of resource owners has 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. But this reasoning is completely different to the asset motive of a resource supplier with market power and her internalized influence on the capital interest rate, which we analyze here.

[18] The publicly available information about the volume of the sovereign wealth funds (cf. SWFI (2016)) provides presumably a lower bound estimate of total capital asset holdings of resource-rich countries as it does not contain private capital holdings.

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

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

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.

provides an incentive for the monopolist to adjust her extraction decision. This also includes an assessment of the monopolistic extraction bias compared to the competitive market outcome.

Equating Hotelling rules (1.24) and (1.31), we observe upon rearranging that pursuing the asset motive will be exactly neutral with respect to the extraction path of the naive monopolist if

$$\frac{F_{2KR}s_{1E}}{F_{1KR}s_{0E}} = \frac{p_2 + \frac{\partial p_2}{\partial R_2}R_2}{p_1 + \frac{\partial p_1}{\partial R_1}R_1} = 1 + i_2 \tag{1.32}$$

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 trigger any change in the monopolist's supply path if the present value of the capital income component of the overall marginal resource value MV_t^{NA} (just like the resource income component MR_t^N) is constant over time. If the marginal value of the resource in terms of gains in capital income grows more strongly over time than the marginal resource revenue, then future resource supply is more valuable to the monopolist with asset motive than to the naive monopolist. The asset motive then creates an incentive to shift extraction to the second period starting from the extraction decision of the naive monopolist (R_1^N, R_2^N), and vice versa.

Taking the naive monopolist's extraction path (R_1^N, R_2^N) (cf. (1.24)) as reference unambiguously determines every variable like the market prices, the capital stock in period 2, and the sensitivity of the interest rate with respect to resource supply F_{tKR} for symmetric countries (cf. 1.2.3) and given factor endowments $\bar{S}$ and K_1, except for households' savings s_{1E}. Therefore, the development of the capital income component $F_{tKR}s_{(t-1)E}$ over time and, thus, the neutrality of the asset motive just depend on the development of the foreign capital holdings. Since Households' savings are a function of the first-period income stream y_{1E} and π_{2E} according to (A.1) (see Appendix A.1.1), we can change savings s_{1E} by altering the distribution of the capital endowment K_1 between both countries while keeping the reference extraction path $(R_1^N; R_2^N)$ unchanged. Such a redistribution does not affect aggregate capital accumulation for symmetric homothetic consumption preferences (see also Section 1.2.3.1).

1.3.4.2 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 monopolist and the naive monopolist, we solve neutrality condition (1.32) for the ratio of country E's asset holdings and obtain the following proposition.

Proposition 1.4. *Pursuing the asset motive according to* (1.31) *does not change the extraction path relative to the naive monopolist without asset motive if*

$$\frac{s_{1E}}{s_{0E}} = \frac{\frac{p_2+\frac{\partial p_2}{\partial R_2}R_2}{F_{2KR}}}{\frac{p1+\frac{\partial p_1}{\partial R_1}R_1}{F_{1KR}}} \equiv \Phi(R_1^N, R_2^N) \tag{1.33}$$

Accounting for the asset motive as in (1.31) *postpones extraction relative to the naive monopolist if* $\frac{s_{1E}}{s_{0E}} > \Phi(R_1^N, R_2^N)$ *and accelerates extraction if* $\frac{s_{1E}}{s_{0E}} < \Phi(R_1^N, R_2^N)$*. A redistribution of capital endowments to country* E *accelerates extraction.*

For symmetric homothetic preferences, the threshold Φ is independent of the distribution of the capital endowment K_1 between country E and country I and (by definition) just a function of the resource extraction path of the naive monopolist (R_1^N, R_2^N).

Condition (1.33) 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: if there is a sufficiently strong increase in asset holdings of country E so that $\frac{s_{1E}}{s_{0E}} > \Phi$, the capital income component grows faster over time than the resource income component represented by the marginal resource revenue. The result is an incentive to postpone extraction relative to the naive monopolist. For $\frac{s_{1E}}{s_{0E}} < \Phi$, the opposite holds true.

In the following, we show that a redistribution of capital asset endowments from country I to country E lowers country E's ratio of asset holdings $\frac{s_{1E}}{s_{0E}}$: the marginal savings propensities (cf. (A.2) in the Appendix) are insensitive to a redistribution of capital endowments, because the overall market equilibrium does not change. Therefore, we can decompose the second-period asset holdings of country E as a linear function of its asset endowment for a given extraction path and given K_1.

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

with the savings level for a zero capital endowment of country E $s_{1E}(0)$. The savings reaction to increases in the first period income $\frac{\partial s_{1E}}{\partial y_{1E}}$ is a positive constant (lower than unity) for a given extraction path. Using this relationship between capital endowment and savings, we obtain the effect of a capital endowment redistribution on the ratio of second to first-period capital holdings[20]

$$\left.\frac{\partial\left(\frac{s_{1E}}{s_{0E}}\right)}{\partial s_{0E}}\right|_{K_1} = \frac{1}{s_{0E}}\left[\frac{\partial s_{1E}}{\partial y_{1E}}(1+i_1) - \frac{s_{1E}}{s_{0E}}\right] = -\frac{s_{1E}(0)}{s_{0E}^2} < 0 \tag{1.34}$$

Increasing country E's first-period capital holdings s_{0E} disproportionally strengthens the capital income component in the present over the one in the future because households only save a fraction of the additional first-period income and the ratio of asset holdings $\frac{s_{1E}}{s_{0E}}$ decreases. As a result, the monopolist's incentive to postpone extraction is more and more reduced and eventually reversed if the ratio $\frac{s_{1E}}{s_{0E}}$ falls below Φ. In turn, if country E does not own any capital assets in the present ($s_{0E} = 0$), but holds shares in the future capital stock, then the asset motive creates an unambiguous incentive to postpone extraction.

Finally, we 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.[21] By (1.34), this observation allows us to conclude that the neutrality condition (1.33) 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 monopolist will always postpone extraction relative to the naive monopolist for any $s_{0E} \leq K_1$.

1.3.4.3 The Asset Motive and the Conservationist Bias

Depending on the intertemporal ratio of country E's capital assets $\frac{s_{1E}}{s_{0E}}$, the asset motive can lead to an acceleration, as well as a postponement of resource extraction relative to the naive

---

[20] We again use the notation $|_{K_1}$ here to point out that we consider a redistribution of capital endowments and no increase in aggregate capital endowment.

[21] For the limiting cases of the capital asset ratio we have

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

monopolist. This can, in principle, strengthen, dampen or even reverse the extraction bias of the naive monopolist relative to the competitive outcome, which is a conservationist bias for $\sigma < 1$, $R_1^C > R_2^C$, and $K_1 < K_2$ (cf. Section 1.3.2). As we have seen, the distribution of capital asset endowments between the countries plays a key role for the effect of the asset motive on the monopolist's extraction bias, but general analytic conclusions are difficult. For iso-elastic resource demand ($\sigma = 1$ in the case of CES technology) the extraction path of the naive monopolist is identical to the competitive extraction path. When the asset motive is added to the monopolist's reasoning, this equality does not hold anymore if the capital income component grows over time at a different rate than the resource income component (cf. (1.32)).

Although by assumption the resource stock is fully extracted in the present model, we can briefly touch upon the question of cumulative extraction if the available resource stock was made endogenous (for instance by investments in exploration or stock-depending extraction costs). Typically, a monopolist who accounts for the reaction of the marginal resource revenue to her supply behavior (like our naive monopolist) increases extraction and resource supply in both periods until the marginal resource revenue falls to zero. The rest of the resource stock is left in the ground to avoid negative marginal resource revenue. A characteristic feature of the asset motive is that it adds a positive component to the total resource value in both periods (as long as country E's capital holdings are positive). This implies that a naive monopolist with asset motive would increase extraction in both periods, this is, cumulative extraction, relative to her naive counterpart. Whether cumulative extraction would also be higher than in the competitive case is a question which requires explicit modelling in future research.

1.3.4.4 The Endogeneity of the Future Capital Stock and the Asset Motive

If the monopolist is already aware of the complementarity-driven influence on the interest rate $\frac{\partial i_t}{\partial R_t}$ and pursues the asset motive, then internalizing in addition the dependency of the future capital stock on the resource supply path $\frac{dK_2}{dR_2}$ affects the monopolist's perceived sensitivity of the future return on capital investments to changes in resource supply (cf. (1.20)):

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

The positive sign holds irrespective of the sign of $\frac{dK_2}{dR_2}$ for symmetric homothetic consumption preferences (cf. Section 1.2.3.2). Since endogenous capital accumulation only affects future production, we can draw our conclusions by only considering period 2, summarized in the following proposition.

Proposition 1.5. *Internalizing the endogeneity of the future capital stock and its role for the asset motive poses an incentive to postpone extraction if* $\frac{dK_2}{dR_2} < 0$ *and to accelератate extraction if* $\frac{dK_2}{dR_2} > 0$.

Due to the diminishing returns to capital ($\frac{\partial i_2}{\partial K_2} < 0$) the feedback effect $\frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2}$ implies a stronger positive reaction of the interest rate i_2 to increases in the future resource supply, if $\frac{dK_2}{dR_2} < 0$. In this case, the future asset motive is strengthened when the monopolist internalizes the endogeneity of the capital stock and an incentive to postpone extraction is established. In contrast, if $\frac{dK_2}{dR_2} > 0$, then the positive influence of future resource supply on the interest rate and, thereby, the future asset motive is attenuated by accounting for the feedback effect from the endogeneity of capital accumulation. This triggers an acceleration of extraction.

1.3.5 The Extraction Path of the Omniscient Monopolist

In the extraction decision of the omniscient monopolist characterized by (1.22) both indirect effects from the capital dynamics (cf. Sections 1.3.3 and 1.3.4.4) are present. These indirect effects have unambiduous signs, irrespective of the sign of $\frac{dK_2}{dR_2}$, but create 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

$$\Psi = \frac{\partial p_2}{\partial K_2} R_2 + \frac{\partial i_2}{\partial K_2} s_{1E} \gtreqless 0 \tag{1.35}$$

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, and negative otherwise.

Given that the asset motive introduces a generally ambiguous extraction incentive as well, there are no unambiguous conclusions about the extraction policy of the omniscient monopolist. Still, we may characterize the supply path along comparisons to the naive monopolist and the competitive outcome. This illustrates the interaction of the additional considerations which are taken into account by the omniscient monopolist in general equilibrium.

1.3.5.1 Comparison to the Naive Monopolist

The comparison with the naive monopolist, which we derive in analogy to (1.33), is summarized in the next proposition.

Proposition 1.6. *The omniscient monopolist follows the same extraction path as the naive monopolist if*

$$\frac{s_{1E} + \frac{\Psi}{F_{2KR}} \frac{dK_2}{dR_2}}{s_{0E}} = \Phi(R_1^N; R_2^N) \tag{1.36}$$

Extraction is postponed relative to the naive monopolist for $\frac{s_{1E}+\frac{\Psi}{F_{2KR}}\frac{dK_2}{dR_2}}{s_{0E}} > \Phi(R_1^N; R_2^N)$ *and accelerated for* $\frac{s_{1E}+\frac{\Psi}{F_{2KR}}\frac{dK_2}{dR_2}}{s_{0E}} < \Phi(R_1^N; R_2^N)$.

The threshold Φ is defined as before, whereas the left side does not only contain the capital holdings ratio $\frac{s_{1E}}{s_{0E}}$, but is extended by the indirect effects from the capital dynamics which are captured in Ψ from (1.35). Similarly to 1.3.4.2, the omniscient monopolist chooses a more (less) conservative extraction path than the naive monopolist if along the naive monopolist's extraction path $(R_1^N; R_2^N)$ the left side of (1.36) is greater (lower) than the threshold Φ.

Consider first the case $\frac{dK_2}{dR_2} < 0$. If the strengthening of the future asset motive dominates the addiction motive (i.e., $\Psi < 0$), then the omniscient monopolist overall has a stronger incentive to postpone extraction relative to the monopolist who just pursues the asset motive without internalizing the capital dynamics (monopolist "NA" from Section 1.3.4.2). Correspondingly, the omniscient follows the naive monopolist's extraction path at a lower asset ratio $\frac{s_{1E}}{s_{0E}}$ than the "NA" monopolist. If the addiction motive dominates the strengthening of the future asset motive (i.e., $\Psi > 0$), the internalization of the capital dynamics leads the omniscient monopolist to accelerate extraction. Then the increase in the asset holdings must compensate for this incentive to keep the omniscient monopolist at the supply policy of her naive counterpart. 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 "NA" monopolist in Section 1.3.4.2. For the omniscient monopolist, however, this is not necessarily the case. Rewriting the left side of condition (1.36), its derivative with respect to capital endowment s_{0E} is given by

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

By (1.34), we know that the first term is negative. Thus, the left hand side of condition (1.36) unambiguously falls with a redistribution of capital endowment to country E if $\frac{dK_2}{dR_2} > 0$ and the omniscient monopolist will speed up extraction just as the "NA" monopolist who only pursues the asset motive. However, if $\frac{dK_2}{dR_2} < 0$, the first and the second term are counteracting. Then it can happen that the additional strengthening of the future asset motive through the redistribution of capital endowments to country E and an according increase in s_{1E} is so strong that the left hand side of (1.36) increases, which induces the omniscient monopolist to postpone extraction compared to the completely naive monopolist.

1.3.5.2 Comparison to the Competitive Outcome

The extraction behavior of the omniscient monopolist and its relation to the competitive outcome is determined by several counteracting effects. Considering the own-price effect of the resource (as the naive monopolist does) induces a conservationist bias for $\sigma < 1, K_1 < K_2$, and $R_1^C > R_2^C$. Assuming that postponement of extraction reduces capital accumulation ($\frac{dK_2}{dR_2}$), the addiction motive (cf. Section 1.3.3) provides an incentive for accelerated extraction, while the capital feedback in the future capital asset motive (cf. Section 1.3.4.4) contributes to postponement of extraction. The asset motive itself can contribute to acceleration, as well as postponement, depending on the development of country E's capital holdings over time. As a result, all these motives together can strengthen, dampen or reverse the conservationist bias of the naive monopolist relative to the competitive outcome. Like in the case of the naive monopolist with asset motive (cf. Section 1.3.4.3), the omniscient monopolist's extraction schedule is generally not identical to the competitive extraction path for iso-elastic resource demand ($\sigma = 1$) and no extraction costs.

Finally, the ambiguity also carries over to the question whether the omniscient monopolist would choose a higher aggregate resource extraction if aggregate extraction was endogenous (not modelled here, cf. Section 1.3.4.3) and the naive monopolist left some resources underground to prevent the marginal resource revenue from falling below zero. Whereas in the first period the marginal resource value to the omniscient monopolist 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, pointing overall towards lower aggregate extraction.

1.4 Numerical Illustration and Limits of Arbitrage Considerations

Figure 1.1 shows both sides of the Hotelling conditions (1.24) and (1.22) for the naive and the omniscient monopolist over the range of possible future extraction rates $0 < R_2 < \bar{S}$ at an exemplary parameter setting.[22] The points where the two respective corresponding curves intersect are the equilibrium extraction paths. For comparison, the vertical line at $R_2^C = 0.233$ designates the future extraction rate in the competitive equilibrium R_2^C. We see that the naive monopolist exhibits a more conservationist extraction path than the competitive market. In this example, the net effect of all general equilibrium feedback effects and the asset motive leads to a reversal of the conservationist bias, so that the omniscient monopolist extracts more quickly than the competitive outcome.

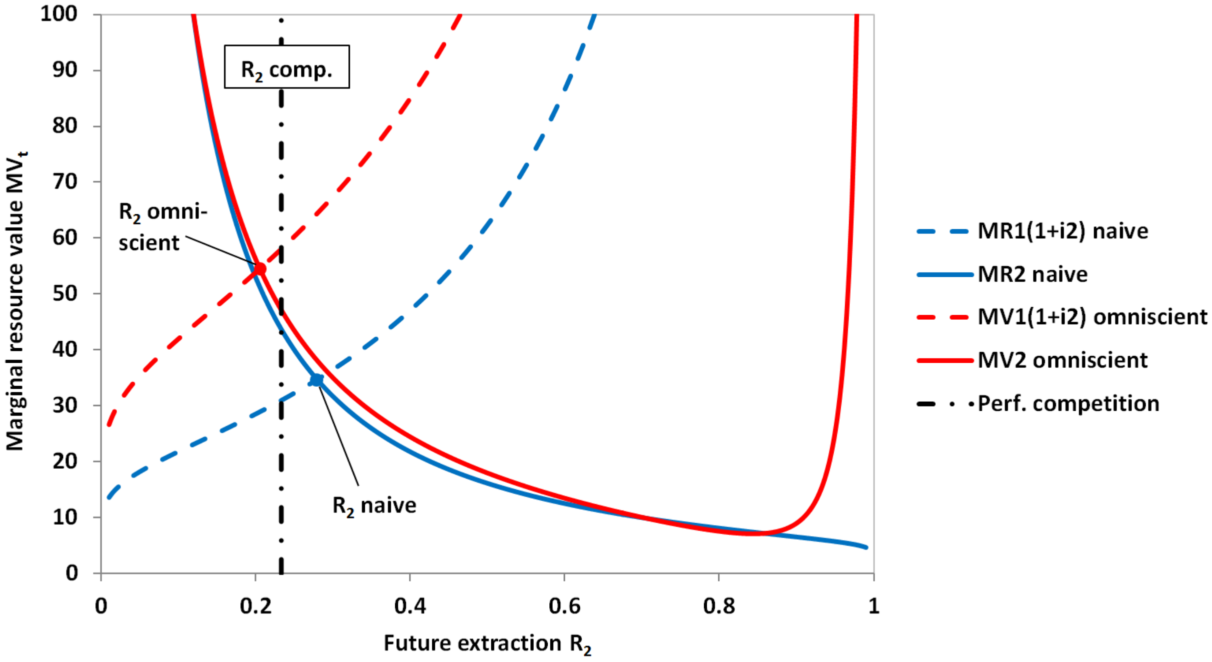

Figure 1.1 : Numerical illustration of the equilibria of the naive and the omniscient monopolist

---

[22] The parameters used in the simulation are: $\sigma = 0.91$, $\eta = 2$, $\beta = 0.3$, $\lambda = 0.1$, $\gamma = 0.4$, TFP parameter $A = 300$, and the exemplar factor endowments $K_1 = 200$, $s_{0E} = 20$, $s_{0I} = 180$, $\bar{S} = 1$

If two curves which represent the two sides of a Hotelling condition are both monotonic in R_2, like in the case of the the naive monopolist, then there can be only one point of intersection, i.e., one equilibrium. But because of the capital dynamics in period 2 with several counteracting channels on the marginal resource value MV_t there can be cases where the marginal resource value is, at least locally, rising in R_2. In the example in Figure 1.1 this is the case for the second-period marginal resource value curve of the omniscient monopolist approximately at $R_2 > 0.85$.

The possibility of such locally rising marginal value curves implies two things. First, multiple equilibria strictly speaking cannot be excluded, although we did not observe any in numerical examples. In this case, the solution procedure would require finding a global utility maximum. Second, in a situation with multiple equilibria our line of argument for the effects of the various supply motives on the extraction path, which is based on arbitrage considerations, might not hold anymore. Assume that the introduction of a supply motive, e.g. the addiction motive, at a certain extraction path leads to a situation where the the first-period side of the Hotelling rule is higher than the second-period side. Our argument hinges upon the notion that the balance in the Hotelling rule can be restored and the new equilibrium can be reached by shifting extraction to the first period. While this logic holds in all observed cases, we cannot be sure that in a case of multiple equilibria the global utility maximum would indeed always be reached.

1.5 Conclusion

We provide an analysis of monopoly power in the market for a crucial fossil resource like oil or rare earths in general equilibrium. Our model captures the impact of resource extraction on the endogenous interest rate, output and capital accumulation, as well as the resulting feedback effects on resource demand and again on the interest rate. The different interactions between the resource market and the capital market yield additional supply motives from the monopolist's perspective: considering how present resource supply fuels capital accumulation in the importing country and its future reliance on and demand for the resource ("addiction motive") poses an incentive for the monopolist to accelerate extraction. As a central new result we find that the resource monopolist not only focuses on resource revenues, but also on capital asset returns as a second income stream for her country. The monopolist accounts for the positive influence of resource supply on her own country's capital returns in both periods via the complementarity of the resource and capital in production.

Thus, the monopolist faces a second parallel intertemporal trade-off (apart from marginal resource revenues) in her dynamic resource supply decision, which we call "capital asset motive". Depending on the development of the exporting country's capital assets over time, the capital asset motive can contribute to acceleration, as well as postponement of extraction. An additional consideration of the role of resource-supply-driven capital accumulation in the context of the capital income component further strengthens the second-period asset motive and contributes to postponement of extraction. The conservationist extraction bias of a monopolist relative to a competitive resource market, which has led to the well-known phrase of the monopolist being "the conservationist's friend", can be amplified, dampened or even reversed by the general-equilibrium supply motives.

The analysis of the strategic capital asset motive makes dynamic changes in the role of a resource exporter with market power visible. Starting with a focus on resource revenues, with a growing stock of capital assets over time the monopolist acquires a double role as resource exporter and capital investor with influence on the capital market via her resource market power. Over time, resource revenues may even lose their role as the primary source of income. Both, the asset motive and the addiction motive constitute different aspects of the mutual dependency of resource exporters and importers. The monopolist's interest in the importing countries' prosperity is twofold: on the one hand, the exporter wants to maintain and increase the importers' "resource addiction" for the future. On the other hand, the monopolist does not want to jeopardize her own capital asset returns. So, overall the general equilibrium perspective has proven very useful for gaining insights, not only into the strategic relation of resource exporters and importers, but also into the complex interlocking of capital and resource markets.

The present framework is a good basis for the analysis of further questions. The reaction of an oil exporting monopolist to the tightening of climate policies by the importing country is the subject and contribution of Chapter 2. In future research, the role of clean or dirty substitutes to the scarce fossil resource can be scrutinized in the context of the supply motives discussed in the present framework. It might be particularly interesting to see under which circumstances the resource exporter will try to keep a substitute out of the market or, to the contrary, support the transition to the substitute if it is beneficial for the resource exporter's capital asset income or if she even invests into the substitute herself. Another direction of adjacent research could be releasing the strict monopoly assumption and modelling a more realistic degree of resource market power like an oligopoly or a monopoly with a competitive fringe.

2 Petrodollar Recycling, Oil Monopoly, and Carbon Taxes

2.1 Introduction

In 2016, Saudi Deputy Crown Prince Mohammad bin Salman, entrusted with Saudi Arabian long-term oil extraction policy, announced a plan to make his country economically independent of oil by 2030. To achieve this, the Saudi government intends to establish the so far largest sovereign wealth fund of US $2 trillion. By investing heavily in all sorts of capital assets, the prince wants to make "investments the source of Saudi government revenue, not oil" (Waldman 2016). Other OPEC countries have also been keeping oil wealth in sovereign wealth funds for many years: as of 2016, Abu Dhabi holds US $792 billion in such funds, Kuwait holds US $592 billion, and Qatar holds US $256 billion (SWFI 2016).[1] OPEC countries appear to be pursuing a two-pillar supply strategy: while they continue to be suppliers of oil, the prince's plan suggests that in the decades to come, they will be shifting toward income from capital assets to prepare for a future post-oil world. The two strategic pillars – oil revenues and capital asset returns – are intertwined by a complex interplay of the oil market and the capital market. The oil price plays a central role in the world economy and can heavily affect the business cycle and the resulting returns for stock- and bondholders, especially in the major oil importing countries.[2] Moreover, long-term paths of economic growth and capital accumulation are affected by the availability of oil.[3] Fast-growing emerging economies like China, in turn, have a significant impact on oil demand and prices.[4]

At the same time, growing concern over climate change drives attempts to limit global carbon emissions and potentially dangerous mean temperature increases, such as the 2015 Paris

---

[1] As of August 2016, the total volume of oil- and gas-related publicly known sovereign wealth funds was US $4,205 billion (SWFI 2016).

[2] Cf. Hamilton (1983, 2013), Kang et al. (2014), Cunado and Perez de Gracia (2014). Kilian (2009) points out in his econometric study that the magnitude of macroeconomic effects of an oil price shock depends on whether it is driven by the supply side, the demand side, or demand-side responses to an anticipated supply shock.

[3] Cf., from an empirical perspective, Berk and Yetkiner (2014) and Stern and Kander (2012); from a theoretical perspective, see Stiglitz (1974).

[4] Cf. Kilian and Hicks (2013) and Fouquet (2014).

Agreement. Naturally, these attempts threaten the oil exporters' revenues. Therefore, for climate policy to be effective, strategic reactions of suppliers of fossil fuels like oil must be taken into account. But, to date, there has been no systematic analysis of climate policy response by an oil supplier with market power[5] that takes into account the two-pillar nature of OPEC countries' strategic behavior and the interplay between both markets.

We analyze the extraction reaction of an oil monopolist with capital investments in the oil importing country to the introduction or increase of a carbon tax on oil imports in a two-country setting. We apply a general equilibrium approach to incorporate the interplay between the oil market and the capital market and to capture the crucial role of capital assets for an oil monopolist's climate policy reaction, which has been neglected in the literature to date. In doing so, we find a new channel for postponement instead of acceleration of oil extraction, due to tightening climate policy. In the literature on the supply-side of fossil fuel markets it has been pointed out that even the credible announcement of climate policies that are tightened over time could very well cause the opposite of the intended effect. The dire prospects for future profits would lead fossil fuel exporters to accelerate extraction in the present and thereby exacerbate climate-change-related damages, which is called the "Green Paradox".

In our general equilibrium model we distinguish between one country that only exports oil and another that imports oil and produces final goods. The time horizon is finite with two periods and we model climate policy with a carbon tax on oil imports. The interest rate and savings, which determine physical capital accumulation, are endogenously affected by oil supply, while the resulting capital stock drives oil demand and revenues for the exporting countries. We build on the scarce literature on fossil resource monopoly in general equilibrium[6], and especially on the framework and crucial role of capital assets in Marz and Pfeiffer

---

[5] There are, of course, many suppliers of oil in the world. But the market share of OPEC, which, according to Statista (2018), was 43.5% in 2017 and 48% in 2040 under the 450ppm carbon scenario (OECD 2014, p. 115, table 3.5), seems to suggest a significant degree of market power in the oil market. We focus on a pure monopoly as the opposite to perfect competition.

[6] Cf. Moussavian and Samuelson (1984) and Hillman and Long (1985), neither of whom considers climate policy.

(2015b).[7] In the present chapter, we introduce climate policy into this framework and analyze its implications for the monopolist's oil supply behavior.

Our key finding is that the simultaneous consideration of oil revenues and capital income gives rise to a new channel for postponement of extraction: the expected income loss due to future oil taxation leads the oil-rich country to increase its savings. This boosts the monopolist's capital asset motive in period 2 and creates an incentive to postpone oil extraction that can dominate the conventional acceleration incentive. In fact, postponement of extraction can be observed numerically for a wide range of plausible parameter settings. The magnitude of postponement can be considerable: in certain parameter settings present extraction drops by almost 30% for a future ad-valorem carbon tax corresponding to a carbon price of about 80 dollars per ton of carbon. The latter number is in line with estimates for the social cost of carbon by Anthoff et al. (2009) or Nordhaus (2010) and lies roughly in the middle of the wide range of estimates. Overall, we show that (even) an over time increasing carbon tax can be a viable policy option in contrast to conventional partial equilibrium analyses of climate policy instruments. Moreover, Sinn (2008) suggested a capital income tax to circumvent a potential acceleration reaction. In our framework with its emphasis on capital assets, however, we find that a capital income tax is no longer immune against undesired acceleration of extraction. Endogenizing cumulative extraction we identify another implication of the interaction of the capital and the resource market in general equilibrium: capital accumulation depends on the exploration investment decision. Accounting for this relationship, the monopolist may choose to reduce cumulative extraction even when reducing first period resource supply.

This chapter contributes to the literature on the supply-side reaction of fossil energy resources, and particularly oil, to a tightening climate policy that has developed since Sinn (2008). Indeed, in most cases (see, e.g. van der Ploeg and Withagen 2012a, 2012; Grafton et al. 2012), the

---

[7] Marz and Pfeiffer (2015b) show (without discussing climate policy) that the interaction of the capital and the resource market already has implications for the supply decision of a resource owner with market power if the monopolist is aware of the more widespread effects of resource supply in a general equilibrium setting (cf. also Bonanno (1990)). More specifically, additional supply motives arise from the interaction of these markets in general equilibrium and from the complementarity of physical capital and the fossil resource in final goods production. In particular, the monopolist takes into account the influence of resource supply on the return of her own capital assets, which are invested in the oil importing countries, and on capital accumulation with resulting feedbacks on capital and resource demand. Higgins et al. (2006) conclude that about half of the oil exporting countries' profits in the 2000s were invested in foreign assets and over different channels ended up in the U.S. In contrast to the conventional partial equilibrium view (cf. Stiglitz 1976) the arising general equilibrium supply motives mentioned above additionally affect the optimal supply path of a monopolist and lead it to deviate from the competitive outcome even for a constant demand elasticity and no extraction costs.

analysis of whether or not acceleration of extraction occurs is based on partial equilibrium models of the fossil resource market and thus does not take into account the role played by capital market adjustments in the extraction decision. We fill this gap. There are only few empirical studies testing the acceleration hypothesis. Di Maria et al. (2014) confirm the underlying mechanisms for the case of the reaction of coal supply to the introduction of the acid rain program in the U.S. But for coal, neither market power, nor capital assets play the prominent role, as in the case of oil. Curuk and Sen (2015) find an increase in oil trade as a reaction to raised R&D spending in renewable energy, but they also neglect the role of capital assets. For recent overviews of the literature on unintended supply-side effects of climate policy, see Jensen et al. (2015), van der Ploeg and Withagen (2015), and van der Werf and Di Maria (2011).

The strand of literature that we directly contribute to deals with supply-side effects of climate policy in general equilibrium, but to date neglects resource market power.[8] Van der Meijden et al. (2015) apply a model that is very similar to ours, but they consider a perfectly competitive oil market. In this sense, their paper and this chapter are complementing each other by looking at the respective extreme of monopoly or perfect competition. They show that general equilibrium feedback effects over a capital market can affect competitive supply-side reactions to an announced carbon tax and that extraction can be postponed for the specific assumption of asymmetric preferences in the importing and the exporting country. However, given that assuming (at least some) oil market power seems to be more realistic to us, we are able to reassess the role of capital asset holdings for the effects of climate policy. We thereby identify a completely new and different transmission channel of climate policy which also gives rise to postponement of extraction but holds even for the more general setting with symmetric consumption preferences. Moreover, in comparison to the competitive case, a more considerable postponement of extraction can be observed for a wider range of relevant parameter settings. Finally, while van der Meijden et al. (2015) point out that the familiar trade-off between postponement of extraction and increase in cumulative extraction (cf., e.g., Gerlagh (2011)) carries over to their general equilibrium setting with competitive supply we find that this no longer holds true with market power and the dependency of capital accumulation on cumulative extraction. The importance of the general equilibrium feedback

---

[8] Hassler et al. (2010) analyze climate policy in general equilibrium with resource market power. But their approach is only static and they neglect general equilibrium effects of climate policy on the resource supply side.

effects for the supply-side reaction to climate policy is also pointed out by van der Ploeg (2015). Long (2015) takes a slightly different perspective by discussing leakage effects from unilateral climate policies or, more generally, effects from trade in final goods or production factors that may either contribute to or counteract acceleration of extraction (see also, e.g., Eichner and Pethig 2011). In contrast to these studies, as well as Smulders et al. (2012) and Long and Stähler (2016), however, we account for oil market power.

We briefly summarize how additional effects of resource supply in general equilibrium (especially the capital asset motive) modify the monopolist's extraction decision in Section 2.2. In Section 2.3 we identify and interpret the mechanism that may lead to postponement of extraction. The theoretical analysis is complemented by a numerical simulation and sensitivity analysis in Section 2.4 so as to evaluate the prevalence of extraction postponement and the role of the most important parameters for the outcome. We analyze the effects of a capital income tax in Section 2.5 and discuss the implications of exploration costs for the effect of carbon taxation on first period and cumulative extraction in Section 2.6. Section 2.7 concludes.

2.2 The Monopolist's Extraction Behavior

The analysis in this Chapter is based on the model as it is described in Section 1.2 in Chapter 1. The difference now is that the resource import tax in the second period τ_2, which we interpret here as a carbon tax, is not neglected, but is in the focus of the study. To analyze the supply-side reaction to a carbon tax increase (see Section 2.3) we first summarize the extraction behavior in the present model with an oil import tax.

In the present study, the monopolist is omniscient in the sense that she takes all the information about general equilibrium feedback effects of her extraction decision via the endogenous adjustment of the capital stock on factor prices and incomes into account. A "naïve" monopolist would be unaware of these general equilibrium feedbacks and behave like in a partial equilibrium world. Our omniscient monopolist is benevolent and seeks to maximize the utility of households in country E, given the conditional market equilibrium:

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

subject to the resource constraint (1.2), the budget constraints (1.9) and (1.10) and the conditional market equilibrium represented by Equations (1.14), (1.15), and (1.16) and the corresponding equilibrium relationships between second-period resource supply and factor market prices (Equations (1.19) and (1.20)). Due to the binding resource constraint, the monopolist's optimization problem is one-dimensional ($R_2 = \bar{S} - R_1$). Moreover, the representative household in country E makes optimal saving decisions for any set of resource income streams and interest rates taking them as given. Therefore, the Euler equation (1.11) holds for any resource supply path chosen by the omniscient monopolist.[9]

Thus, substituting the marginal rate of substitution from the Euler equation (1.11) into the first-order condition and simplifying the first-order condition for the optimal resource supply path gives the modified Hotelling rule

$$(1+i_2)\left[p_1 + \frac{\partial p_1}{\partial R_1}R_1 + \frac{\partial i_1}{\partial R_1}s_{0E}\right] = \tilde{p}_2 + \frac{d\tilde{p}_2}{dR_2}R_2 + \frac{di_2}{dR_2}s_{1E} \tag{2.1}$$

where $\frac{d\tilde{p}_2}{dR_2} = (1-\tau_2)\frac{dp_2}{dR_2}$ for an ad-valorem resource tax (and $\frac{d\tilde{p}_2}{dR_2} = \frac{dp_2}{dR_2}$ for a unit resource tax). Interestingly, there appears no derivative of the market discount factor $(1+i_2)$ in the modified Hotelling rule (2.1), although the oil monopolist accounts for her influence on the capital return i_2. This is due to the fact that the discount factor $(1+i_2)$ derives from the separate savings decision of the households (cf. Euler equation (1.11)) which act as price takers on the capital market. In benevolently maximizing household utility in country E the monopolist takes the households' Euler equation (1.11) as given.

From the monopolist's perspective, the overall marginal resource value consists of the marginal resource revenue and the marginal capital income effect of resource supply:

$$MV_t^{\tau} = \tilde{p}_t + \frac{d\tilde{p}_t}{dR_t}R_t + \frac{di_t}{dR_t}s_{(t-1)E} = (1-\tau_t)MR_t + \frac{di_t}{dR_t}s_{(t-1)E} \tag{2.2}$$

---

[9] See Appendix A.2 for a more extensive presentation of the monopolist's optimization problem.

with $\frac{dp_1}{dR_1}$ from (1.17), $\frac{di_1}{dR_1}$ from (1.18), $\frac{d\tilde{p}_2}{dR_2} = (1-\tau_2)\frac{dp_2}{dR_2}$ from (1.19), $\frac{di_2}{dR_2}$ from (1.20), and the marginal oil revenue before taxes MR_t.[10] As in the standard resource extraction problem, the modified Hotelling rule requires that the present value of the *overall marginal resource value* (not marginal resource revenue) is equal in both periods. A key conclusion of Chapter 1, which is important here, is that an omniscient benevolent monopolist accounts for the influence of her oil supply on the return on capital assets of country E's households. In the modified Hotelling rule (2.1), this capital asset motive is present in each period, represented by the terms $\frac{\partial i_1}{\partial R_1} s_{0E}$ and $\frac{di_2}{dR_2} s_{1E}$. The endogeneity of the capital stock in period 2 is included in the factor price reactions $\frac{d\tilde{p}_2}{dR_2}$ and $\frac{di_2}{dR_2}$ and additionally modifies the supply pattern compared to that of a naïve partial equilibrium monopolist.

2.3 Policy Analysis

Given the modified supply decision as characterized above, we discuss the effect of future climate policies on the extraction path chosen by the benevolent and omniscient monopolist. By use of a comparative statics analysis we show that a marginal increase in the future resource tax may induce postponement of resource extraction due to the asset motive, and elaborate on the drivers of this result. We also show that the reaction of resource supply to a future resource tax increase is monotonous in the tax rate. This allows us to consider discrete increases in the tax rate.

2.3.1 Supply Reaction to Future Climate Policy

The modified Hotelling rule (2.1) enhances the extraction decision with additional motives and market reactions that the monopolist takes into account, particularly the capital asset motive (cf. Section 2.2). It appears that these additional considerations also affect the monopolist's reaction to future climate policies. We evaluate the change in the extraction path by use of

---

[10] In the case of an ad-valorem resource tax, we have

$$MV_2^{\tau} = (1-\tau_2)\left[p_2 + \frac{dp_2}{dR_2}R_2\right] + \frac{di_2}{dR_2}s_{1E}$$

whereas for a unit resource tax

$$MV_2^{\tau} = p_2 + \frac{dp_2}{dR_2}R_2 - \tau_2 + \frac{di_2}{dR_2}s_{1E}$$

comparative statics with respect to a marginal increase in the resource tax in period 2 and obtain the following proposition.

Proposition 2.1. *The reaction of the equilibrium extraction path to an increase of the future ad-valorem tax is given by*[11]

$$\frac{dR_2^*}{d\tau_2} = \frac{-MR_2 + \frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2}}{\frac{d[(1+i_2)MV_1]}{dR_2} - \frac{dMV_2^{\tau}}{dR_2}} \gtreqless 0 \tag{2.3}$$

Pursuing the asset motive while savings adjust endogenously can lead the monopolist to postpone resource extraction upon a future tax increase.

Proof. See Appendix B.2. □

The denominator of (2.3) measures how the Hotelling condition (2.1) changes with a marginal adjustment of the extraction path and is always positive (cf. Appendix B.2). The following analysis thus focuses on the numerator. The numerator captures the direct effects of the tax change on the two components of MV_2^{τ} (cf. Equation (2.2)): the resource income component given by the general equilibrium marginal resource revenue and the capital income component introduced by the asset motive. Since the conditional market equilibrium does not directly depend on the resource tax for symmetric homothetic preferences, there are no direct effects of a tax change on (1.17), (1.18), (1.19), and (1.20).

We start by considering the direct effect of the resource tax increase on the capital income component, which is captured by the last term in the numerator of (2.3) and arises for the ad-valorem tax, as well as for the unit resource tax case. Raising the resource tax for a given consumer resource price p_2[12] leads to a pure redistribution of income, or resource rents, from country E to country I, which is measured by $\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2} < 0$. This income redistribution is completely neutral with respect to aggregated capital accumulation for symmetric homothetic consumption preferences, as we have already discussed, but not with respect to the savings in both countries. The representative household in country E – having rational expectations – correctly foresees the loss in its future period's resource income. Since $\frac{\partial s_{1E}}{\partial \pi_{2E}} < 0$ from (1.12),

---

[11] The asterisk "*" in R_2^* indicates the monopolist's optimal extraction path (R_1^*, R_2^*).

[12] Recall that the numerator measures the effect of the tax rate increase for a given extraction path.

the household reacts to this anticipated income loss by *increasing* its savings so as to smooth consumption over time given its constant first-period income.[13]

Regarding the monopolist's extraction incentives, the larger savings directly strengthen the asset motive in the second period because the marginal return on resource supply in the second period, in terms of the capital income gain, is larger. From the monopolist's perspective, therefore, the value of the future period's resource supply increases. This creates an incentive for the monopolist to shift oil extraction into the future. Thus, the resource-tax-induced adjustment of the future asset holdings unambiguously works toward postponement of extraction if the monopolist pursues the asset motive.[14]

The marginal resource revenue before taxes MR_2 in the numerator of (2.3) captures the effect of a marginal increase in the resource tax on the resource income component of the marginal resource value MV_2^{τ} from (2.2). Note that (2.3) gives the comparative statics for the effect of an ad-valorem resource tax. In the case of a unit resource tax, the marginal effect of a tax increase on the marginal resource revenue, that is, on the resource income component, would be -1. But for a unit tax, the marginal effect of a tax increase on the exporting country's saving behavior and, thus, on the capital income component is different, too.

If the marginal resource revenue is positive, both tax policies have the same qualitative effect. An increase in the resource tax reduces the marginal oil revenue and thereby creates an incentive for the monopolist to shift resources from the future to the present. It is exactly this devaluation of future resource supply that drives the unintended acceleration of extraction upon the introduction or strengthening of future climate policies in a standard partial equilibrium framework. The same holds true if we consider a naive resource monopolist instead of the omniscient monopolist in our general equilibrium setting.[15]

---

[13] In turn, the households in country I will decrease their savings due to the higher resource tax revenue and thereby will exactly compensate for the larger capital supply from country E so that overall the capital stock remains unaffected by the tax increase.

[14] Note that this postponement incentive must not be confounded with the endogenous adjustment of the market interest rate in general equilibrium, which occurs as soon as the tax policy triggers a change in the extraction path. The latter general equilibrium feedback is already known from the competitive resource market case in van der Meijden et al., 2015 and is also present in our monopoly setting.

[15] Note, however, that, in contrast to these conventional approaches, in our general equilibrium framework the marginal resource revenue from the omniscient monopolist's perspective not only includes the direct own price effect of resource supply but also the indirect price effect via the endogeneity of capital accumulation as we have $\frac{dp_2}{dR_2}$ from (1.19) instead of $\frac{\partial p_2}{\partial R_2}$.

Overall, if the marginal oil revenue is positive, there are two counteracting effects, so that the marginal tax effect is generally of ambiguous sign. If the strengthening of the asset motive via the endogenous savings reaction dominates the reduction in the marginal resource revenue in the resource market, the future marginal resource value to the monopolist will increase and the monopolist will be induced to shift resources to the period in which the resource is taxed more heavily and thus extraction is postponed. This supply reaction is exactly opposite to the one in a comparable partial equilibrium framework, that is, monopolistic resource extraction, without extraction costs, and opposite to the naive monopolist who does not pursue the asset motive. It crucially depends on the endogeneity of savings with respect to future resource income (π^{τ}_{2E}).

As a very rough numerical illustrative example, we can conduct a similar exercise as found in van der Meijden et al. (2015): with a stock of oil of $\bar{S} = 1$ (corresponding to a global carbon stock of 150 billion tons in the form of oil reserves (cf. Abdul-Hamid et al. 2013)), an ad-valorem carbon tax on oil of $\tau_2 = 0.8$ corresponds to a carbon price of 80 dollars per ton of carbon and leads to a drop in present oil extraction of almost 30%.[16] When the monopolist, however, neglects the capital market channel, then the same tax in this example in contrast leads to an increase of present oil extraction by approximately 20%.[17] The magnitude of the extraction shift can vary substantially with different model parameters, but large effects, like in this example, are possible for plausible parameter settings.

2.3.2 Inelastic Oil Demand

Empirical evidence suggests that oil demand is inelastic (cf. the overview in Hamilton 2009 and Kilian and Murphy 2014). In this case, marginal oil revenue MR_t is negative. Nevertheless, and in contrast to most of the literature on resource monopoly (cf. Stiglitz, 1976 and Tullock, 1979),

---

[16] This is the biggest relative change in present extraction that we have observed in our model for still roughly reasonable parameter values and should be seen as a sort of upper bound for the effect's magnitude. The first-period output of $F_1 = 2650$ in the model corresponds to approximately 33 years multiplied by US $79.6 trillion world GDP (cf. CIA 2014)). Other model parameters for this example are: utility discount factor $\beta = 0.3$ corresponding to a time preference rate of 0.0375 over the length of period 1 of 33 years and an elasticity of intertemporal substitution $\frac{1}{\eta} = 0.5$, capital asset endowments $s_{0E} = 20$ and $s_{0I} = 180$, labor input $L = 1$, the productivity parameters $\lambda = 0.05$ (oil) and $\gamma = 0.45$ (capital), the elasticity of factor substitution $\sigma = 0.95$, and total factor productivity $A = 300$.

[17] Note that "the monopolist neglecting the capital market channel" means that the initial equilibrium for a tax of zero is also slightly different.

in our framework inelastic oil demand[18] can be consistent with the assumption of resource scarcity (1.2): due to the positive contribution of the capital asset motive, the overall marginal value of oil MV_t^τ (cf. (2.2)) can still be positive. Considering the effect of an *ad-valorem resource tax* under these circumstances leads to the following proposition.

Proposition 2.2. *In the case of inelastic resource demand the increase of an ad-valorem resource tax will always lead to postponement of extraction (*$\frac{dR_2^*}{d\tau_2} > 0$*).*

Proof. See Appendix B.2. □

This case can only occur for an ad-valorem resource tax that reduces the *negative* contribution of MR_2 to the total income in country E and therefore *raises* the future marginal resource value MV_2^τ. This creates an incentive for extraction postponement. The (negative) marginal resource revenue MR_2 increases in absolute terms because a higher ad-valorem resource tax lowers the negative effect of resource supply on the oil price for the infra-marginal resource quantities sold.[19] Since the induced savings reaction already creates an incentive to postpone extraction, negative marginal resource revenue is a sufficient condition for unambiguous postponement of extraction. In contrast to the unit tax case and the price elastic resource demand case, the endogenous savings reaction is no longer crucial for a postponement reaction in the case of inelastic oil demand.

Andrade de Sá and Daubanes (2016) suggest the notion of permanent limit-pricing to deter market entry of competitors in a partial equilibrium framework to reconcile monopolistic oil supply behavior with inelastic oil demand. In their setting, a carbon tax increase has no effect on the oil extraction path. In contrast to them, our extended general equilibrium supply behavior always yields a postponement reaction to a carbon tax increase with inelastic oil demand.

The possibility that a higher tax increases the future marginal resource value MV_2^τ also has an interesting implication for our scarcity assumption (1.2): the resource constraint may become binding only with an increase in the tax rate.[20] Contrary to our scarcity assumption, the

---

[18] Our notion of demand elasticity already takes into account endogenous adjustment of the capital stock and the resulting changes in the demand curve in period 2.

[19] Resource demand after taxes becomes more price elastic from the monopolist's perspective, which increases the marginal resource revenue. Note also that in the case of an ad-valorem resource tax and inelastic resource demand, climate policy induced postponement of extraction at the margin may even reduce the absolute carbon tax revenue collected.

[20] Simulations confirmed the possibility of such cases.

resource can be so abundant before the policy intervention, that fully exhausting the stock would lead to a negative marginal resource value ($MV_t^\tau < 0$), even accounting for the capital asset motive. In this case, the monopolist leaves a part of the resource stock in the ground. But the policy-induced rise in marginal resource value MV_2^τ increases aggregate extraction and possibly leads to complete extraction of the resource stock. Total carbon emissions would rise in this case.

2.3.3 Discrete Tax Changes

The ambiguity of the numerator in (2.3) suggests that a borderline case is possible in which resource taxation is completely neutral so that the (discrete) introduction of the resource tax policy would not alter the extraction path. The comparative statics in (2.3), however, characterize the local effect of a marginal increase in the resource tax. We can draw a conclusion about such a non-marginal tax policy change based on the (marginal or local) comparative statics analysis. For the symmetric country case, this is, as long as the transfer of resource rents does not affect aggregate capital accumulation, the following proposition holds true.

Proposition 2.3. *The effect of the resource tax on second-period resource supply is strictly monotonous for symmetric homothetic consumption preferences.*

Proof. See Appendix B.2. □

Therefore, the sign of the tax reaction is the same for marginal and large discrete changes in the tax rate, irrespective of the initial tax path over time.[21] The monotonicity of second-period resource supply now allows us to explain an intertemporally neutral tax policy by just considering the marginal tax effect. By the monotonicity we may also interpret (2.3) for an initially time-constant ad-valorem resource tax in *both* periods or the case where initially there is no resource taxation at all. This gives us the following proposition. An analogue proposition holds for the unit tax case.

---

[21] In an extreme case, if the tax rate is set high enough, our model framework could reach its limits: if the tax burden in period 2 becomes too high, then the monopolist in the present model might be better off only extracting oil in period 1, even if this means reducing period 2 output to zero. In reality, the role of oil substitutes and green or dirty backstop technologies would be crucial in this context. However, this extension is beyond the scope of this chapter and we leave it for future research. Also, we excluded the case of extraction in only one period in Section 1.2.1.1. Within these limits of our model's explanatory power, the monotonicity result holds. At very high tax rates, the monopolist continues to supply oil in order to secure his capital asset income stream.

Proposition 2.4. *In contrast to the standard case of a naïve monopolist without extraction costs, even an over time increasing ad-valorem resource tax or the introduction of an ad-valorem resource tax in the future may have no effect on the equilibrium extraction path due to the asset motive and the endogeneity of savings.*

Neither an over time increasing ad-valorem resource tax nor the introduction of an ad-valorem resource tax in the second period will induce any adjustment of the extraction path if the numerator in (2.3) is exactly zero, that is, both elements must be counteracting. This holds true as long as the marginal resource revenue is positive and exactly compensates the second term $\frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2}$. By the monotonicity of the tax reaction we know that if a marginal change in the future resource tax does not induce any adjustment of the extraction path, this must also be true for a discrete increase in the resource tax or, similarly, for the introduction of a resource tax in the second period. In fact, irrespective of the tax rate, resource taxation will always be without effect with respect to the extraction path in this case. Generally, this result is in contrast to the resource economics literature. From there we know that (without extraction costs) only a time-constant ad-valorem resource tax rate does not create any incentive to reallocate resources between periods both for a competitive resource sector and for a resource monopolist (see, e.g., Dasgupta and Heal 1979).[22]

2.4 What Drives Postponement of Extraction?

We conduct a numerical sensitivity analysis to carve out the role that different model parameters are playing in the policy reaction. Due to monotonicity of the tax effect on extraction (cf. Section 2.3.3) the strictness of the carbon tax policy does not have any influence on whether extraction is postponed or accelerated. Instead, the direction of the extraction shift depends on the resource demand side, on capital demand and supply, and on the interaction of these markets. As the following analysis shows, the parameters of the production technology, that is, the elasticity of substitution σ and the productivity parameter of oil λ, have a profound influence on the policy reaction in our model. They are in the focus our analysis. In contrast, the influence of the factor endowments K_1 and $\bar{S}$, the parameters of the households' utility

---

[22] Note that, without the assumption of symmetric preferences, monotonicity of the tax reaction is not guaranteed. The reason is that the tax then is no longer neutral with respect to aggregate savings. Therefore, the result that the reaction of the extraction path to a tax increase can be zero *independently of the tax rate* does not necessarily hold with asymmetric preferences. But as a special case or locally at a specific tax rate it may still occur.

function β and η, and the distribution of the initial capital asset endowment $\frac{s_{0E}}{K_1}$ is very small at values of the productivity parameter of oil λ lower than 0.1 and more pronounced at higher values (The sensitivity analysis with respect to these parameters can be found in the online Appendix B.6). However, values of λ higher than 0.1 are less consistent with empirical observations: the reason is that λ is closely related to oil's income share in the model (θ_{tR}),[23] which, in the real world, has been below 10% throughout the recent decades.[24]

Tightening the climate policy will lead to a postponement of oil extraction if the increase in savings and the accompanying strengthening of the second-period asset motive overcompensate the larger tax deduction. Thus, the numerator of (2.3) must be positive:

$$-MR_2 + \frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2} > 0 \tag{2.4}$$

Our simulations show that extraction postponement is a robust outcome of an announced future carbon tax increase in our model even if we choose $\lambda < 0.1$ and $\sigma < 1$, which is most consistent with empirical observations.

2.4.1 The Role of the Elasticity of Substitution

In our framework, the crucial relationship between the capital market and the oil market is strongly dependent on the production technology and is thereby particularly characterized by the elasticity of substitution σ. In general, the elasticity of substitution determines the mutual dependency of resource and capital demand via the substitutability of capital and fossil resources in final goods production ("substitutability effect"), but also the overall production possibilities given the capital and resource endowments ("scale effect"). Transforming (2.4) by use of (1.19) and (1.20) and standard properties of the CES production function demonstrates that the monopolist postpones extraction if the substitution elasticity σ lies below the

---

[23] In the case of Cobb-Douglas production (substitution elasticity $\sigma = 1$) λ corresponds to the income share of oil θ_{tR}. For $\sigma < 1$ (deviating from Cobb-Douglas production), our simulations showed that a realistic expenditure share of oil $\theta_{tR} < 0.1$ corresponds to parameter settings with $\lambda < 0.1$. For the productivity parameters of oil and capital we assume throughout the simulations $\lambda + \gamma = 0.5$. This is motivated by the fact that the income share of labor in global GDP amounts to at least 50% according to OECD (2015).

[24] According to data by World Bank Group (2016) the ratio of global oil rents to world GDP in the period 1970 to 2014 was between 0.5% (1970) and 5.5% (1980). Oil expenditures as a share of GDP peaked at 6.6% (1981) for the U.S. and at 5.3% for the aggregate of OECD countries except the U.S. (cf. Figure B.1 in Appendix B.3).

following threshold:[25]

$$\sigma < 1 - \theta_{2R}\left(1 + i_2 \frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}}\right) - \frac{dK_2}{dR_2}\frac{R_2}{K_2}\left(\theta_{2K} + (\theta_{2K} - 1) i_2 \frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}}\right) \tag{2.5}$$

with the future income share of oil θ_{2R} and the future income share of capital θ_{2K}. This postponement condition is compatible with a positive marginal resource value MV^{τ}_t. Numerical simulations show that the postponement condition indeed holds for many parameter settings with $MV^{\tau}_t > 0$: in Figure 2.1 we vary the elasticity of factor substitution σ and the productivity parameter of oil λ to map the according tax reaction to a discrete increase of an ad-valorem tax from $\tau_2 = 0$ to $\tau_2 = 0.1$. The corresponding figure for a unit tax can be found in Appendix B.5. In the following, we discuss the influence of σ with the help of condition (2.5).

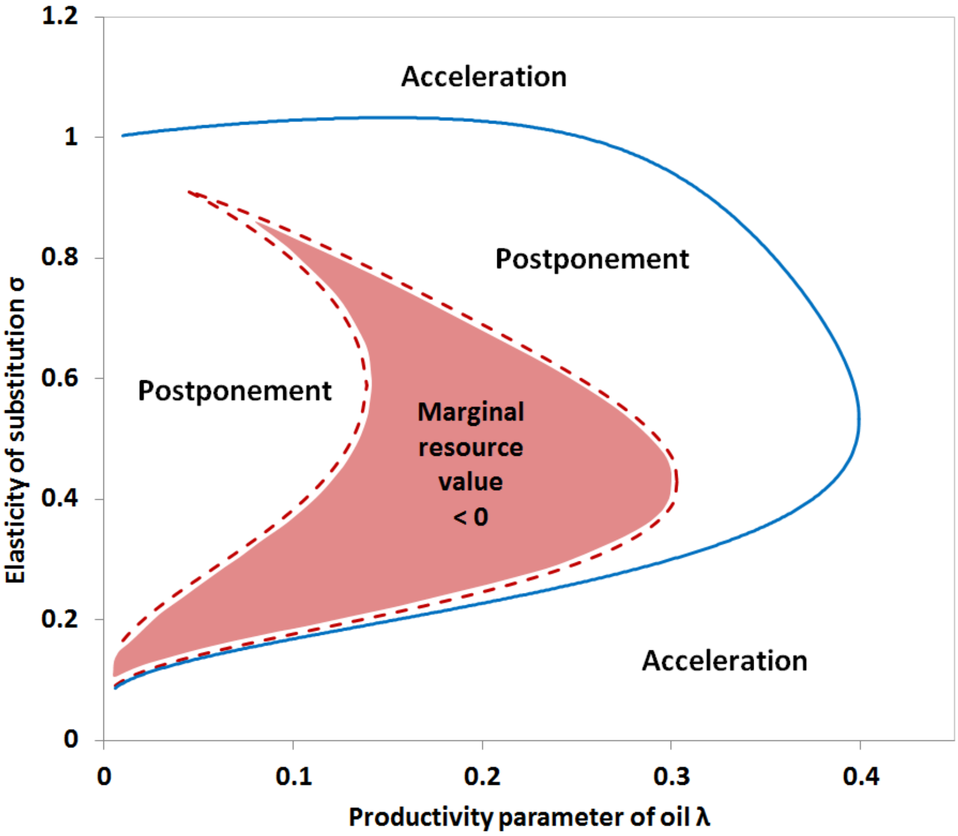

Figure 2.1 : Zones of acceleration and postponement of extraction over the elasticity of substitution σ and the productivity parameter of oil λ for an ad-valorem tax.[26]

---

[25] This threshold itself changes with σ, but nevertheless allows for some interpretation. The variables θ_{2R} and θ_{2K} (both < 1) denote the output shares of the resource and of capital, respectively, in the second period.

[26] Parameter values used in the simulation: $\beta = 0.3, \eta = 2, s_{0E} = 20$, and $s_{0I} = 180$, yielding $K_1 = s_{0E} + s_{0I} = 200$, $\bar{S} = 1$. In all shown simulations the TFP parameter from (1.3) is $A = 300$ and the labor input is $L = 1$.

With $-1 < i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} < 0$ (see (1.12)), the postponement condition (2.5) means that if the monopolist was ignorant about her influence on the capital stock dynamics $\frac{dK_2}{dR_2}$ (cf. (A.3) in Appendix A.1.3), then the border line between acceleration and postponement of extraction would lie in the area $\sigma < 1$. But given that the monopolist takes account of the general equilibrium feedback between the factor markets and that $\frac{R_2}{K_2}\left(\theta_{2K} + (\theta_{2K} - 1) i_2 \frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\right)$ is always positive, we obtain the following result: the feedback effect from the endogeneity of the second-period capital stock in general equilibrium works toward a postponement (acceleration) of extraction if $\frac{dK_2}{dR_2} < 0$ ($\frac{dK_2}{dR_2} > 0$). Intuitively, for $\frac{dK_2}{dR_2} < 0$ the price elasticity of resource demand is greater (reducing the acceleration incentive of the marginal resource revenue MR_2 in (2.3)) and $\frac{di_2}{dR_2}$ is stronger (increasing the postponement incentive from the savings reaction in (2.3)).

An analysis of the limits of $\frac{dK_2}{dR_2}$ for $\sigma \to \infty$ (see Appendix B.4) shows that the right side of (2.5) is bounded from above in any case so that the postponement condition must be violated for sufficiently increasing σ above unity. The change in production structure brought about by the rising elasticity of substitution and reflected in the change of the price elasticities of oil and the cross-price elasticity of capital demand prevents postponement of extraction for sufficiently high σ. Therefore, technological change in the form of an increase in the elasticity of substitution can increase the possibility that a future carbon tax will accelerate oil extraction and undermine mitigation goals. In contrast, a better substitutability of oil is often seen as necessary to overcome the dependency of economic growth and development on fossil resources and to make climate change mitigation compatible with economic growth in the long run.

A decrease in the elasticity of substitution σ until the extreme case of a Leontief production function at $\sigma = 0$ shows that the resource scarcity is of crucial importance for the direction of the tax-induced extraction shift. The higher the scarcity of the resource compared to other production factors, the higher the marginal resource revenue MR_t and the stronger the incentive to accelerate extraction after a tax increase. When approaching the Leontief case, the scarcest factor increasingly dominates production. If the resource is not the binding factor in the Leontief economy, then the resource will stop to be scarce at some value of σ (which

---

Remember, that, due to monotonicity of the extraction path's reaction to a tax increase (see Section 2.3.3), the level of the tax rate τ_2 does not affect the borderline between the acceleration zone and the postponement zone in the figure. In the shaded area the resource is abundant in the sense that $MV_t^{\tau} < 0$ for $\tau_2 = 0$ if the monopolist was forced to completely extract the stock. Recall from Section 2.3.2 that for a higher τ_2 before the policy intervention the shaded area is smaller.

we excluded from the outset), the marginal value of the resource will fall below zero, and the monopolist will have an incentive to leave a part of the resource in the ground. If the resource is scarce in the Leontief case ($R_t < L_t$, capital was chosen to be always abundant), then the marginal resource revenue at low values of σ will be rising with a decrease in σ. Given that $\frac{di_2}{dR_2}$ approaches zero for $\sigma \rightarrow 0$ and that the asset motive becomes vanishingly small, extraction will then necessarily be accelerated for $\sigma \rightarrow 0$.

2.4.2 Productivity Parameter of Oil λ

The productivity parameter of oil λ denotes the weight of oil in the production function and corresponds to the income share of oil in the Cobb-Douglas case ($\sigma = 1$). When shifting weights between oil (parameter λ) and capital (parameter γ) in the production structure for the sensitivity analysis we assumed that these two parameters together sum up to 0.5 and that the productivity parameter of capital γ is at least 0.1, while the one of labor is always 0.5. Increasing the weight of oil thus always implies reducing the weight of capital.

An increase of λ has two effects: first, it directly raises the marginal resource revenue MR_t and the monopolist's losses via the carbon tax increase. This contributes to acceleration of extraction. Second, it affects the complementarity between both factors and, therefore, the postponement incentive: since the capital endowment in the numerical example is significantly higher than the resource endowment (200:1), the complementarity is highest at a rather low value of λ (a high value of γ) and falls with a further increase of λ.[27] Thus, at low (high) values of λ (in the case $\sigma < 1$) the postponement incentive due to the complementarity is strong (weak) and the acceleration incentive is weak (strong), overall making postponement more (less) likely (cf. Figure 2.1). For sufficiently low λ, oil demand can even be inelastic, so that extraction is unambiguously postponed (cf. Section 2.3.2[28]).

There is an interesting implication for the case of inelastic oil demand ($MR_t < 0$) with even a negative marginal value of oil ($MV_t < 0$, shaded area in Figure 2.1), so that, initially, a part of the resource is left in the ground: if technological progress makes the production technology less dependent on oil and λ decreases, then it is possible that the economy moves from the

---

[27] In fact, when λ, starting at zero, is rising, then factor complementarity will first increase quite quickly until it reaches its peak value. For this reason, the upper part of the boundary line between the postponement zone and the acceleration zone in Figure 2.1 is slightly rising when λ rises above zero. Only with a further increase in λ the complementarity driven postponement incentive weakens.

[28] For $\sigma > 1$, oil demand is always elastic.

shaded area in Figure 2.1 to the left into the non-shaded area. Here the resource is scarce again and extracted completely due to the prominent role of factor complementarity and the capital asset motive. Similar to technological change in the form of rising σ, increasing resource efficiency in this case would, paradoxically, lead to higher resource extraction and carbon emissions.

2.5 Capital Income Tax

To avoid an unintended acceleration of extraction, Sinn (2008) suggests a capital income tax on assets owned by the oil supplying countries. In his framework, such a policy-driven reduction in the exporting countries' capital returns slows down extraction. Throughout the present chapter we emphasize the prominent role of capital assets for the supply-side effect of climate policies. Naturally, the question arises whether the interaction of the oil market and the capital market and the resulting modified monopolistic supply behavior in general equilibrium change the effect of taxing the capital returns of resource-rich countries.

The government of the oil importing country levies a tax κ_2 on the capital market returns of country E's assets in period 2 (cf. Habla 2016, who analyzes a capital income tax with a competitive oil market in general equilibrium). Capital assets of country E, thus, yield an effective interest rate of $i_2(1-\kappa_2)$ instead of i_2. Capital income of households in country I, however, is not taxed. The tax revenues are distributed in a lump-sum fashion among the households of country I. To understand the effects of the capital income tax, we have to answer two questions: how does the tax affect the savings of country E s_{1E} and the aggregated capital stock K_2? And what are the resulting consequences for the monopolist's optimal oil extraction path?

Proposition 2.5. *The reaction of the monopolist's optimal resource supply path to an increase in the future capital income tax κ_2 is determined by several counteracting effects, so that the sign of the overall reaction is ambiguous:*

$$\frac{dR_2^*}{d\kappa_2} = \frac{\frac{\partial}{\partial\kappa_2}\left(\frac{dp_2}{dR_2}\right)R_2 + \frac{\partial}{\partial\kappa_2}\left(\frac{di_2}{dR_2}\right)s_{1E} + \frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial\kappa_2} + i_2 MV_1}{\frac{d[(1+i_2(1-\kappa_2))MV_1]}{dR_2} - \frac{dMV_2^{\kappa}}{dR_2}} \gtreqless 0 \tag{2.6}$$

Proof. To derive the comparative statics (2.6), we totally differentiate (2.1) with respect to R_2 and κ_2 taking into account $dR_1 = -dR_2$ by (1.2) and (1.17), (1.18), (1.19), and (1.20). The denominator of (2.6) is strictly positive (cf. Appendix (A.2)). Like in Sinn (2008), a decrease in the effective interest rate for country E contributes to a postponement of extraction (positive term $i_2 MV_1$). Due to the asset motive and the endogeneity of savings in both countries, however, there are additional effects of a capital income tax in our setting. First, the capital income holdings in country E may increase or decrease due to an income effect and a counteracting substitution effect induced by the capital income tax (ambiguous term $\frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \kappa_2}$). If an increase in the future capital income tax leads to a decrease (an increase) in capital assets of country E, then it weakens (strengthens) the second period's capital asset motive and creates an incentive to accelerate (postpone) oil extraction. Second, the aggregate capital stock K_2 is unambiguously reduced by the capital income tax. The reason is that only the substitution effect in country E changes the aggregate capital stock K_2. The income effect only implies a redistribution of income from country E to country I, which is neutral due to symmetric homothetic preferences. The reduction of the capital stock K_2 affects both, the slope of the oil demand curve $\frac{dp_2}{dR_2}$ and the influence of oil supply on the interest rate $\frac{di_2}{dR_2}$ (cf. (1.19) and (1.20)) in our general equilibrium model. However, both terms ($\frac{\partial}{\partial \kappa_2}\left(\frac{dp_2}{dR_2}\right)$ and $\frac{\partial}{\partial \kappa_2}\left(\frac{di_2}{dR_2}\right)$) have ambiguous signs. Thus, the sign of (2.6) is ambiguous. □

With several ambiguous and potentially counteracting terms in the numerator of (2.6) the overall effect of a change in the capital income tax on the optimal extraction path is no longer analytically tractable. However, numerical simulations show that the introduction of a capital income tax can indeed lead to the intended postponement of extraction. But, in our general equilibrium setting, extraction can also be accelerated for a wide range of parameters (cf. Figure 2.2).

The curvature of the utility function η, or its inverse, the elasticity of intertemporal substitution $\frac{1}{\eta}$, plays a significant role in the outcome: it determines the relative weights of the income and the substitution effect in country E and, thus, country E's savings reaction to the capital income tax. For lower values of η, the substitution effect of the interest rate reduction, which is caused by the capital income tax, dominates the income effect and country E reduces its capital assets s_{1E}. The monopolist's future capital asset motive is weakened, which creates an incentive to accelerate extraction. The elasticity of factor substitution σ also has a significant influence on the oil supply reaction to the introduction of a capital income tax on assets held by country E.

Similar to the carbon tax case, the observations of partial equilibrium models with respect to the supply-side reaction to a capital income tax policy can be reversed if the analysis

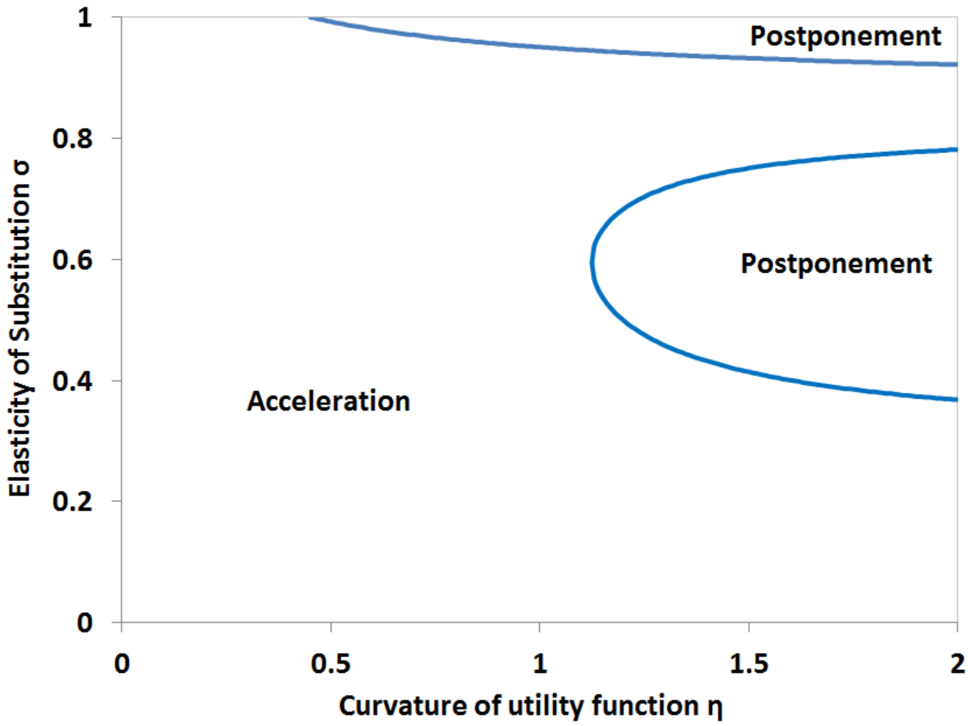

Figure 2.2 : Effect of a capital income tax on the equilibrium extraction path ($\beta = 0.3$, $K_1 = s_{0E} + s_{0I} = 20 + 180 = 200$, $\bar{S} = 1$, $\lambda = 0.1$).

accounts for a capital asset motive of a monopolistic oil supplier and endogeneity of savings in general equilibrium. As a result, the capital income tax policy might have counterproductive consequences. If both, the carbon tax and the capital income tax lead to postponement of oil extraction, then the carbon tax, which directly targets the climate externality, is preferable to the capital income tax in welfare terms. This is because the capital income tax distorts the capital market and dampens capital accumulation, whereas the carbon tax with symmetric homothetic preferences has no such effect.

2.6 Cumulative Extraction

Not only short term emissions but also cumulative extraction is crucial for mitigation of climate change. To study the role of market power given the general equilibrium interdependencies of the resource and the capital market for the effects of carbon taxation on cumulative extraction we introduce exploration activities into our framework. We assume that the resource stock available for extraction over both periods is a function of exploration investments X with

$S_1(X)$ and $S_1'(X) > 0, S_1''(X) < 0$. Exploration expenditures reduce first period's resource profits ($\pi_{1E} = \tilde{p}_1 R_1 - X$) so that the budget constraint (1.9) is modified.[29]

The (benevolent) monopolist now faces a two-dimensional maximization problem

$$\max_{R_2, X} u(c_{1E}) + \beta u(c_{2E}) \qquad \text{subject to } R_1 = S_1(X) - R_2$$

The monopolist thereby takes into account that exploration investments and endogenous cumulative extraction modify the conditional market equilibrium from Section 1.2.3, as we discuss in Appendix B.1. More specifically, the equilibrium future resource and capital prices are each functions of the cumulative resource supply represented by X and the intertemporal resource supply for a given resource stock explored represented by R_2, in contrast to (1.19) and (1.20).[30]

The equilibrium outcome is now characterized by two first-order conditions which are derived analogue to Section 2.2 for the modified conditional market equilibrium. First, the optimal intertemporal supply path *given* some exploration investments X is again characterized by Hotelling rule (2.1).[31] Second, for an ad-valorem oil tax optimal exploration efforts, and thereby optimal cumulative supply over both periods, are such that[32]

$$S_1'(X) MV_1 - 1 + \frac{1}{(1+i_2)} \left. \frac{dK_2}{dX} \right|_{R_2} \left[(1-\tau_2) \frac{\partial p_2}{\partial K_2} R_2 + s_{1E} \frac{\partial i_2}{\partial K_2} \right] = 0 \tag{2.7}$$

with MV_1 defined as in (2.2). To interpret this first-order condition, note that we set $R_1 = S(X) - R_2$ and therefore that for any given R_2 an increase in exploration investments directly raises R_1. Condition (2.7) states that in equilibrium further exploration must not be of any positive net value to the monopolist at the margin. The net present value of exploration expenditures for given R_2 comprises two different elements. First, an increase in exploration efforts incurs costs of -1 at the margin but raises R_1 by $S'(X)$ which, similar to more standard settings, has a present value of MV_1 from the monopolist's perspective. Second, as captured by the last term in (2.7), physical capital accumulation adjusts to a change in exploration

---

[29] Like in the case without exploration costs, we still assume $\tau_1 = 0$.

[30] To indicate that and to clearly separate the influence of both choice variables R_2 and X, we use the notation $\left. \frac{dp_2}{R_2} \right|_X$, for example, to redefine (1.19). Also see Appendix B.1.

[31] Note that strictly speaking the Hotelling rule now is defined for given exploration expenditures X.

[32] For a unit tax, $(1 - \tau_2)$ drops out and condition (2.7) does not directly depend on the tax rate.

activities for a given second period supply R_2 which is indicated by the term $\frac{dK_2}{dX}\big|_{R_2}$ defined in Appendix B.1 and influences future resource and capital income of country E at the margin.

Since the influences of capital accumulation on resource and capital income are counteracting and $\frac{dK_2}{dX}\big|_{R_2}$ is ambiguous, the last term (2.7) is generally ambiguous. However, given that the present value of the induced future capital stock adjustment in the last term may be positive, equilibrium outcomes, defined by (2.1) and (2.7) holding simultaneously, may even entail MV_t < 0 (see (2.2)). This was excluded before without exploration efforts (see, for example, Figure 2.1). In fact, the monopolist "freely" choosing to explore so much that even the extended marginal resource value MV_t turning negative may seem counterintuitive at first. But note that exploration, by altering capital accumulation separately from R_2, may be of additional value to the monopolist which can compensate for the losses induced by the accompanying increase period supply.[33] Overall, since with exploration activities equilibrium outcomes are not only defined for $MR_t < 0$ but also $MV_t < 0$ (where $|MV_t| > |MR_t|$ by (2.2)), this also implies that even more inelastic demand schedules can be reconciled with market power in a Hotelling-type framework than before (cf. Section 2.3.2).

The effects of climate policy in this setup are determined by the two first-order conditions and their interaction. In this section we choose to use the terms "postponement" and "acceleration" of extraction only for the change in first-period extraction R_1, because R_2 can move independently and we want to connect to the line of reasoning of Sections 2.3 and 2.4. We focus on the climate-policy-induced changes in present extraction R_1 and cumulative extraction S_1, as these variables are the most relevant ones from the perspective of climate policy, and obtain the following proposition.

Proposition 2.6. *The conventional trade-off between postponement of extraction and reduction in exploration due to the expectation of climate policy does not always hold anymore because the monopolist takes the influence of her exploration decision on the physical capital stock and, therefore, on both income streams into account. Thus, postponement can be accompanied by a decrease in cumulative extraction. The opposite case of accelerated and higher cumulative extraction is also possible.*

---

[33] There are two possible mechanisms for which the last term in (2.7) can be positive. First, additional exploration c.p. can raise the future capital stock, which then raises oil demand and oil related income of the monopolist more strongly than it decreases the interest rate and capital-related income. Or, second, additional exploration can decrease the future capital stock and, thus, increase the interest rate and capital market income by more than it reduces oil-related income.

For illustration assume that the monopolist would ignore the influence of exploration on capital accumulation, (2.7) would be just given by $S_1'(X)MV_1 - 1 = 0$. An increase in τ_2 then would affect optimal exploration only indirectly via the Hotelling rule (2.1) and the adjustment of MV_1 from there. Exploration investments would have to directly counterbalance this change in MV_1. Thus, if MV_1 increased (decreased) leading to postponement (acceleration) of extraction, exploration investments and thereby cumulative extraction would have to rise (decrease) to reduce (increase) $S_1'(X)$. Only by the effect of exploration on capital accumulation this trade-off between first-period extraction and cumulative extraction can be resolved.

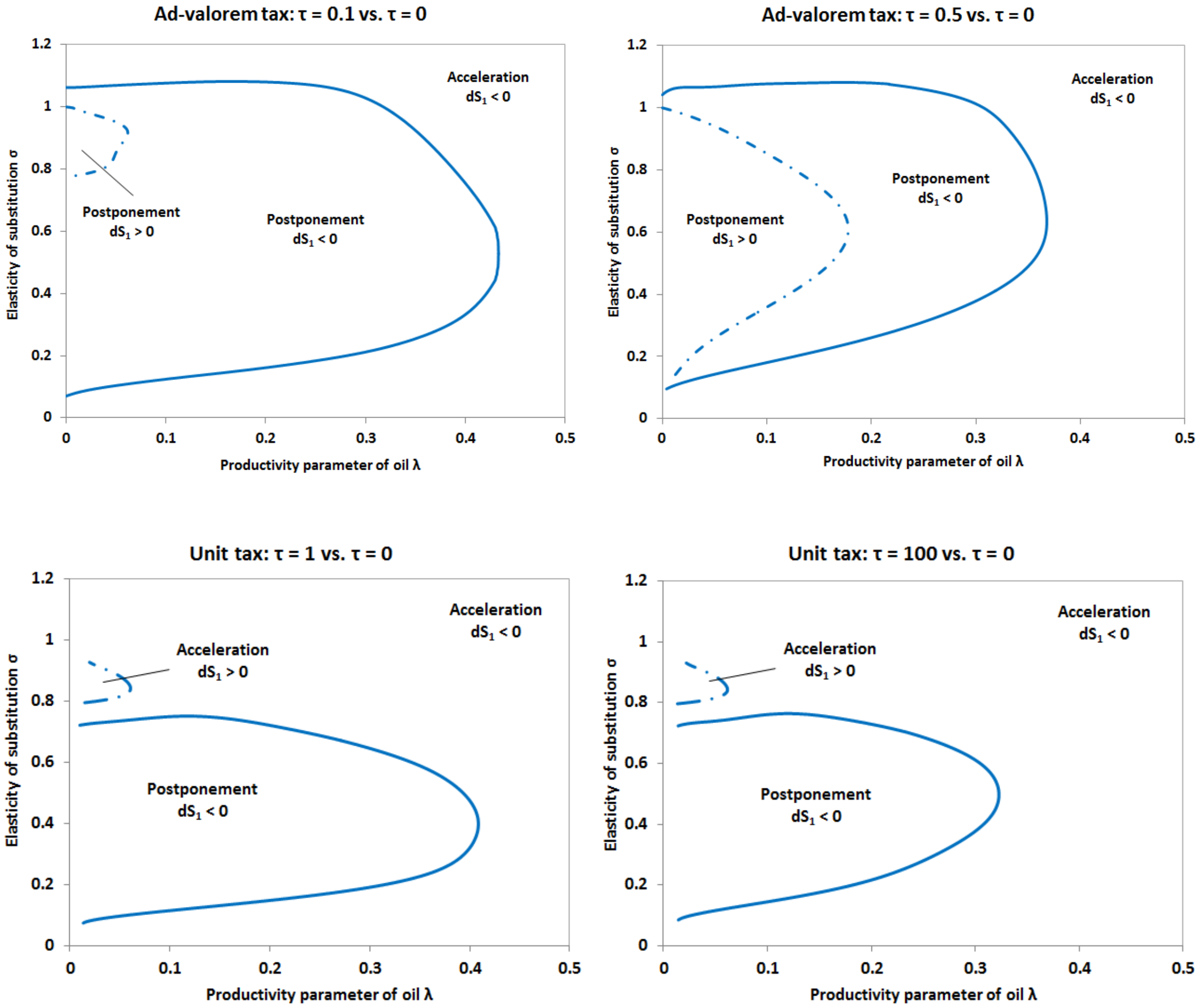

Figure 2.3 : Reactions of both periods' extraction and cumulative extraction to low and high carbon taxes for the ad-valorem tax case and the unit tax case.[34]

In all four parts of Figure 2.3 there is a zone of postponement of extraction with decreasing cumulative extraction. An increase in cumulative extraction is accompanied by postponement of extraction in the case of an ad-valorem tax and by acceleration in the case of a unit tax. The latter is contrary to the conventional trade-off.

The effects of the carbon tax do not exhibit monotonicity in the level of the tax rate like in Section 2.3.3 anymore due to an interaction of the two first-order conditions. This means that $\frac{dR_2}{d\tau_2}$ and $\frac{dX}{d\tau_2}$ can change their sign at more ambitious tax rates for both types of taxes. On the one hand, the size of the postponement zone changes with the tax rate. On the other hand, the area of increasing cumulative extraction grows considerably with the tax rate for the ad-valorem tax.

For the choice of the appropriate policy instrument this means that an ad-valorem tax has the advantage that it avoids the catastrophic scenario of faster extraction with more exploration. Also, the probability of postponement of extraction is higher. But the main advantage of a unit tax is that the increase of the zone with growing cumulative extraction is not as much an issue as with an ad-valorem tax. In the case of an ad-valorem tax this zone grows considerably with the tax rate because of two reasons: first, the tax rate explicitly appears in the first-order condition for exploration. Second, in the case of negative marginal resource revenue, which particularly occurs close to the σ-axis, an ad-valorem tax effectively works like a subsidy of oil extraction (cf. Section 2.3.2).

2.7 Conclusion

In contrast to the conventional partial equilibrium literature on unintended supply-side effects of climate policy, we account for the two-pillar nature of strategic oil extraction by an oil monopolist in general equilibrium: while banking rents from exporting oil, the monopolist also considers oil supply's influence on her petrodollar-financed capital asset returns ("capital asset motive") and on capital accumulation and the resulting general equilibrium feedbacks. We show that unintended acceleration of extraction (a "Green Paradox") may not occur if the resource monopolist pursues the capital asset motive: due to consumption smoothing, an increase (or introduction) of a future carbon tax raises future capital assets which by the

---

[34] For the numerical illustrations in figure 2.3 we use the exemplary exploration function $S_1(X) = \bar{S}(1 - e^{-\mu X})$ with the parametric constant $\mu = 0.03$ and a given amount of oil $\bar{S} = 1$ in the ground. The other parameter values are $\beta = 0.3$, $\eta = 2$, $K_1 = s_{0E} + s_{0I} = 20 + 180 = 200$, $A = 300$.

asset motive can create a sufficiently strong incentive to postpone extraction. For inelastic oil demand, which is supported by some empirical evidence, extraction is always postponed whereas in the limit pricing setting with inelastic demand of Andrade de Sá and Daubanes (2016) carbon taxation does not affect the monopolist's supply at all.

Whether extraction is accelerated or postponed particularly depends on the sensitivity of the two income pillars with respect to the carbon tax which in turn depends on how valuable the resource is in production (especially for limited factor substitutability), how strong the link between the capital and the resource market is and how strongly the exporting country's savings react to the tax increase. As the numerical sensitivity analysis confirms, the value of the resource and the link between the capital and the resource market are predominantly determined by the parameters defining the production structure (elasticity of factor substitution, productivity parameters of oil and capital in the production function, factor endowments) while the magnitude of the savings reaction is particularly influenced by household preferences. Postponement is more likely if the capital endowment is lower (and the resource endowment higher), if the discount factor is lower, and also if postponement reduces capital accumulation more strongly.

Overall, and confirmed by simulations over a wide range of parameter values, even a steeply rising carbon tax appears as a viable climate policy option. We also find in contrast to the literature that a capital income tax no longer is immune against counterproductive supply-side reactions when taking into account resource market power and the asset motive. If the resource stock has to be explored first, the trade-off between first period supply and cumulative extraction, which typically is found in the literature so far, may be resolved: short term supply together with cumulative extraction may be reduced but, unfortunately, the opposite is not excluded, too.

The role of the new transmission channel of climate policy given the asset motive may also be illustrated considering the ongoing debate on so called "stranded assets". The term stranded assets refers to losses in asset values due to unexpected consequences of climate policies. However, it is often rather unclear why market investors would not adequately assess the effects of climate policy and systematically misvalue assets. In the context of the present study we may argue that such a systematic expectation bias is introduced when the economy-wide relevance of oil and the asset motive are not taken into account so that the supply reaction of oil rich countries to climate policy is not fully understood by market participants. In our framework and the exemplary parameter setting of Section 2.3.1[35], for example, the present value of cumulative oil profits decreases by 18.0 percent when the monopolist pursues the asset motive and reduces first-period extraction. If market participants do not account for the asset motive and therefore expect the monopolist to increase period 1 extraction instead, they would predict a climate-policy-induced loss in the present value of the oil stock of 16.4 percent. Thus, the devaluation turns out about 10 percent higher than expected in this case.

Our analysis demonstrates that the widely acknowledged fact that there is market power in the global oil market can be of fundamental importance for the effects of climate policies. With the exception of limit pricing, this is in contrast to the existing literature, in which market power changes the supply-side reactions only quantitatively, but not qualitatively. An oligopolistic or a competitive fringe setting might be even more realistic and yield further insights but is left for future research. While interesting, the analysis of a clean or dirty backstop technology for future research is also beyond the scope of the present chapter. Climate-policy-induced postponement of extraction reduces future resource prices. A threat of a future backstop technology which the oil monopolist counters, for instance, by limit pricing, therefore, does not seem to undermine the postponement reaction to climate policy. But a more comprehensive analysis is clearly warranted. Introducing climate damages and analyzing green welfare is a possible next research step, too. From a macroeconomic perspective, in our framework, postponement of extraction always reduces current output but future output may increase (fall) if the induced shift of resources to the future is accompanied by a higher (lower) capital accumulation. In either case, due to the redistribution of resource rents from the resource-rich to the resource-importing country and the induced savings reactions, the future share of the resource-rich country in the global capital stock increases raising the potential capital market influence of "petrodollars" as a further topic for future research.

---

[35] The only difference to Section 2.3.1 is that here we use a productivity parameter of oil $\lambda = 0.1$ instead of $\lambda = 0.05$.

3 CAFE in the City: A Spatial Analysis of Fuel Economy Standards

3.1 Introduction[1]

Reducing carbon emissions in the transportation sector is crucial in combating climate change. Policy instruments like first-best gasoline taxes and second-best fuel economy standards are discussed in the academic literature and implemented in the political arena.[2] For the choice and design of the appropriate policy instrument it is important to understand the transmission channels and welfare implications of every measure (besides their effectiveness) relative to the first-best solution. Moreover, political economic and distributional concerns, which can constitute significant policy constraints, must be considered.[3]

The literature discusses important mechanisms like the (rather short-run) rebound effect[4] in the case of increasing fuel efficiency and fuel demand elasticities in the case of fuel taxes. But they do not analytically consider the complex long-run interplay between the spatial urban

---

[1] I would like to sincerely thank Frank Goetzke, Ken Gillingham, and Jan Brueckner for many extensive discussions and helpful comments on the study presented in this chapter. I am also very grateful to the participants of the SURED, EAERE, NARSC, EEA conferences, the Yale Prospectus Environmental Economics Seminar, and the research seminar of the Mercator MCC group on Land Use, Infrastructure and Transport.

[2] In the United States transportation contributes to about 30 percent of all carbon emissions, and, worse, transportation carbon emissions are growing both in absolute numbers and also relative to the other sectors. To this end, besides reducing dependence on imported foreign oil, the Obama Administration issued in 2010 together with the National Highway and Transportation Safety Administration ("NHTSA", cf. National Highway Traffic Safety Administration (2010)) and the Environmental Protection Agency (EPA) stricter rules for the Corporate Average Fuel Economy (CAFE), the main environmental policy in the U.S. transportation sector. The goal is to almost double the vehicle fleet fuel efficiency standards for newly manufactured cars sold in the United States from 27.5 miles per gallon ("mpg") to more than 54 mpg in 2025. The EPA and the Department of Transportation proposed in 2018 to resort to less strict mileage which has not been enacted to date (cf. Davenport (2018)).

[3] Although taxes are the first-best way to internalize an externality, their generally low popularity in the electorate, for instance, can lead to the implementation of second-best measures. This was arguably the case with fuel economy standards for each new vehicle fleet since the 1970s in the U.S.

[4] Gains in technical efficiency, e.g. of fuel consumption, which aim at reducing total consumption or harmful emissions, can decrease the marginal costs of the good or fuel and lead to increased consumption. The term “rebound effect” refers to the share of reduced emissions that is offset by the according increase in consumption. For an extensive overview of microeconomic and macroeconomic rebound and according welfare effects see Gillingham et al. (2016).

structure on the one hand and vehicle choice, environmental policies, and driving patterns on the other hand. The present chapter integrates urban economic modelling and environmental economic analysis to yield two main contributions. First, it investigates the role of urban parameters (like land price, income level, population size, amenities and construction norms) for the welfare costs of partial equilibrium compliance with the environmental policies before an urban adjustment taking household level vehicle choice into account. Second, this is the first study to analytically integrate the long run effects of these environmental policies on driving behavior and vehicle choice based on fuel economy and the interdependent choice of location and commuting distances of households in general equilibrium. Again, urban economic factors play an important role for the magnitude and the spatial pattern of resulting urban expansion or contraction. Taking into account how the adjustment of the urban form feeds back into the individual choice of vehicle fuel efficiency, this chapter presents a new channel through which fuel economy standards and fuel taxes affect aggregate welfare and emissions.

This chapter incorporates two new mechanisms into the monocentric city model, a workhorse model in urban economics: first, household-level vehicle choice based on fuel economy and, second, an endogenous adjustment of the vehicle pricing scheme in the automobile sector for a change in fuel economy standards. This and recycling of land rents and fuel tax revenues as household income in turn affects all equilibrium values of the model variables. Therefore, the model has no closed-form solution and is solved numerically. This allows for a disentangling of welfare channels for both policies. A sensitivity analysis illustrates the role of the main model parameters.

In the analysis of welfare channels it is considered how the policies affect household utility from the consumption of housing and a composite good by inducing monetary costs and benefits for different emission reduction targets. There is no direct effect on utility from carbon emissions or climate damages. To better understand the welfare channels of both policies, the resulting effects are decomposed into a partial equilibrium and a general equilibrium welfare effect. The partial equilibrium effect ("step 1") considers additional compliance costs from the households' choice of cleaner vehicles while keeping household locations and real estate prices fixed ("compliance before urban adjustment"). The general equilibrium effects ("step 2") adjust for changes in household locations and housing prices ("urban adjustment"), which leads to two simultaneous, but counteracting, welfare channels: first, a change in vehicle and driving costs from the new choice of vehicle efficiency at the new locations and, second, the welfare effect from the change in housing prices and the according adjustment in consumption bundles.

The results show that the partial welfare cost of compliance before urban adjustment rises up until 1 to 6 percent of total welfare for an emission reduction of 75 percent, depending on the parameter setting. In all relevant parameter settings for the CAFE policy, the decrease in the marginal cost of driving leads to an expansion of the city area in the long run equilibrium. The corresponding commute-related rebound effect is between 2 percent and 16 percent for low emission reduction goals and falls significantly and monotonically to 0.5 to 3 percent for a high aggregate emission reduction of 75 percent. This expansion yields additional welfare costs from the choice of cleaner vehicles and additional welfare gains from an increase in housing supply and average consumption. The net welfare effect of urban adjustment, however, is negative, despite the additional degrees of freedom of location choice and adjusting housing prices. The reason is that the cross subsidy from dirty to clean vehicles via the CAFE mechanism creates a distortion of vehicle prices. This distortion is not accounted for by households in their vehicle choice and leads to a deadweight loss. The adjustment in spatial equilibrium imposes an additional net welfare cost of 10 to 65 percent over the partial equilibrium welfare cost for given emission reduction targets and decreases with more ambitious climate policy goals. The urban adjustment is, therefore, a major component in the overall welfare balance of the policies, but plays a smaller role in the decarbonization of the transportation sector.

In the case of the fuel tax policy urban adjustment implies a contraction of the city because of the increase in marginal driving costs. This leads to additional welfare gains from the choice of less costly and less fuel efficient vehicles and additional welfare costs from a decrease in housing consumption. The net welfare effect of urban adjustment ("step 2") for the fuel tax is positive and lies in the range of 5 to 40 percent of the welfare cost of compliance before urban adjustment. The positive net welfare effect of urban contraction due to the fuel tax policy even increases with progressive decarbonization.

The total resulting welfare gap between the fuel tax and fuel economy standards after urban adjustment lies in the range of 10 to 80 percent of the welfare cost of CAFE compliance without urban adjustment. Overall, the welfare cost of compliance before urban adjustment, the commute-related rebound effect and the welfare cost of urban adjustment are all higher for lower household income, for a larger city population and higher prices for vehicle efficiency technology and for gasoline. Taking the urban economic dimension of the problem into account, therefore, adds weight to the choice of the right climate policy instrument. This is even more the case for low income countries with large average city size.[5] If policy makers nevertheless must resort to second-best fuel economy standards, like in the U.S., a simultaneous introduction of urban growth boundaries is recommended. A combination of the two measures reduces the additional welfare cost of urban expansion by roughly one half and closes between 20 and 40 percent of the total welfare gap between the fuel tax and fuel economy standards. A discussion of distributional implications reveals that fuel economy standards can have regressive effects. In contrast, fuel taxes tend to be more progressive. But further research is needed in this direction.

This study contributes to the literature on welfare effects of fuel economy standards by bringing the urban economic dimension into the picture. The literature to date, on the one hand, considers direct effects of fuel economy standards on welfare over three channels connected to the vehicle market: first, the cost of compliance (cf. Austin and Dinan (2005), Anderson and Sallee (2011), Klier and Linn (2012), Jacobsen (2013)[6]), second, the opportunity cost from the car manufacturers' trading off of vehicle characteristics like horsepower against higher fuel efficiency (cf. Klier and Linn (2016) and West et al. (2017)), and, third, the effects on scrappage and values of used cars (cf. Jacobsen and van Benthem (2015)). On the other hand, indirect channels of fuel economy standards on welfare via their influence on externalities[7] from gasoline consumption (climate and local pollution) and from driving (congestion and traffic safety, cf. Jacobsen (2011)) are discussed. But none of the (mostly structural empirical) studies mentioned takes explicitly into account the welfare gains in housing consumption from urban expansion.[8] Nor do they consider that these direct and indirect welfare channels and the magnitude of the resulting effects are affected significantly by urban parameters and the adjustment of the urban form in the long run. The present chapter fills that gap by identifying new channels of fuel economy standards on welfare 1) via the adjustment of

---

[5] Newly industrializing countries like China and India exhibit relatively low income, at least compared to OECD countries, and rapid urbanization. But for a reasonable comparison with the U.S. or Europe, the role of public transit and mobility mode choice patterns, which are not modeled here, would have to be taken into account.

[6] While National Highway Traffic Safety Administration (2010) optimistically expects positive monetary net effects of compliance (with savings from reduced gasoline consumption exceeding additional vehicle costs), the other studies yield net costs of compliance. This view is supported by the evidence that Sallee et al. (2016) find for the households' full valuation of fuel efficiency and, therefore, against the notion that they might be myopic with respect to possible gains from increased fuel efficiency.

[7] A good overview over different automobile related externalities can be found in Parry et al. (2007)).

[8] National Highway Traffic Safety Administration (2010) considers an increase in consumer surplus from increased driving as "half of the product of the decline in vehicle operating costs per vehicle-mile and the resulting increase in the annual number of miles driven" (National Highway Traffic Safety Administration (2010)).

the housing market and 2) via the role of urban parameters and the long-term adjustment of the urban form for the welfare channel of compliance. The theoretical urban economic perspective allows the present chapter to go beyond empirical studies, whose time horizon is necessarily short due to data constraints, and simulate very long-term emission reduction scenarios. The influence of the urban form channel on the other welfare effects in the literature beyond compliance costs (opportunity costs of vehicle features, changes in used-car values, traffic safety, congestion, and local pollution) is left for future research.

The present chapter's analysis of fuel taxes in a spatial urban context also extends the literature on the effects of gasoline prices on gasoline consumption and fuel economy (cf. Burke and Nishitateno (2013); Klier and Linn (2013); Li et al. (2014)) and on the welfare costs of gasoline taxes (cf. Langer et al. (2017)). Like the studies on welfare effects of fuel economy standards, this empirical literature also has a short to medium time horizon and does not consider the long-term change of urban form and the new channels of gasoline taxes on welfare over vehicle choice and the real estate market which the urban adjustment creates. Again, the present theoretical framework enables the simulation of long-term scenarios for a fuel tax policy, just like for fuel economy standards.

This study also contributes to the literature on rebound effects in driving since Greene (1992) and to the according discussion about the right climate policy instrument in the transportation sector. Gillingham et al. (2013) argue in favor of fuel efficiency standards, referring to empirical studies which find relatively small rebound effects for the United States (cf. Small and van Dender (2007), Hughes et al. (2008), and Greene (2012)[9]). On the other hand, Frondel and Vance (2013) advocate fuel taxes as the more cost-effective alternative, pointing to much higher rebound effects (around 60 percent) found in German data (cf. Frondel et al. (2008), Frondel et al. (2012))[10]. To tackle these questions it is of key importance to understand the endogenous interplay of distance driven (location choice), vehicle fuel economy, and gas price (as already Greene et al. (1999) pointed out) and to disentangle the resulting welfare effects.[11]

---

[9] Small and van Dender (2007), estimate for the time period 2000 to 2004 a rebound effect of between 1.1 percent (short-run) and 5.7 percent after a few years. Hughes et al. (2008) observe for the time period 2001 to 2006 a price elasticity of -0.037 to -0.077, corresponding to a similar magnitude of the earlier obtained rebound effect. Greene (2012) does not find a significant effect of fuel efficiency on vehicle travel.

[10] Linn (2016) provides an intermediate rebound estimate of 20 to 40 percent taking additional aspects like multivehicle households and the correlation of fuel economy and vehicle and households attributes into account.

[11] Chan and Gillingham (2015) provide a systematic framework to analyze rebound related welfare effects like benefits from energy service use and costs from additional energy service provision, fuel externality, and

The present chapter incorporates these relations, especially the simultaneous choice of long-run housing location and vehicle fuel efficiency, and allows for a long-run perspective on rebound and on non-linear relationships which go beyond the available data base of empirical work. Given the prominent role of location choice, this chapter focuses on commuting trips. Trips for recreation or shopping are abstracted from here, but they can be expected to be correlated to commuting trip lengths.

Moreover, this study establishes a connection of the urban economic literature in the tradition of monocentric city modelling (cf. Alonso (1977), Muth (1969), Mills (1967), Henderson (1985), Fujita (1990)) with the energy and environmental economic literature on fuel economy standards, fuel taxes, and rebound effects. Thus, I include urban economic and spatial considerations into the design of environmental policy in the transport sector. I extend the numerical simulation approach of a monocentric city model taken by Brueckner (2007) and Kim (2012) to incorporate household level vehicle choice based on fuel economy and a consistent implementation of fuel economy standards. Kim (2016) is, to my knowledge, the only other example of vehicle choice in a more stylized monocentric urban model. But there households base their vehicle choice on vehicle size and resulting inconvenience in congestion and not fuel economy, which is, in contrast, the focus of the present chapter and of fuel economy policies in general. The present chapter also goes beyond Kim (2016) in its modelling of endogenous adjustment of vehicle price policy after tightened fuel economy standards.

The remainder of the chapter is organized as follows. After presenting the model in Section 3.2 and the way the policies are implemented in it in Section 3.3 I analyze the environmental and welfare effects of the policies in Section 3.4. An extension with urban growth boundaries is presented in Section 3.5. In Section 3.6 a brief discussion of distributional and political economic aspects follows. Section 3.7 concludes.

3.2 The Model

3.2.1 Households

The core of the model is the monocentric city model (in the tradition of Alonso (1977), Muth (1969), and Mills (1967)), as it is described in Brueckner (2007). The city is closed in the sense

---

energy service externality. But they do not consider the urban economic dimension of location choice and all the resulting effects that the present chapter focuses on.

that population size L is exogenously given. All households receive income only from working in the central business district (CBD), to which they commute by car. There is no public transit. At each distance x from the CBD households maximize their Cobb-Douglas utility that they derive from the consumption of a composite good c and housing q by choosing their consumption bundle and – and this is an addition to the model of Brueckner (2007) – their car's mileage mpg, measured in miles per gallon.[12]

$$\max_{c,q,mpg} u(c,q) = c^{1-\alpha} q^{\alpha} \tag{3.1}$$

subject to the budget constraint

$$c + p(x)q = y - t(mpg)x - v(mpg) \tag{3.2}$$

with the price of the consumption good c being normalized to 1 and $p(x)$ being the price of a 'unit' of housing at every distance x. On the RHS of (3.2) there is the part of annual per capita income y which is available for consumption after the annual expenses for commuting $t(mpg)x$ and for the vehicle costs $v(mpg)$ have been made. Annual per capita income y is uniform across the city and consists of an exogenous part y_0, of lump-sum recycled land rent from the whole city y_{RPC}, and lump-sum recycled revenues from the fuel tax y_{Tax}, if there are any:

$$y = y_0 + y_{RPC} + y_{Tax} \tag{3.3}$$

Rent income y_{RPC} and tax income y_{Tax} both depend on the resulting general market equilibrium (cf. Equation (3.20) in Section 3.2.3 and Equation (3.27) in Section 3.3.2). The annual travel costs per meter $t(mpg)$ read as follows

$$t(mpg) = \frac{p_G F}{mpg} + t_{main} \tag{3.4}$$

with the exogenous gasoline price per gallon p_G, the factor F for adjusting the units[13], and annual maintenance costs per meter of distance t_{main}. Annual vehicle cost $v(mpg)$ is a linear

---

[12] The maximization problem could be set up with the households maximizing over x as well. But since, in equilibrium, utility must be uniform over x to ensure non-arbitrage, this dimension is redundant.

[13] The factor $F = \frac{1}{1.6}\frac{miles}{km}\frac{1}{1000}\frac{km}{m} \cdot 2 \cdot 250 \frac{round-trips}{a} = 0.3125 \frac{miles}{m \cdot a}$ converts the costs of a singular trip into annual expenses and miles into meters.

function[14] of the vehicle mileage mpg chosen and, in the initial state before any policy, equals the technological vehicle production costs $v_{tech}(mpg)$:

$$v(mpg) = v_{tech}(mpg) = v_{0,tech} + m_{tech} \cdot mpg \tag{3.5}$$

with the intercept $v_{0,tech}$ and m_{tech} being the technological cost of a marginal increase in vehicle mileage mpg. The vehicle price rises with increasing fuel efficiency because more fuel efficient technology (like hybrid engines or synthetic materials with certain features) is more expensive. Automakers are assumed to be perfectly competitive making zero profits. Without any binding policies they set the price of each vehicle equal to its production costs. The households' first-order condition for mpg reads

$$-\frac{p_G F}{mpg^2} x + m_{tech} = 0 \tag{3.6}$$

The benefit of a marginal efficiency increase in the form of a reduction in driving costs must equal its marginal technological cost. The resulting choice of vehicle mileage then reads

$$mpg^*(x) = \sqrt{\frac{p_G F}{m_{tech}} x} \tag{3.7}$$

changing (3.4) and (3.5) to

$$t(x) = \sqrt{\frac{p_G F m_{tech}}{x}} + t_{main} \tag{3.8}$$

and

$$v(x) = v_0 + \sqrt{p_G F m_{tech} x} \tag{3.9}$$

respectively. If fuel economy is the only factor determining vehicle choice, then households with a longer commute will buy more fuel efficient cars than those closer to the city center.[15]

---

[14] Following Austin and Dinan (2005), the vehicle cost curve implicitly incorporates future R&D related cost reductions, so that its shape is not convex, but linear.

[15] In principle, the household vehicle choice could be influenced by two factors: the economics of fuel consumption depending on distance driven and the convenience of the vehicle which is correlated with vehicle size and directly affects utility while driving and additionally with congestion. Vehicle choice in Kim (2016) only relies on vehicle size while abstracting from fuel economy as a choice criterion. Instead, I focus on fuel economy as the crucial choice criterion, which is more consistent with the micro foundation of households as rational

Since the households' utility level in spatial equilibrium must be the same at every point x, higher commuting costs $t(x)x$ at higher distances x are counteracted by lower housing prices. This trade-off is incorporated in equations (3.1) and (3.2). Substituting the first-order conditions for c and q into (3.2) yields the expenses for the composite good

$$c(x) = (1-\alpha)(y - t(x)x - v(x)) \tag{3.10}$$

and the rent expenses

$$p(x)q(x) = \alpha(y - t(x)x - v(x)) \tag{3.11}$$

which are equal to constant shares $(1-\alpha)$ and α, respectively, of available income. By substituting (3.10) and (3.11) into (3.1) we obtain the housing price function in the city:

$$p(x,u) = \Psi(y - t(x)x - v(x))^{\frac{1}{\alpha}} u^{-\frac{1}{\alpha}} \tag{3.12}$$

with $\Psi = \alpha(1-\alpha)^{\frac{1}{\alpha}-1}$ and a parametric utility level u.[16] Substituting (3.12) into (3.11) leads to the housing demand equation

$$q(x,u) = \Gamma(y - t(x)x - v(x))^{1-\frac{1}{\alpha}} u^{\frac{1}{\alpha}} \tag{3.13}$$

with $\Gamma = (1-\alpha)^{1-\frac{1}{\alpha}}$.

3.2.2 Housing Production

As in Brueckner (2007), housing is produced by developers with the inputs land and housing capital S. The housing output per unit of land is θS^{β} with the constant θ. The exponent β is smaller than one and, thus, implies decreasing returns to scale, that is, building higher.[17]

---

agents and the empirical observation of Sallee et al. (2016) that consumers are not myopic and do value the gains in transportation costs correctly while choosing their car.

[16] In the urban economic equilibrium, household utility u is uniform over all households and distances x to ensure non-arbitrage. Since the utility level u (as well as the city boundary $\bar{x}$) is endogenously and numerically determined only under usage of additional conditions in the urban economic equilibrium (cf. Section 3.2.3), it appears as a parameter from the perspective of a single household in the derivation here.

[17] The parameter β can be interpreted as capturing a technologically determined increase in effort for building higher, like more robust steel structures and a rising necessity for elevators. But it could also incorporate the degree of construction regulation: with low regulation (low β), one-story buildings can be built in a very simple way, so that the step toward a second and third floor involves a disproportionate increase in capital

Perfectly competitive developers maximize profits per unit of land at every distance x[18]

$$\max_S \Pi(S) = p(x)\theta S^{\beta} - S - r(x) \tag{3.14}$$

with the price of capital S being normalized to 1 and $r(x)$ being the rent per unit of land at distance x.[19] Substituting Equation (3.12) into the resulting first-order condition for S yields the housing capital demand function

$$S(x,u) = \Lambda(y - t(x)x - v(x))^{\kappa} \cdot u^{-\kappa} \tag{3.15}$$

with the constants $\Lambda = (\theta\beta\Psi)^{\frac{1}{1-\beta}}$ and $\kappa = \frac{1}{\alpha(1-\beta)}$. Setting (3.14) equal to zero and substituting (3.12) and (3.15) leads to the land rent function:

$$r(x,u) = \Omega(y - t(x)x - v(x))^{\kappa} \cdot u^{-\kappa} \tag{3.16}$$

with the constant $\Omega = \theta\Psi\Lambda^{\beta} - \Lambda$.

3.2.3 General Market Equilibrium

A condition that is necessary to determine the city limit is that the land rent at the city boundary $\bar{x}$ has to equal the exogenous agricultural land rent r_A (using (3.16)).

$$r(\bar{x},u) = \Omega(y - t(\bar{x})\bar{x} - v(\bar{x}))^{\kappa} \cdot u^{-\kappa} = r_A \tag{3.17}$$

Dividing the amount of produced housing per unit of land (with $S(x,u)$ from (3.15)) by the amount of housing per person (3.13) yields the number of people per unit of land, which is the population density:

$$D(x,u) = \frac{\theta S(x,u)^{\beta}}{q(x,u)} = \Phi(y - t(x)x - v(x))^{\kappa-1} \cdot u^{-\kappa} \tag{3.18}$$

---

costs. In a highly regulated construction sector (high β), in contrast, already low buildings have to meet strict requirements. Adding more floors then raises capital costs more proportionally.

[18] Similarly to the utility maximization by households (cf. (3.1)), developers' profits in equilibrium are equal (and zero) at all distances x to exclude arbitrage. Therefore, profit maximization over x is redundant.

[19] Here the term "rent" is used because it is consistent with annual payments for the vehicle and driving costs and annual income in the household budget. In an efficient market the price for land must be equivalent to the present value of an infinite stream of rent payments.

with $\Phi = \frac{\theta \Lambda^{\beta}}{\Gamma}$. To close the model, we need to add the condition that the whole population, that is, the integral over the whole inhabited city area of the population density $D(x,u)$ from (3.18), has to be equal to the exogenously given city population L

$$\iint_{city} D(x,u)\, dA = \int_0^{\bar{x}} D(x,u) 2\pi x\, dx = L \tag{3.19}$$

With conditions (3.17) and (3.19) the model can be solved and the city radius $\bar{x}$ and the utility level u can be calculated.[20] With the equilibrium solution also the aggregate land rent payments can be calculated. But only the excess rents, i.e., the difference between land rents r and the agricultural rent r_A, are redistributed to the households in a lump-sum fashion (cf. income components in Equation (3.3)) to be accounted for in the welfare balance.

$$y_{RPC} = \frac{1}{L} \iint_{city} r(x,u) - r_A\, dA = \frac{1}{L} \int_0^{\bar{x}} (r(x,u) - r_A) 2\pi x\, dx \tag{3.20}$$

A classical interpretation of excess rent recycling in the urban economic literature is that the city population owns the land that the city is built on collectively over a "city corporation". The "city corporation" receives the excess land rent payments and redistributes them to the citizens as lump-sum payments to avoid further distributional distortions. The agricultural rent component, in contrast, is often seen as the opportunity cost of land and does not contribute to the relevant welfare balance from a policy maker perspective. Therefore, the agricultural rent here is paid to land owners outside the city.[21]

To calculate aggregate annual carbon emissions E_{CO2} in tons of CO_2, individual commuting distances divided by the individual car mileage and weighted with the population density

---

[20] Because of the integral in (3.19) the model must be solved numerically. With the numerical value for u and Equations (3.13) and (3.12) the housing consumption function $q(x)$ and the housing price function $p(x)$ ("bid-rent curve") can be determined explicitly. In equilibrium, available income after expenses for mobility $(y - t(x)x - v(x))$ decreases over x. Therefore, $\frac{\partial c(x)}{\partial x} < 0$ holds as well. But at the same time we have $\frac{\partial p(x)}{\partial x} < 0$ and $\frac{\partial q(x)}{\partial x} > 0$. So, suburban residents are compensated for their high mobility expenses by larger dwellings and the resulting utility level is identical to central residents.

[21] In the present case, the recipients of agricultural rent reside outside the city and the according payments leave the system. Alternatively, all the land inside and outside the city (up to a maximal radius which then would have to be chosen) could be seen as owned by all city households collectively. Then households would also receive the agricultural rent payments for the entire land inside and outside the city boundary. However, if different land owners inside and outside the city limits were assumed, then the owners of the land outside of the city would have to be modeled explicitly and included in the welfare balance from a neutral policy maker's perspective. This is avoided here.

$D(x,u)$ are integrated over the inhabited city area:

$$E_{CO2} = F_{CO2} \int_0^{\bar{x}} \frac{x}{mpg(x)} D(x,u) 2\pi x \, dx \tag{3.21}$$

The factor $F_{CO2} = 2.48027 \cdot 10^{-3} \frac{MPG}{m} \frac{t_{CO2}}{a}$ transforms gallons of E10 gasoline to tons of CO_2 emitted to the atmosphere and meters of geographical distance to the CBD to annual miles driven.[22]

3.3 Implementation of Policy Measures

3.3.1 CAFE Standards

Since the 1970s fuel economy standards have been the main environmental policy measure in the U.S. transportation sector. As its name “Corporate Average Fuel Economy” indicates, the policy puts a lower bound for the average fuel economy of the whole car fleet of every car producing corporation. Each company chooses how many vehicles of each type to produce and how to price them on the market as long as the company’s average car fulfills the standard. As empirical evidence in Sallee et al. (2016) suggests, households optimally choose their car’s fuel efficiency for the given vehicle prices, that is, they are not myopic.

If a binding fuel economy standard is tightened, it requires automakers to sell more fuel efficient vehicles, which people do not voluntarily choose in the first place. To incentivize the required purchasing behavior and achieve the goal, automakers will have to reduce the price of more fuel efficient vehicles relative to the price of less fuel efficient ones. At the same time their revenues must be high enough to cover the sum of all production costs. This mechanism is modelled as follows.

The slope of the vehicle cost curve m_{tech} is the only model parameter that drives vehicle choice for a given distance x and gas price p_G in the pre-policy equilibrium (cf. (3.7)). Now, with fuel economy regulation, the vehicle price curve is assumed to remain linear so that car producers can choose its slope and the according intercept.[23] This allows for a one-to-one mapping of

---

[22] $F_{CO2} = 7.983226 \frac{kg_{CO2}}{gallon E10 gas} \cdot \frac{500 \frac{one-way\, trips}{a}}{1000 \frac{kg_{CO2}}{t_{CO2}} 1000 \frac{m}{km} 1.609344 \frac{km}{mile}} = 2.48027 \cdot 10^{-3} \frac{mpg}{m} \frac{t_{CO2}}{a}$ with the CO_2 content of a gallon of E10 gasoline of $7.983226 \frac{kg_{CO2}}{gallon}$ (Energy Information Administration (2018))

[23] In reality automakers are free to choose their marketing and pricing policies according to many different strategic considerations. The present model abstracts from a number aspects which play a role in real automobile markets like taste, heterogeneity of consumer groups, particularly with respect to income, etc. A more

each fuel economy standard onto the slope m_{CAFE} of the post-policy vehicle price curve for a given parameter setting: implicitly, car companies choose the slope m_{CAFE} which triggers the required household vehicle choice to fulfill the new fuel economy standard. Therefore, the policy shock of a tightening CAFE standard is implemented in the model as a shock directly on the slope of the vehicle price curve (3.5) ($m_{CAFE} < m_{tech}$). As a result, households at every distance x in the model increase their vehicle mileage by the same factor due to the policy shock:

$$mpg_{CAFE}(x) = \sqrt{\frac{p_G F}{m_{CAFE}} x} > \sqrt{\frac{p_G F}{m_{tech}} x} \tag{3.22}$$

Aggregate production costs for these cleaner vehicles increase according to (3.5) and must be covered by aggregate revenues. Therefore, car companies endogenously increase the intercept of the vehicle price curve, so that $v_{0,CAFE} > v_{0,tech}$, until they exactly ensure full cost coverage and zero profits again, according to the following condition:

$$\begin{aligned} \sum v_{Revenues} &= \sum v_{Costs} \\ \int_0^{\bar{x}} D(x,u)(v_{0,CAFE} + \sqrt{m_{CAFE} p_G F x})\, 2\pi x\, dx &= \\ \int_0^{\bar{x}} D(x,u) \left(v_{0,tech} + m_{tech} \sqrt{\frac{p_G F x}{m_{CAFE}}} \right) 2\pi x\, dx & \end{aligned} \tag{3.23}$$

This means that automakers do not choose the intercept independently of the slope of the vehicle price curve. Also, household preferences, which play a role for location choice, affect vehicle choice and, thus, (indirectly) the intercept $v_{0,CAFE}$. The new vehicle price curve then is

$$v_{CAFE}(x) = v_{0,CAFE} + m_{CAFE} \cdot mpg_{CAFE}(x) = v_{0,CAFE} + \sqrt{m_{CAFE} p_G F x} \tag{3.24}$$

Figure 3.1 illustrates the decrease in slope and increase in intercept of the vehicle cost curve due to a CAFE policy shock.

On average, vehicle expenses increase. But owners of less fuel efficient cars in the city center to a certain degree effectively subsidize cleaner cars in the suburbs. As long as we leave the

---

elaborate pricing policy in the model than the choice of the slope and the intercept of a linear vehicle price curve would considerably increase model complexity and require additional assumptions without adding much to explanatory power.

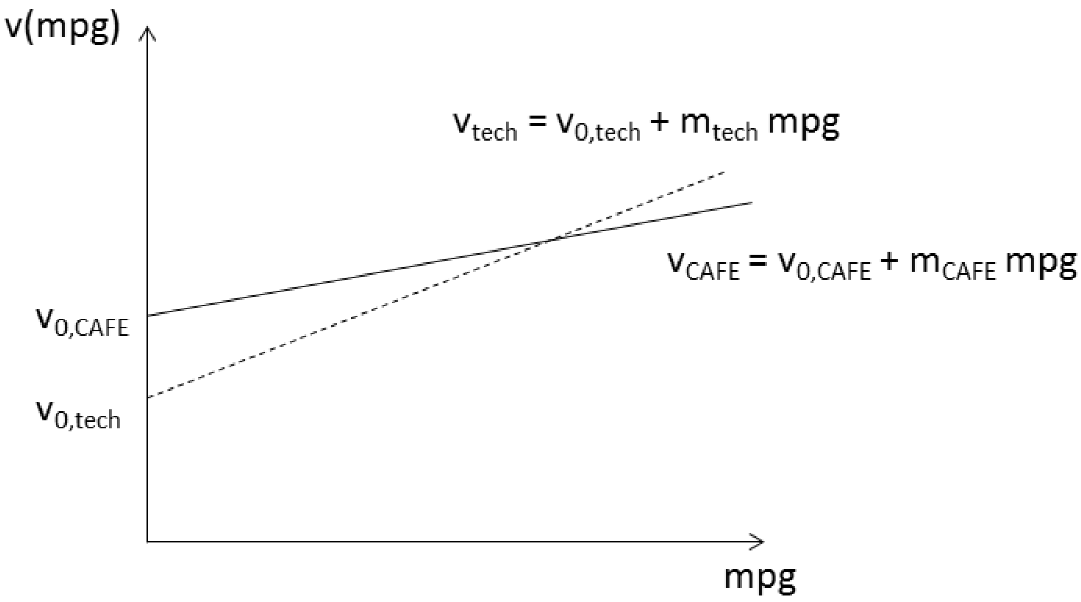

Figure 3.1 : Change in the vehicle cost curve through CAFE policy

adjustment in the urban form out of the picture, driving expenses $t(x)x$ for each household go down due to increased fuel efficiency. But since the marginal cost of driving decreases, distance to the CBD becomes cheaper and households at each distance x have an incentive to move further away from the center to benefit from lower housing prices in the suburbs compared to the center. The result is an overall expansion of the city with an increase of the average commuting trip length.

This can be seen as an urban economic long-term rebound effect. The energy economic literature on the rebound effect of driving typically deals with short term changes in driving distance after increases in efficiency. Reasons can be a higher frequency, as well as an increased length of all trips, that is, beyond commuting, also those for shopping and recreation. The agents' motives can be monetary as well as behavioral like a “greener feeling” when driving. I focus on this urban-form driven commute-related long-term rebound component. Even if we released the assumption that people only drive to commute to work in the present model and allowed for shopping and recreational trips, it would be plausible that an overall expansion of the city would also increase the average length of these trips. However, the increased commuting distances x in turn incentivize the choice of even more fuel efficient cars, reinforcing the effect of the flatter slope of the vehicle price curve on vehicle choice. The net effects of the adjustments of the real estate market and the car market on aggregate emissions and welfare are dealt with in more detail in the analysis in Section 3.4.

3.3.2 Fuel Tax

The alternative first-best environmental policy in the transportation sector is a fuel tax. The fuel tax τ is a unit tax. It is implemented as a markup on the price of gasoline and thus contributes to an increase in transportation costs and to a contraction of the city. Like CAFE standards, however, it also provides an incentive for households to buy more fuel efficient cars:[24]

$$mpg_{Tax}(x) = \sqrt{\frac{(p_G + \tau)F}{m_{tech}}x} > mpg_0^*(x), \quad for\ \tau > 0 \tag{3.25}$$

And the efficiency increase contributes to a decrease in driving costs. But, unlike the CAFE policy, a fuel tax does not require a different pricing policy from the car companies. They continue to set vehicle prices equal to technologically determined production costs. The vehicle cost curve over the distance x from (3.9) changes into

$$v_{Tax}(x) = v(x) = v_0 + \sqrt{m_{tech}\,(p_G + \tau)\,F\,x} \tag{3.26}$$

because vehicle efficiency changes with (3.25), even though the vehicle cost curve over mileage (3.5) does not. Tax revenues are recycled on a per-capita basis:

$$y_{Tax} = \frac{1}{L}\int_0^{\bar{x}} D(x,u)\frac{\tau\,F\,x}{mpg_{Tax}^*(x)}2\pi x\,dx \tag{3.27}$$

Since households at a higher distance bear a higher tax burden, the fuel tax redistributes income from suburban to central residents. With the tax, the marginal cost of driving from (3.8) turns into

$$t_{Tax}(x) = \sqrt{\frac{(p_G + \tau)Fm_{tech}}{x}} + t_{main} \tag{3.28}$$

As $\frac{\partial t_{Tax}(x)}{\partial \tau} > 0$, the marginal cost of driving overall increases with the tax despite the increase in fuel efficiency. This contributes to an overall contraction of the city, which in turn, according to (6), creates an incentive to invest less in fuel efficiency. These effects will also be discussed in more detail in the following Section 3.4.

---

[24] Burke and Nishitateno (2013) and Klier and Linn (2013) empirically confirm that higher gasoline prices lead customers to the choice of more fuel efficient vehicles.

3.4 Numerical Analysis

In the following, the effects of both policy instruments on the urban form, welfare, and emissions are analyzed. For tractability, I look at the effects in two steps, which actually take place simultaneously: first, in “step 1”, I introduce a policy measure while keeping housing prices $p(x)$ and housing locations x unchanged. In this way I observe the costs and benefits of compliance of all households’ vehicle choices with the policy measure before allowing for the urban economic adjustment. In this intermediate state utility levels vary over x (which they do not with endogenously adjusting housing prices $p(x)$ and household locations x). But the change in average utility indicates the per-capita welfare cost of compliance without urban adjustment with the new fuel economy standard. In “step 2”, the urban form adjusts and triggers not just a change in location choice, but also an additional change in vehicle choice. The implications of urban adjustment for welfare and emissions are identified and the magnitude of the effects is compared to the case of compliance without urban adjustment in step 1. Step 1 is analyzed for fuel economy standards in Section 3.4.1, and step 2 in Section 3.4.2. Section 3.4.3 deals with both steps for a fuel tax policy.

For the entire analysis, a reference city is defined. Then the different model parameters are changed to illustrate their influence on the results. The (exogenous) parameter setting of the reference city is summarized in Table 3.1. It could be interpreted as a country’s average metro area.

Population, L	1,000,000
Annual income p.c., y_0	50,000
Annual marginal cost of vehicle fuel efficiency, m_{tech} $[\frac{\$}{MPG\,a}]$[25]	15
Gas price p_G $[\frac{\$}{gal\,a}]$	2.5
Consumption share of housing, α	0.3
Scale exponent in housing production, β	0.85
Scaling constant in housing production, θ	0.025
Agricultural rent r_A $[\frac{\$}{m^2\,a}]$	0.5
Maintenance cost t_{main} $[\frac{\$}{m\,a}]$	0.05

Table 3.1 : Parameter setting of the reference city

---

[25] The long-term cost of technological improvements of fuel efficiency of course depend on uncertain factors like technological pathways and the pace of development. According to National Research Council (2015, p. 270), estimated additional technology costs per vehicle for each percent of reduction in fuel consumption roughly lie in the range between 25$ and 100$.
Starting at an average fuel economy of $25MPG$, or 0.04 gallons per mile, a reduction of fuel consumption

The initial equilibrium state before the introduction of any policies is summarized in Table 3.2.

City radius $\bar{x}$[m]	30,509.06
Average commuting trip length [m]	18,441.96
Average car mileage [Miles per Gallon]	30.14
Average carbon emissions p.c. [$\frac{t}{a}$]	1.436
Utility [-]	7569.28

Table 3.2 : Initial equilibrium values of reference city before any policy

3.4.1 Step 1 - Partial Equilibrium CAFE Compliance without Urban Adjustment

In step 1, CAFE standards are introduced while keeping real estate prices from the pre-policy state $p(x)$ and locations x of all households artificially constant. In this intermediate state, every household chooses a more fuel efficient vehicle so that its carbon emissions, and, thus, also average carbon emissions, decrease. While paying more for the more fuel efficient vehicles, households save money on driving their still unchanged commuting distances. As CAFE standards imply a cross-subsidy from central residents to suburban residents, the latter may actually have declining vehicle costs (despite the choice of higher efficiency) and a resulting monetary net benefit in some cases. But, nevertheless, the increased average fuel efficiency leads to higher aggregate vehicle production costs in the system and an according increase of the intercept of the vehicle price curve $v_{0,CAFE}$. This contributes to a decline in average utility, although some suburban households may be better off.[26] Starting from the pre-policy state without any CAFE standard ($v_{CAFE}(mpg) = v_{tech}(mpg)$), the fuel economy standard is continuously increased.

Vehicle choice adjusts to the CAFE regulation according to (3.22) and, thus, the household budget (3.2) is modified by the new vehicle cost curve (3.24) (that takes into account (3.23) with the pre-policy population density curve $D_0(x, u_0)$ and the pre-policy utility level u_0) and

---

by one percent from 0.04 to 0.0396 gallons per mile implies an increase of fuel economy by $0.253MPG$ to $25.253MPG$. Assuming a vehicle lifetime of 10 years, an annual marginal cost of fuel efficiency of $m_{tech} = 15\frac{\$}{MPG\,a}$ implies total (not annualized) marginal technology costs for a mileage increase by $0.253MPG$, that is, for a one-percent reduction in fuel consumption, of $15\frac{\$}{MPG\,a} \cdot 10a \cdot 0.253MPG = 37.95\$$. This is well in the range of 25 to 100$ from National Research Council (2015, p. 270).

The figure for a three-times higher annual marginal technology cost of $m_{tech} = 45\frac{\$}{mpg\,a}$ that is used in the sensitivity analysis later on in this section, thus, is three times higher as well with 113.85$ per percent of reduction in fuel consumption. This can be interpreted as an approximate upper bound of technology costs.

[26] Note, that utility is the same for all households in the full urban economic equilibrium. But in this intermediate state with $p(x)$ and x fixed utility differs over the distance x.

the change in driving costs (3.4) with new vehicle efficiency. The components of household income (3.3) remain unchanged. With the household budget modified in this way, individual household utility at distance x after step 1 is calculated according to (3.1), (3.10), and (3.11) with the pre-policy bid-rent curve $p_0(x, u_0)$ taken as exogenously given:

$$u_{1,CAFE}(x) = \frac{\alpha^{\alpha}(1-\alpha)^{(1-\alpha)}}{p_0(x, u_0)}(y - t(mpg_{CAFE}(x))x - v_{CAFE}(x)) \tag{3.29}$$

To calculate average utility after step 1 $u_{\varnothing\,1,CAFE}$, utility values at each distance x are weighted with the population density of the pre-policy state $D_0(x, u_0)$, integrated over the city area, and divided by the population L:

$$u_{\varnothing\,1,CAFE} = \frac{1}{L}\int_0^{\bar{x}} u_{1,CAFE}(x)D_0(x, u_0)2\pi x\, dx \tag{3.30}$$

Aggregate emissions are calculated according to (3.21), again with pre-policy population density $D_0(x, u_0)$, but with newly chosen fuel economy of vehicles.

Figure 3.2 shows average utility as a function of emission reduction in step 1 $u_{\varnothing\,1,CAFE}$ relative to the initial utility level over the aggregate emission reduction in percent that results from a progressing increase in fuel economy standards. The blue curve in Figure 3.2 (and all subsequent figures) depicts the reference case. The other curves show parameter settings with one parameter deviating from the reference case. Figure C.1 in the Appendix shows the same figure for absolute values of average utility and average per capita emissions. Since the pre-policy state is different for every parameter setting, the normalization enables comparability of the different cases.

For an aggregate emission reduction of up to approx. 40 percent, the welfare costs of compliance (which correspond to a relative income decrease of the same magnitude) are below one percent, that is, relatively small. They increase at different rising rates for more ambitious emission reduction goals.

Proposition 3.1. *Relative short-term welfare costs of compliance with fuel economy standards before an adjustment of the urban form are higher for a larger city population L, lower household income y_0, a higher gasoline price p_G, more expensive marginal annual technological costs of fuel efficiency m_{tech}, a higher elasticity of utility with respect to housing α, and a lower degree of decreasing returns to scale in housing production β.*

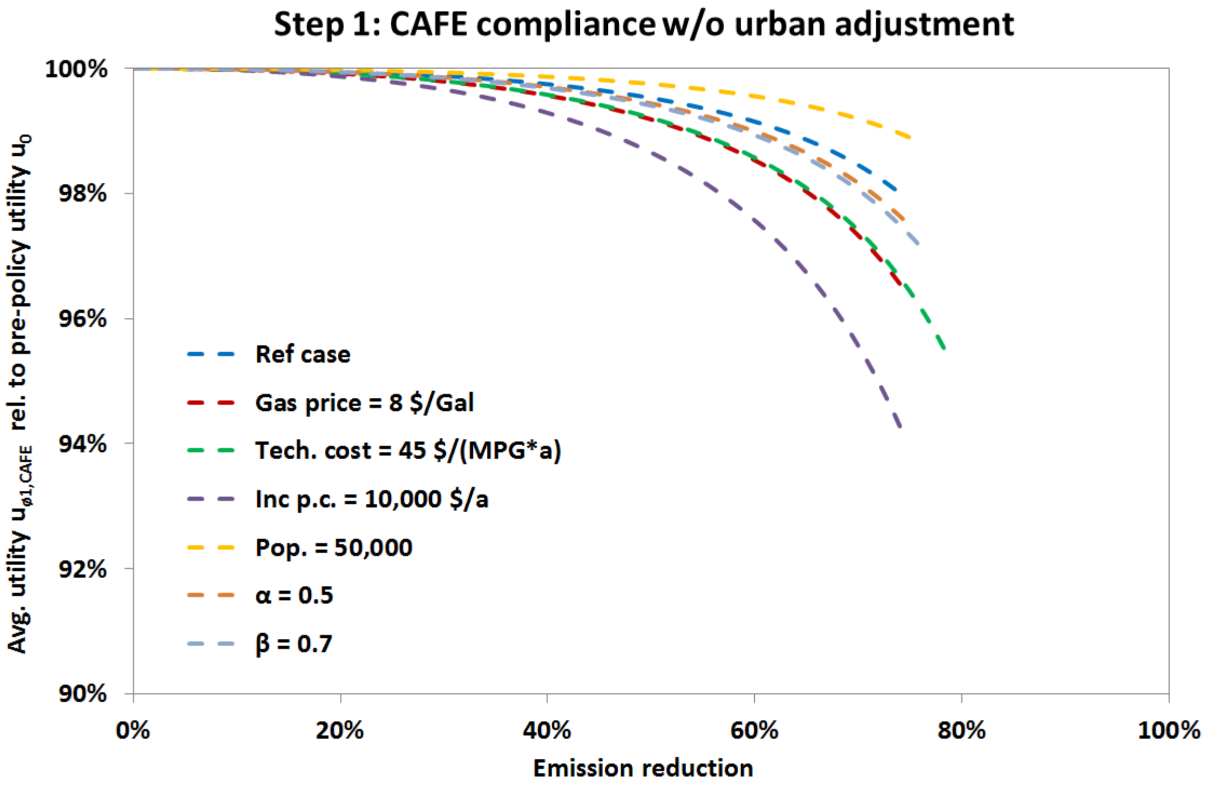

Figure 3.2 : Average utility trajectories for CAFE compliance without urban adjustment ("step 1") relative to the pre-policy utility level.

For a higher gas price, the city is smaller and denser in the first place with a shorter average commuting distance. Thus, the gains in driving costs are smaller, too. Also, higher gas prices lead to higher average fuel efficiency of the vehicles in the pre-policy state. But if fuel efficiency is already high, then a further increase in efficiency through a tightening CAFE standard leads to higher welfare costs due to a higher upward shift of the vehicle cost curve (because of a higher share of more expensive cleaner cars in the system compared to a "dirtier" car fleet in a case with cheap gasoline) .

Welfare costs are also higher for a higher slope of the technology cost curve of $m_{tech} = 45\frac{\$}{MPG\,a}$. With this parameter setting, households on average choose dirtier cars initially because of the marginal cost of efficiency. This (similarly to high gas prices) leads to a smaller and denser city with shorter commuting distances before the CAFE policy. The policy measure itself then comes with higher additional costs for vehicles and lower gains from saving gasoline. The same logic applies to a low elasticity of utility with respect to housing α and a high β which implies a low degree of decreasing returns to scale in housing production. Both lead to smaller and denser cities and the described consequences.[27]

A city with a low household income (e.g., 10,000 $\frac{\$}{a}$) is also relatively small with short driving distances and small gains from lower marginal costs of driving. But the monetary costs of the CAFE policy lead to higher welfare losses because of higher marginal utility at lower income levels. A high-income city which is smaller than in the reference case because of smaller population, in contrast, suffers smaller welfare losses than in the reference case.

Overall the welfare costs without urban adjustment seem low, but not trivial: in the reference case, a reduction of carbon emissions in the transportation sector by roughly 75 percent induces a welfare loss of about 2 percent. For the average commuting distance in the reference case these 2 percent correspond to an average annual monetary loss of about $940\frac{\$}{a}$. The adjustment of the urban form, which is left out of the picture here, takes place in the medium and long term. So, the resulting welfare effects may be interpreted as reflecting the short term.

3.4.2 Step 2 - General Equilibrium Urban Adjustment due to CAFE Policy

3.4.2.1 Rebound Effect

In the second step, household locations x and housing prices $p(x)$ become free to endogenously adjust to the CAFE policy shock and the city reaches its post-policy equilibrium according to (3.17) and (3.19). With higher fuel efficiency, the marginal cost of driving for all households is unambiguously lower than before the CAFE policy. So, every household moves further away from the CBD. The increase in the average commute contributes to higher carbon emissions and partly counteracts the emission reductions from the choice of more fuel efficient vehicles. This is the commute related part of the rebound effect in the long run. Figure 3.3 shows the average rebound effect from urban expansion over the degree of reduction in average carbon emissions for different parameter settings.

The rebound effect here is the share of the emission reduction in step 1 that is offset by the urban expansion of step 2. In the reference case it lies between 1 percent and 5 percent. This

---

[27] If the elasticity of utility with respect to housing α is low, then households' preference for housing is low compared to the composite good and households consume less housing on a smaller land area. If there is a low degree of decreasing returns to scale in housing production (high β), then it is cheaper to build high on a small land area than building low houses on a large area with high driving costs.

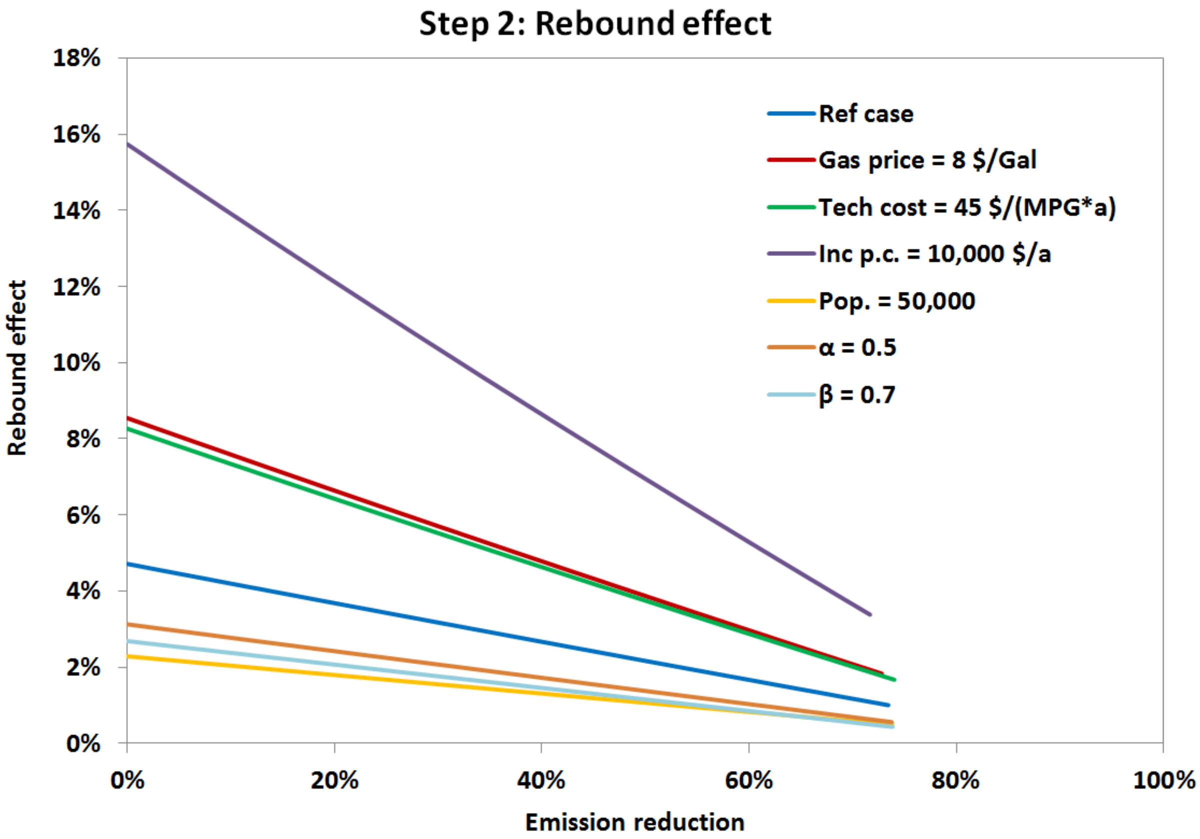

Figure 3.3 : Commute related long-term rebound effect for the reference case and deviating parameter settings

magnitude is well in the range of empirical estimates for the rebound effect in the U.S. (cf. Small and van Dender (2007), Hughes et al. (2008)) where public transit does not play as big a role as in Europe.[28]

The rebound effect for the same relative emission reduction, however, is much larger for lower exogenous household income y_0. It is also larger in the scenarios with higher gas prices p_G and with higher marginal technological costs of fuel efficiency m_{tech}.[29] This is in line with the empirical rebound literature. The new urban related effects on the rebound are summed up in the following proposition:

---

[28] Non-commuting trips also constitute a component of the rebound effect, but as long as we do not assume different magnitudes of rebound for different types of trips, the observed magnitude of the commute rebound effect should be the same as the size of the total effect.

[29] This is at least consistent with the empirical finding of Frondel et al. (2012) that the rebound effect is greater in Germany with its higher gasoline prices – but also many other different features like the public transit system – than the U.S.

Proposition 3.2. *The rebound effect is large for relatively small, dense cities. It is larger than in the reference case for higher city population L, for a lower elasticity of utility with respect to housing α, this is, lower consumer preference for housing*[30]*, and for more strongly decreasing returns to scale in construction β.*

The relative differences in the rebound effect for different parameter settings can in large part be explained by the parameters' effect on population density and the resulting urban form: for instance, high gasoline prices lead to high marginal travel costs (despite the choice of more fuel efficient vehicles by households). This, in turn, leads to a much denser city in the first place because people consume less housing. The same is true for high marginal technological costs of fuel efficiency: households choose less fuel efficient cars and face higher marginal costs of travel. The two numerical scenarios with a high gasoline price p_G (red) and high marginal technological costs of fuel efficiency m_{tech} shown in Figure 3.3 happen to yield very close results in terms of marginal driving costs, city size and rebound effect. A lower household income of $10,000\frac{\$}{a}$ (instead of $50,000\frac{\$}{a}$) leads to an even more compact, dense city with small dwellings for relatively poor households.

But in a relatively dense city the average commute must increase more strongly to reach a new equilibrium after a decrease in marginal driving costs. In the urban economic equilibrium the housing price gradient over the distance x must correspond to the marginal costs of an increase in commuting distance. If travel costs decrease because of the fuel economy policy, then households must move away from the CBD to cause a sufficient decrease in the housing price gradient and to reach the new equilibrium. With high population density on a geographically small city area, a one-percent increase in the average commute only yields a small relative increase in additional area for new developments, causing only a small adjustment in the housing price gradient. But if the same population in the beginning is distributed over a larger area, a one-percent increase in the (also longer) average commute yields a significantly larger increase in city area and housing supply. This is because, on the one hand, one percent of a longer distance is longer in absolute terms and, on the other hand, the circular area increases quadratically with radius, but the average commute only increases approximately linearly. Therefore, in a denser city a larger relative increase in the average commute is needed to achieve the required adjustment of the housing price gradient after a CAFE-driven increase in driving costs. Coming back to Figure 3.3, for expensive gasoline

---

[30] The elasticity of utility with respect to housing α can also be interpreted as the level of amenities in the city, which leads to a higher preference for housing compared to the composite good.

and marginal technology improvements, the city is dense and the resulting rebound is high, even more so for low income. In contrast, for cities with low, but wealthy, population, high preference for housing α and low degree of decreasing returns to scale in construction β (possibly due to low regulation in construction), density is low, as is the magnitude of the rebound effect.

It is also interesting that the commute related long-term rebound effect decreases with tightening CAFE policy in all parameter settings. The reason for that is that for more ambitious emission reduction goals the rising aggregate vehicle costs in the system contribute to a contraction of the city due to lower available income, counteracting the rebound effect.[31]

While rents in the city center decrease, rents in the suburbs increase and a ring of additional land is developed around the city. The dwelling size in the center increases, while it decreases in the outskirts due to the rise in population density. On average, however, dwelling size rises. But since the choice of fuel efficiency is also a function of distance to the CBD (cf. Equation (3.22)), households at the new location choose even more efficient vehicles, decreasing the marginal costs of driving even further. Increasing distance and rising fuel efficiency, thus, reinforce each other until a new equilibrium is reached. Table 3.3 shows how the city size, the average commuting trip length, and carbon emissions are affected by the CAFE policy in the two analytic steps.

	Pre- policy	Step 1 CAFE compliance w/o urban adjustment	Step 2 CAFE w/ urban adjustment
m_{CAFE} [$\frac{\$}{MPG\,a}$]	15	3	3
City boundary $\bar{x}$ [m]	30,509.06	30,509.06	31,330.07 (+2.69%)
Avg. commute [m]	18,441.96	18,441.96	19,285.76 (+4.6%)
Avg. CO_2 emissions [$\frac{tons\,p.c.}{a}$]	1.436	0.642	0.658 (+2%)
Avg. mileage [$\frac{Miles}{Gal}$]	30.145	67.405	69.035 (+2.4%)

Table 3.3 : Change of city characteristics for CAFE compliance without and with urban adjustment. Change of step 2 rel. to step 1 in brackets.

---

[31] Additionally, the more fuel efficiency rises on average, the lower is the share of actual gasoline expenses in the marginal cost of driving and the higher is the share of marginal costs of maintenance. Therefore, tightening the fuel economy standard even further only triggers a smaller decrease of marginal driving costs in percentage terms and, thus, a smaller rebound effect. But the magnitude of this effect is clearly subordinate to the first effect.

3.4.2.2 Welfare Analysis

After the urban adjustment in step 2, the city reaches its uniform post-policy utility level $u_{2,CAFE}$. The urban adjustment leads to two new channels of fuel economy standards on welfare summed up in the following proposition.

Proposition 3.3. *The long-term expansion of the urban form leads to two counteracting effects on welfare on top of the welfare costs of compliance of step 1: additional welfare costs from an additional increase in fuel efficiency and welfare gains from an increase in housing supply. The net welfare effect is negative and large for a strong rebound effect.*

First, the additional increase in every household's chosen fuel efficiency and simultaneous change in travel costs lead to additional monetary costs. The decrease in available income translates into additional welfare costs. Here, the increase in average commuting distance and vehicle costs outweighs the gains from the reduction in marginal driving costs. On top of that, a distortion in the vehicle market that the CAFE policy creates amplifies this negative welfare channel: the adjustment in vehicle choice causes additional production costs of m_{tech} for each additional mile per gallon, but households only account for m_{CAFE} for each additional mile per gallon in their vehicle choice decision (3.22). The difference of $(m_{tech} - m_{CAFE})$ is shifted equally to all households through the increase of the intercept $v_{0,CAFE}$ in the CAFE mechanism. This distortion in the vehicle market creates a cross-subsidy from central owners of less efficient cars to suburban owners of more efficient cars. The result is an according deadweight loss.

The second effect is the welfare effect from the increase in average dwelling size. It is always positive in the case of urban expansion. Since the city population distributes over a larger area housing supply rises. Also, the decreasing returns to building higher imply that a flatter city leads to lower housing production costs. These factors contribute to a decrease in average housing prices and, therefore, an increase in average consumption of housing and of the composite good.

It is difficult to quantitatively disentangle the two components of the welfare effect of urban expansion in an analytically consistent way because both effects necessarily happen simultaneously. Also, the increase in housing supply is the incentive for households to increase their distance to the CBD in the first place. The housing supply component works through housing prices and the vehicle choice component works through an effect on available household income. Thus, it would be interesting, despite the logical simultaneity, to calculate the effect of this change in available income (due to the change expenses for the vehicle and for driving the new increased distance) on household utility while assuming the housing price curve $p_0(x)$ from before the urban expansion. However, there is no clear way of matching new distances x_2 and vehicles $mpg(x_2)$ of every household after the expansion with the same household's location x_1 before the expansion because the model does not contain discrete households, but instead a continuous population density function. But a way to at least gain some insight from a rough approximation is to compare utility of a household at the average distance with the average vehicle before the expansion to that of its counterpart after the expansion. In this exercise for the parameter setting of the reference case (cf. Appendix C.1.2) the (negative) vehicle related component and the (positive) housing related component of the total welfare effect of step 2 have a magnitude between 10 percent and 120 percent of the welfare costs of compliance in step 1.

The resulting net welfare effect of long-run urban expansion is negative because of the distortion in the vehicle market and the resulting deadweight loss. Despite the additional degree of freedom in the system via urban adjustment, utility decreases because the deadweight loss due to the distortion of the vehicle market is not accounted for by households in their vehicle choice. Figure 3.4 shows the size of this net welfare cost of long-term expansion in step 2 ($\Delta u_{2,CAFE} = u_{\varnothing 1,CAFE} - u_{2,CAFE}$) relative to the welfare cost of short-term CAFE compliance without urban adjustment in step 1 ($\Delta u_{1,CAFE} = u_0 - u_{\varnothing 1,CAFE}$) for the reference case, but also for the same deviating parameter settings as in Figures 3.2 and 3.3.

Figure 3.4, as well as the following figures, starts at a reduction of aggregate emissions by 20 percent. Since long-term decarbonization paths are in the focus, smaller emission reduction targets are not as politically relevant. Another technical reason to leave the area below 20 percent out of the picture is that limits in numerical accuracy can lead to a non-negligible bias of the results for very small emission reduction targets.

A common pattern of all cases is that for small emission reductions the additional welfare loss of urban adjustment is large relative to the welfare effect of compliance without urban adjustment. However, absolute welfare costs are rather small (cf. Figure 3.2). For more ambitious climate goals the magnitude of the additional welfare loss of urban expansion decreases relative to compliance without urban adjustment, but the total welfare loss is larger, so that in absolute terms the welfare cost of urban adjustment is still larger than for small emission reductions. The order of cases is the same as for the size of the rebound effect. Urban expansion (and the according increase in emissions and chosen fuel efficiency

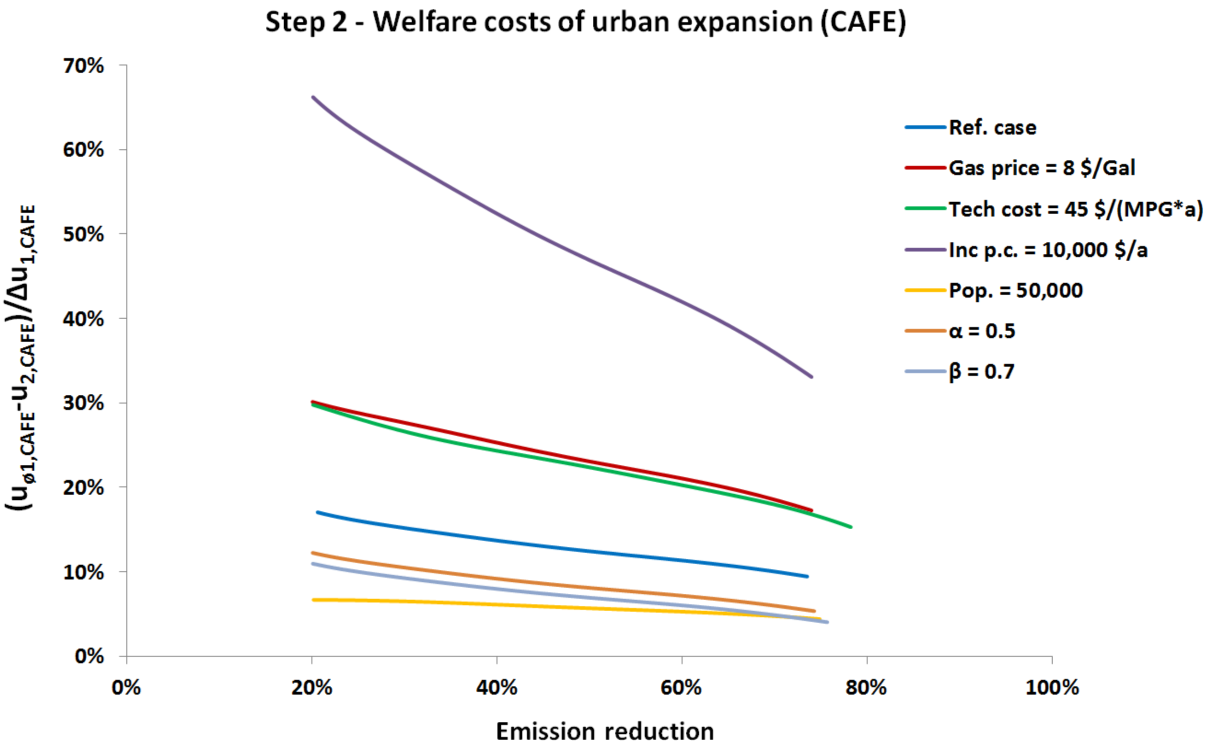

Figure 3.4 : Net welfare costs of urban expansion (step 2) relative to the welfare cost of CAFE compliance without urban expansion (step 1) for different emission reduction targets

of vehicles) induces between 10 percent and 20 percent additional welfare costs on top of CAFE compliance in step 1 for the reference city. These values rise to 20 percent to 35 percent for the scenarios with significantly more expensive gasoline and vehicle technology. For lower household income (from $50,000\frac{\$}{a}$ to $10,000\frac{\$}{a}$) near the level of emerging economies the additional welfare cost of urban adjustment is in the range of 40 percent to 70 percent of the welfare cost of compliance without urban adjustment. The cases with a stronger urban expansion (and higher rebound effect) also exhibit higher additional welfare costs due to this expansion.

3.4.3 Fuel Tax Policy

The urban parameters of a city obviously play a role for the magnitude of welfare costs of the "command-and-control" CAFE policy in the compliance case without urban adjustment, and of the welfare costs of urban adjustment itself. But the welfare costs of a fuel tax, which is the first-best policy instrument here, are also affected by the very same urban parameters. On the one hand, households' vehicle choice is influenced differently by the tax at different distances x, depending on the city's parameters. On the other hand, there is also an adjustment of the urban form with a fuel tax, but in the opposite direction than with CAFE: the increase of the consumer fuel price leads to a contraction of the city and to the choice of less efficient vehicles than without a contraction. Again, the welfare effects of the policy measure are analyzed in two steps: in step 1, real estate prices $p_0(x, u_0)$ and distances x are frozen and households only react to the tax increase by choosing more efficient vehicles by (3.25), leading to short-term welfare costs of compliance. But despite the improvement in fuel efficiency, the marginal cost of driving increases. In step 2 the real estate market reaches its new equilibrium and the city exhibits a contraction.

3.4.3.1 Step 1 - Fuel Tax Compliance before Urban Adjustment

In analogy to the CAFE policy (cf. (3.29)), the household budget ((3.2) and (3.3)) is modified by using (3.26) and (3.28), while $p_0(x, u_0)$ and $D_0(x, u_0)$ remain unchanged in step 1. Also, the utility level after step 1 of the fuel tax policy is calculated using (3.1), (3.12), and (3.13):

$$u_{1,Tax}(x) = \frac{\alpha^\alpha (1-\alpha)^{(1-\alpha)}}{p_0(x, u_0)} (y - t_{Tax}(x)x - v_{Tax}(x))$$

Average utility after step 1 $u_{\varnothing\,1,Tax}$ is calculated like in (3.30):

$$u_{\varnothing\,1,Tax} = \frac{1}{L} \int_0^{\bar{x}} u_{1,Tax}(x) D_0(x, u_0) 2\pi x \, dx$$

For step 1, (short-term tax compliance without urban adjustment) the trajectory of welfare over reduction of carbon emissions in all observed cases is relatively close to the CAFE policy: for the reference city the difference between the welfare costs of CAFE and the fuel tax is below 5 percent of compliance costs for CAFE (cf. Figure 3.5). Again, for low income, the deviation between CAFE and the fuel tax policy of welfare costs in step 1 is the largest with up to 15 percent of $\Delta\, u_{\varnothing\,1,CAFE}$.

All commuting distances remain unchanged at this stage. The only variable that can adjust is the vehicle choice. Therefore it is not surprising that an emission reduction over the same variable (vehicle mileage) leads to similar welfare costs. What accounts for the difference are the different market distortions and according welfare costs of the two policies: with the CAFE policy households do not internalize the correct cost of fuel technology due to the cross subsidy from owners of dirty cars to owners of cleaner ones. But the fuel tax distorts the gas price and, despite the lump-sum recycling of revenues, causes a deadweight loss different to the CAFE distortion on the vehicle market.

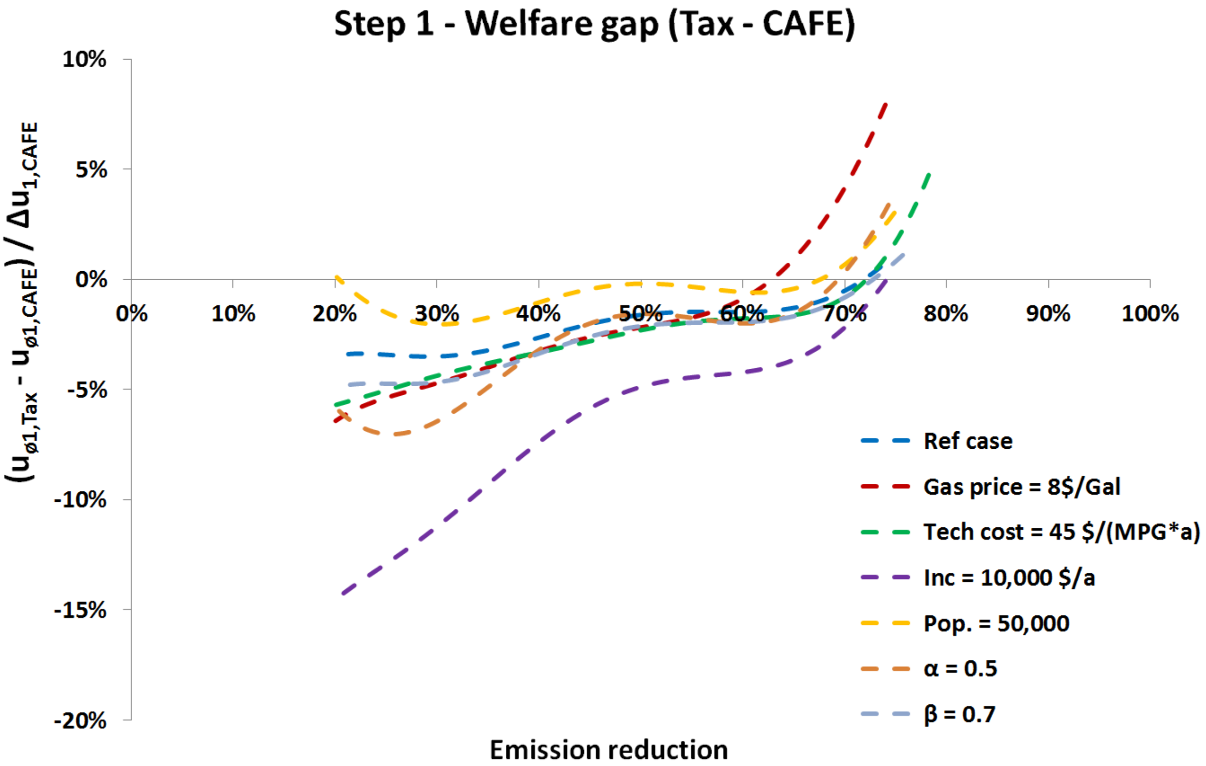

Figure 3.5 : Difference in the welfare cost of compliance without urban adjustment (Step 1) between the fuel tax policy and the CAFE policy

3.4.3.2 Welfare analysis of urban contraction

The urban adjustment induced by the fuel tax policy yields, similarly to the CAFE policy (cf. Proposition 3.3), two new welfare channels, summarized in the following proposition.

Proposition 3.4. *The long-term urban contraction leads to two counteracting effects of fuel taxes on welfare: welfare gains from reduced expenses due to less fuel efficient vehicles and welfare costs from a reduction in average housing consumption. The net welfare effect is positive and large for the parameter settings which cause a large rebound effect in the case of the CAFE policy.*

Figure 3.6 illustrates the trajectories of utility after the steps 1 and 2 for different aggregate emission reduction targets for the fuel tax policy (green) and, for comparison, for the CAFE policy (blue).

The trajectory of short-term compliance without urban adjustment (step 1, dashed line) is almost identical for both policies here. While the CAFE curve with urban adjustment (solid, blue) lies below the short-term CAFE compliance curve (cf. Section 3.4.2), the fuel tax curve

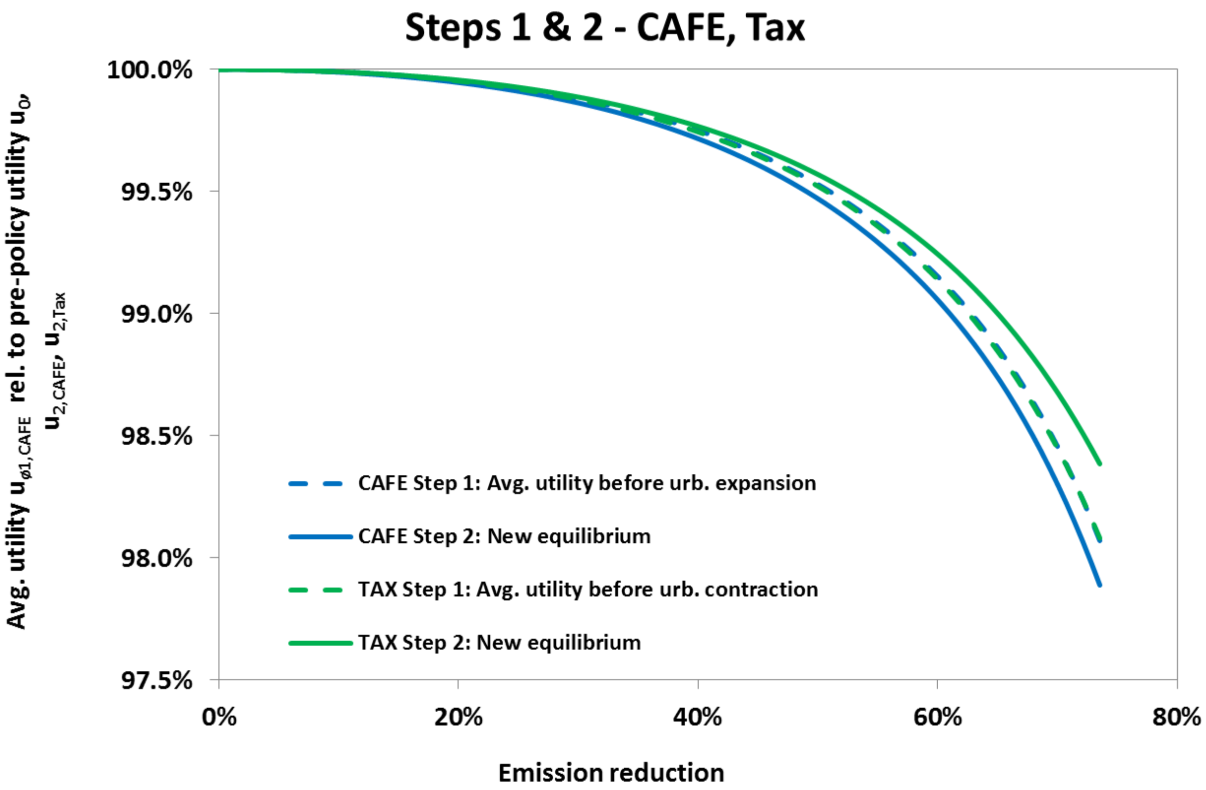

Figure 3.6 : Welfare effects of CAFE and the fuel tax policy over emission reduction goals for the reference case

with urban adjustment (solid, green) lies above the short-term pure tax compliance curve. The reason is exactly opposite to the CAFE case: the urban contraction reduces the average commuting trip length and emissions, while it also yields an increase in available income and resulting utility due to vehicle cost reductions because of the choice of less fuel efficient vehicles at shorter commuting distances x. The positive net welfare effect of urban contraction in the tax policy case ($\Delta u_{2,Tax} = u_{2,Tax} - u_{\varnothing 1,Tax}$) relative to the welfare costs of compliance in step 1 is depicted for different parameter values in Figure 3.7.

Of course, it is clear from the outset that the fuel tax policy, which is the first-best instrument, leads to higher welfare than a command-and-control CAFE policy for a given emission reduction target. But the final (post step 2) welfare gap between the two policies in this model is largely driven by the welfare effects of urban adjustment. The size of the total welfare gap between CAFE and the fuel tax policy, therefore, depends on the model parameters which determine the magnitude of urban expansion (CAFE) and contraction (fuel tax), as is summarized in the next proposition, and as we see in Figure 3.8.

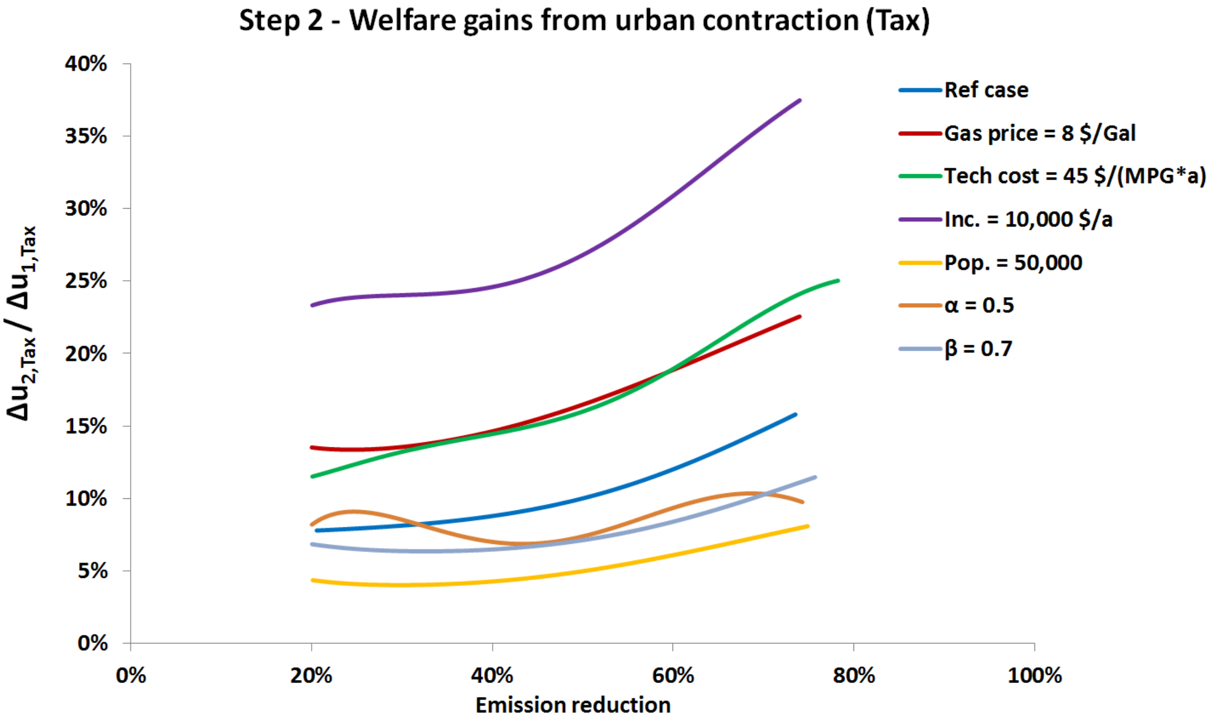

Figure 3.7 : Welfare gains from urban contraction for the fuel tax policy rel. to the welfare costs of tax compliance without urban adjustment $\Delta u_{1,Tax}$

Proposition 3.5. *The total welfare gap between the fuel tax and fuel economy standard policy is large for the parameter settings which also put a large weight on the welfare costs of urban adjustment under both policies.*

The order of cases is the same for the different parameter settings as in Sections 3.4.1 and 3.4.2. This is plausible since the magnitude of urban expansion or contraction, that drives the size of the commute related rebound effect in Section 3.4.2, also drives the magnitude of the welfare effect of expansion or contraction.[32]

For the reference city the welfare gap is in the range of 20 percent to 30 percent. For a smaller rebound effect (cf. Figure 3.3) the welfare gap is smaller, and vice versa. Again, a low income level of $10,000\frac{\$}{a}$ yields the largest effect: the welfare gap between CAFE and a fuel tax policy has a considerable magnitude of 70 percent to 80 percent of $\Delta u_{1,CAFE}$. Not only are the (step 1) welfare costs of any of the two policies without urban adjustment significantly higher

---

[32] Note, that the total size of the welfare gap between CAFE and a fuel tax policy does not exactly equal the sum of the absolute values of the CAFE policy's expansion related welfare costs and the contraction related welfare gains of the tax. The average utility levels after step 1, which are used for the calculation of the respective welfare effect of urban adjustment, slightly differ for the two policies (cf. Figure 3.5).

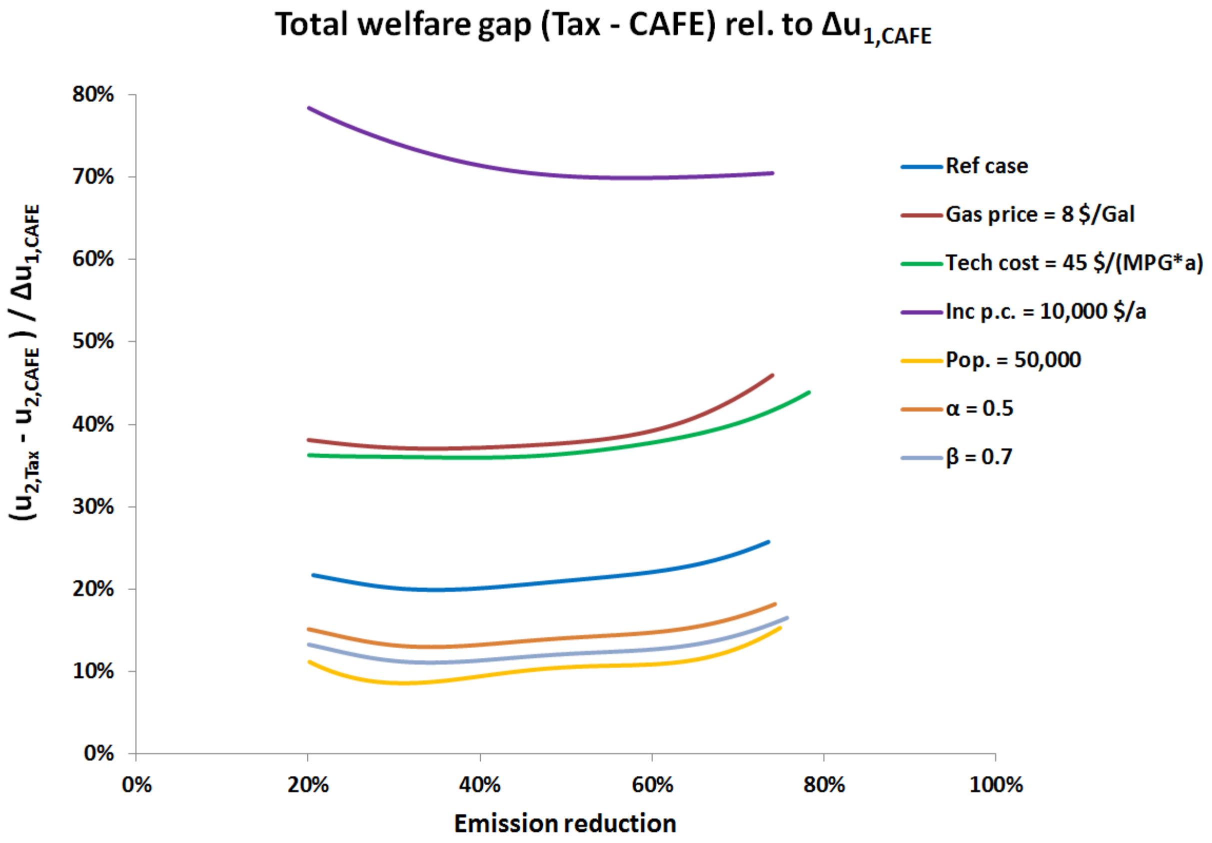

Figure 3.8 : Total welfare gap between the fuel tax and CAFE rel. to $\Delta u_{1,CAFE}$

for low household income (cf. Section 3.4.1). But in poor cities the additional welfare costs of (step 2) urban adjustment – expansion in the case of CAFE, as well as contraction in the case of a fuel tax – are much greater too. The big welfare gap between the two policies leads to the conclusion that the importance of the instrument choice decreases with the income level. While in high income countries the welfare gap does not seem to be crucial for the policy choice, its importance is higher for low income countries. But for a reasonable policy advice, e.g., for newly industrializing countries additional aspects like mobility patterns and development of public transit e taken into account.

3.5 CAFE with Urban Growth Boundaries

The reaction of the urban form is an important factor for the overall welfare implications of different environmental policies in the transportation sector. An expansion leads to additional welfare costs in the form of higher spending on fuel efficiency technology for cars to reach a certain emission goal. An additional spatial constraint like a policy-driven urban growth boundary (UGB) should be expected to affect the results. In this section, this influence on the results of the welfare analysis from above is analyzed.

Urban growth boundaries are discussed in urban economics as a measure to reduce urban sprawl (see, e.g., Turnbull (2004), Dempsey and Plantinga (2013)) and traffic congestion (cf. Brueckner (2007), Anas and Rhee (2007)). The outer boundary of the city becomes fixed at the preexisting magnitude ($\bar{x} = \bar{x}_0$), so that the city cannot expand into the surrounding area. Households can still move within the boundary. But the density profile, the housing market, and – in the present case – vehicle choice at every point of the city are affected by the presence of an urban growth boundary. If the UGB is binding, then at the edge of the city the land rent lies above the agricultural rent ($r(\bar{x}) > r_A$), so that (3.17) does not hold anymore. In the case of a fuel tax policy, an urban growth boundary has no effect since it does not stop the city's contraction. But in the case of fuel economy standards a growth boundary can be, and mostly is, binding.[33] Households still move away from the center, but within the spatial limit. They also choose more fuel efficient vehicles, but only according to their smaller increase of distance to the CBD. Overall, the CAFE-driven increase in average commuting distance and decrease in emissions still takes place, but in a dampened fashion. Figure 3.9 depicts the influence of an urban growth boundary on the welfare effect of urban expansion for the reference case (zooming in on a section of the trajectory).

The dashed blue curve is the compliance case without urban adjustment known from Section 3.4.1. And the solid blue curve is the outcome unrestricted by an urban growth boundary from Section 3.4.2. The red dashed curve is the final equilibrium outcome of CAFE combined with an UGB.

Proposition 3.6. *A combination of fuel economy standards with an urban growth boundary reduces urban expansion to the increase of commuting distances* x *within the initial city boundary* $\bar{x}_0$*. It decreases the according welfare costs of urban expansion for a given emission reduction goal by roughly one half.*

---

[33] There might be cases in which CAFE standards also lead to contraction. The monetary loss through rising vehicle cost, which is contributing to contraction, might outweigh the expanding effect of decreasing marginal costs of driving. There are parameter settings where the CAFE-induced expansion stopped and the city started to shrink if the fuel economy standard was raised further.

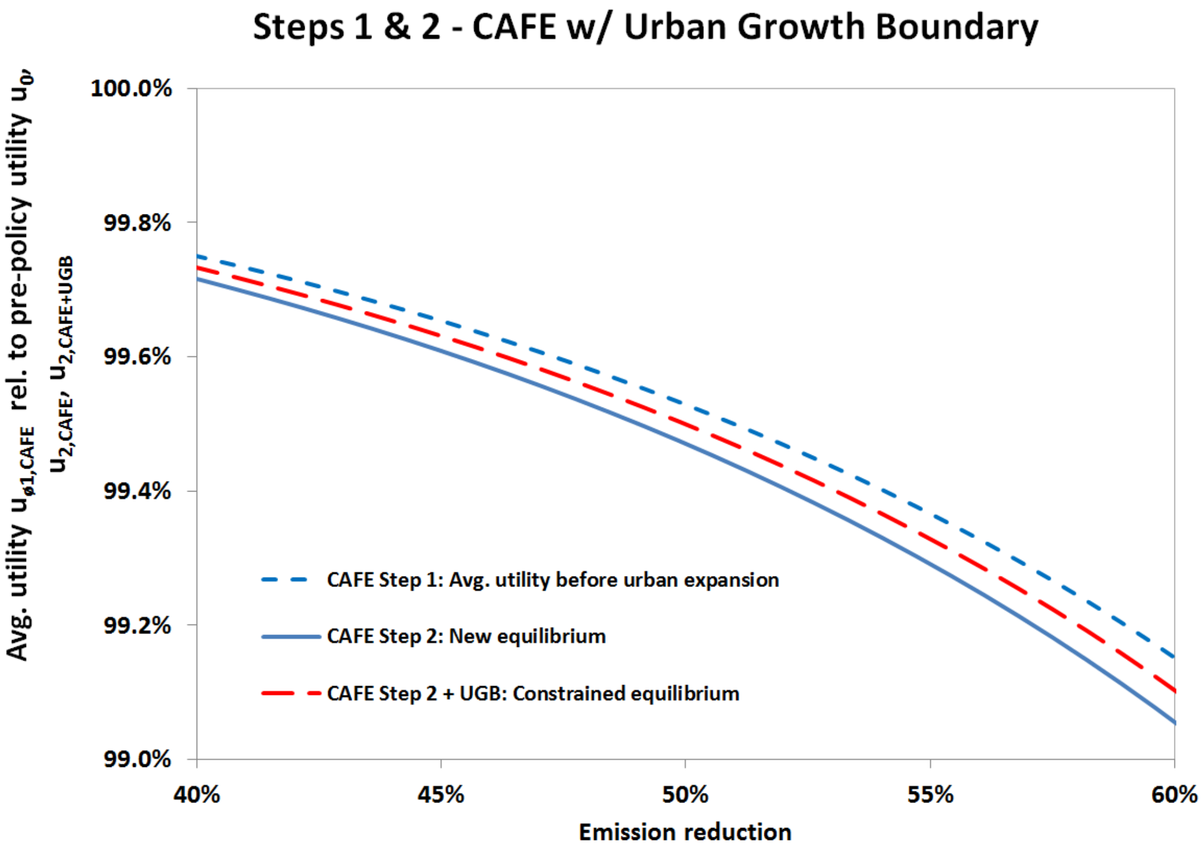

Figure 3.9 : Influence of an urban growth boundary (UGB) on the welfare effect of urban adjustment for CAFE

Figure 3.10 gives an overview over how strongly the combination of fuel economy standards with an UGB reduces the welfare costs of urban expansion for the reference city and again for deviating parameter settings.

For all analyzed parameter settings between 40 percent and 60 percent, so roughly half, of the detrimental welfare effect of urban expansion is avoided by the combination of CAFE with an UGB. Differences in model parameters and the strictness of the climate goal do not seem to play a big role for this effect of UGB. Figure 3.11 shows the reduction of the total welfare gap between the case of a fuel tax, as the first-best policy, and a second-best fuel economy standard which results from the combination of CAFE standards with UGB.

Between 20 percent and 40 percent of the welfare gap can be closed, mostly uniformly over the different parameter settings. For more ambitious climate goals the advantage in percentage terms decreases below 20 percent. But the absolute gains from the use of UGB are still higher since absolute welfare costs of compliance are higher for stronger emission reductions too.

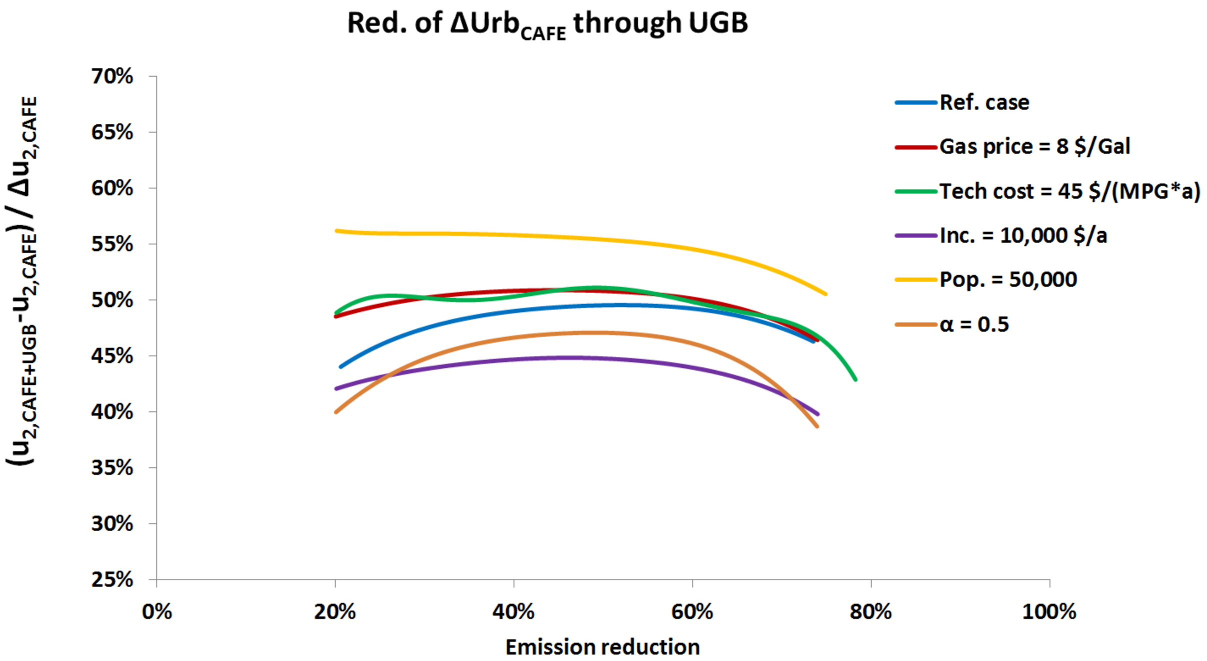

Figure 3.10 : Reduction of the welfare costs of CAFE-driven urban expansion relative to $\Delta u_{1,CAFE}$ due to the combination of CAFE with an UGB for different parameter settings

This shows that UGBs should be seriously considered as a complementary policy together with fuel economy standards, and the more so in countries with a lower income level. The fact that in many European countries metro areas have de-facto UGB is favorable to the use of fuel economy standards as climate policy in the transportation sector.

3.6 Distributional Aspects

Both environmental policies have distributional effects which can play a role for long-term public support and democratic political feasibility. On the one hand, there are distributional effects between different households within one city. On the other hand, the policies lead to monetary redistribution between different cities, if applied on the national level.

3.6.1 Distributional Effects within a City

In the case of fuel economy standards, owners of less fuel efficient cars cross-subsidize owners of cleaner cars. Considering the role of commuting trip lengths for vehicle choice (cf. (3.22)) this means that central residents in a city subsidize the cleaner vehicles of suburban residents. In the U.S., neighborhoods close to the city center are often less wealthy than suburbs. This seems to imply that CAFE standards might have a regressive distributional effect and hit

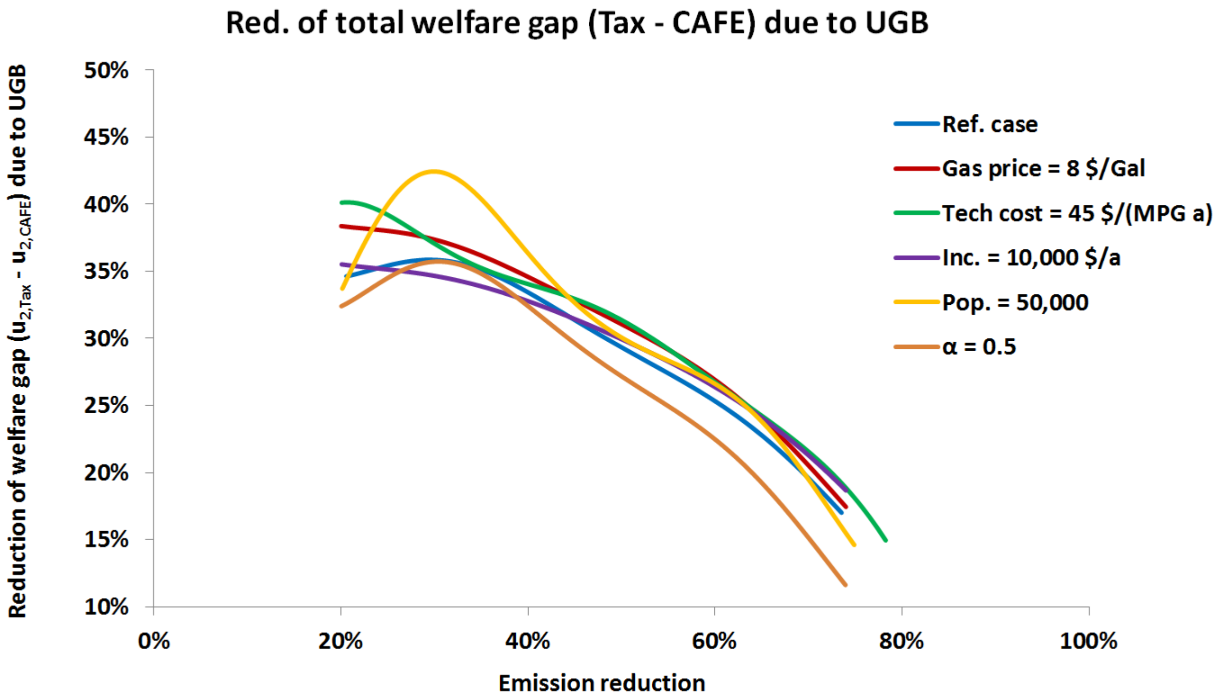

Figure 3.11 : Reduction of the total welfare gap between a fuel tax and CAFE standards through the addition of UGB

poor central households harder than more wealthy suburban households. Such a regressive environmental policy could be considered unfair, especially for a high degree of income inequality, and suffer from the lack of public support. In Europe or developing countries poor neighborhoods are often located far away from the centers. Then the distributional effect of fuel economy standards could be progressive and run from rich central residents to poor suburban residents.

For a fuel tax, the direct redistributive monetary effect of the policy has the opposite direction: households at long commuting distances pay a higher amount of fuel taxes than central households. This is despite more fuel efficient vehicles in the suburbs because distance rises linearly, but fuel efficiency only increases according to a root function (cf. (3.25)). The lump-sum tax refund is the same for all households. Therefore, suburban residents will be net payers and central residents will be net receivers.

The role of these redistributive effects on welfare hinges on the incorporation of heterogeneity among the city population in terms of income and of a mechanism that determines the location of income groups in the city. Different consumption levels imply different marginal utilities of households, while the resulting location of income groups would relate them to vehicle choice and the respective distributive effects of CAFE or a fuel tax policy. At the same time, the question is how the capitalization of monetary advantages or disadvantages of different locations into the respective housing prices would affect the welfare balance of the environmental policies for heterogeneous income groups. This question requires an in-depth analysis in future research.

3.6.2 Distributional Effects between Cities

The distributional effects within a city, as well as the results of the welfare analysis in Sections 3.4 and 3.5, strictly speaking apply to cases where the policies are introduced on the municipal level or where the model city is seen as representative for a country with many identical cities. But when a country's municipalities differ with respect to their parameters (income, population size, the elasticity of utility with respect to housing α, and the scale exponent in construction β) and the environmental policies are introduced on the national level with an identical tax rate τ or an identical vehicle price curve m_{CAFE} across cities, then there will be distributional effects between different cities with uniform income or between different income groups of various cities.

The choice of vehicle efficiency (cf. (3.22) and (3.25)) holds irrespectively of income and population size. But the upward shift of the vehicle cost curve (cf. Figure 3.1) depends on the frequency distribution of chosen vehicles in all other cities, too. The payers of the cross subsidy via the CAFE mechanism will then be all households with relatively inefficient cars at low commuting distances in the country up to a certain distance x. These can be inhabitants of small cities in the countryside or central residents of big metropolitan areas.[34] The cross subsidy will be received by drivers of very fuel efficient vehicles at high commuting distances, especially in large metro areas. Again, in the U.S. small town dwellers and central residents in big cities tend to have a lower income than households in suburbs of big metropolitan areas. In this case, these cities are relatively smaller and their households chose additionally less fuel efficient cars. Therefore, the monetary distributional effect can be expected to have a higher welfare effect there. Considering such a typical American spatial distribution of income groups, the regressive distributional effect of the CAFE mechanism within one city seems likely to take place in a system of heterogeneous cities as well.

---

[34] Note that the administrative autonomy of a municipality is not as important as its economic role in the region. An independent town close to the edge of a big metro area will count as a suburb here.

Like in the case of a single city, a fuel tax policy with lump-sum tax recycling will redistribute money from (often wealthy) households in suburbs of big cities to (often less wealthy) central residents or residents in small towns in the countryside. In this case the fuel tax would again yield a progressive distributional effect on the national level. Of course, if recreational and shopping trips were taken into account, the distributiove result might change.

It is important to keep in mind here that the magnitude of the respective monetary and welfare-related distributional effects on the national level depends on the frequency distribution of city sizes, commuting distances and income. In a country with a high share of the population living in small towns close to the CBD and a considerable share living in big metro areas the borderline household between net payers and net receivers will lie at a different distance from the center than in a country with most people living in one of the few big metro areas (like Australia). A systematic theoretic and quantitative analysis of distributional effects between cities that takes these frequency distributions into account is left for further research in a follow-up paper.

3.7 Conclusion

This chapter shows the important role of urban economic factors and mechanisms for the welfare costs of fuel economy standards and fuel taxes as environmental policies in the transportation sector. Even in the short term, before an adjustment of the urban form and of the simultaneous vehicle choice takes place, urban parameters affect the welfare costs of compliance. But the long-term urban adjustment opens up two new welfare channels for each policy: in the case of fuel economy standards, the increase in fuel efficiency implies an urban expansion with longer commuting distances and a self-reinforcing feedback loop on vehicle efficiency with welfare gains from additional housing and welfare losses from additional compliance costs. This commute related long-run rebound effect is large for all parameter setting which make the city small and dense: for low household income, high city population, a low preference for housing, and strongly decreasing returns to scale in building high. Similarly, a fuel tax policy leads to urban contraction with shorter commuting trips and less fuel efficient vehicles, again reinforcing each other. The welfare losses from the reduction in housing consumption are outweighed by welfare gains from lower expenses for fuel efficiency. The magnitude of these new welfare channels is significant: especially for low household income, high gasoline prices, and/or high marginal costs of fuel efficiency technology the welfare effects of housing adjustment and additional compliance can have similar or even a greater magnitude than the short-term welfare costs of compliance before any urban adjustment.

The total resulting welfare gap between the fuel tax policy and fuel economy standards is strongly affected by the magnitude of induced urban adjustments. In countries with small average city size, high household income, a high amenity value (that is, high preference for housing in the consumption bundle), and strongly decreasing returns to scale in housing production, which might often well describe U.S. cities, the disadvantage of fuel economy standards is actually not very high. In contrast, for emerging economies like China, India or Brazil, where most traffic takes place in (on average) large metro areas with a relatively low income, and often low amenities, applying fuel economy standards instead of fuel taxes might incur a much greater additional welfare cost with a magnitude of some 80 percent of short-run welfare costs of compliance. Measures which reduce urban expansion, like urban growth boundaries, therefore, can significantly improve the welfare balance of fuel economy standards by cutting the additional welfare costs of urban expansion roughly in half.

Both, fuel economy standards and fuel taxes, involve distributional effects which can play an important role for the political economy of these measures. In a short discussion, I provide an overview over different spatial distributional effects in this context. While fuel economy standards constitute a cross subsidy from central to suburban residents, a fuel tax policy has exactly the opposite effect. Depending on the location of different income groups (which have not been modelled here) this can overall imply progressive or regressive effects. But since the policies are typically introduced on a national (or, in the case of the E.U., even supranational) level, they might lead to significant distributional effects between cities with different characteristics. This complex of questions and effects will be analyzed in a subsequent study.

A crucial next step for future research is the incorporation of public transit and a plausible mobility mode choice mechanism into the model. It can be expected that the changes in marginal costs of driving and the according cross-subsidies due to the environmental policies affect mode choice to a significant extent, depending on the household location. The switching of a considerable share of households into or out of public transit might constitute an important determinant of the degree of transit capacity utilization and the according pricing schemes. A subsequent increase in transit prices might reinforce the choice of individual vehicles even more, or vice versa. This issue deserves further examination.

Another energy economic issue which is not addressed here is the transition to electric vehicles and their economic and environmental implications in an urban framework. Electric vehicles could be included in the model as having a high "fuel efficiency" in terms of miles per kg of carbon emissions, but a limited driving range. For now, combustion engines constitute the lion’s share of the vehicle fleet and the vehicle markets. But especially in the long run, the role of a higher share of electric cars and transition pathways towards it should be taken into account. The present chapter provides an advance relative to the scarce previous literature in the modelling of household vehicle choice based on fuel economy and the according implications of fuel economy standards for automakers’ pricing and R&D policies, but abstracts from the role of vehicle convenience (for also which driving range issues might play a role). An enhanced view on vehicle choice based not only on fuel economy, but also on vehicle convenience, would certainly contribute to a more realistic analysis and a more informed perspective on the importance of this vehicle choice dimension. Moreover, the assumption of linear pricing schedule could be relaxed in favor of a more elaborate vehicle pricing policy.

Of course, the underlying monocentric urban model is stylized, but it allows for this type of energy economic extensions in a relatively tractable way. Real cities are often polycentric in varying degrees. Also, I use a static model without any forward-looking behavior on the side of households, although it is quite plausible that some long-term developments like demographics play a role for household decisions like buying a house. The significance of these factors for environmental economic questions like in the present chapter should be taken care of in future work.

4 Climate Policy and Inequality in Two-Dimensional Political Competition

4.1 Introduction[1]

For the last three decades international negotiations on the reduction of greenhouse gas emissions did not deliver significant results. The voluntary national emission reduction goals which are part of the Paris Agreement are by far not enough to reach the agreed-upon two-degree target (not even to speak of the even more ambitious 1.5-degree target), as the according report by UNFCCC (2016) emphasizes. There is constant technological progress in the area of "green" technologies. And, despite many open questions of regulatory details, a well-equipped tool box of economic policy (carbon pricing, subsidies, etc.) is in principle available for an effective reduction of carbon emissions. But a key remaining challenge for an effective tackling of climate change is the lack of "political will" or, depending on the perspective, public support for ambitious climate policy measures.

The literature and the public debate have paid much attention to international negotiations of a global climate treaty and the important free-riding problem on the international level.[2] But legally binding and effective environmental policy measures still happen on the level of national politics (in Europe in a complex interplay with the European Union). Therefore, the present chapter sees and follows the necessity for more attention to the multi-scale nature of the climate problem, emphasized, e.g., by Ostrom (2010), and examines political economic mechanisms on the national level which could undermine the voters' willingness to engage in climate policy and focuses on the following question: how is public support for climate policy measures like the taxation of carbon emissions affected by their (actual or expected) impact on incomes and on income inequality; by the level of existing socioeconomic inequality and the degree of redistribution in the country; and by the set of values in the population with respect to redistribution, (in)equality, environmental policy, and, in general, government intervention in the economy? The underlying idea is that redistributive policy and climate

---

[1] I am very grateful to John E. Roemer for his invaluable advice on the PUNE concept and the framework in this chapter.

[2] For instance, Heitzig et al. (2011), Nordhaus (2015), and Walker et al. (2009).

policy require an integrated analysis, because distributive effects and existing socioeconomic inequality might constitute national impediments to climate policy even if there is a public consensus on the general importance of climate protection.

In the present study I employ a model of two-dimensional policy competition following Roemer (2006) with the dimensions carbon tax and proportional income tax to analyze how income inequality affects the endogenous policy platforms of the two parties in equilibrium. To the best of my knowledge, this analysis is the first to model two-dimensional political competition on an environmental policy with distributional implications and redistributive policy at the same time. The effects of the policies on household incomes are derived in a static model of production of one final good with inelastic labor supply and carbon-intensive energy as inputs. Voter types are heterogeneous in terms of income (log-normal distribution between zero and infinity) and "collective orientation" (uniformly distributed between zero and one) which simultaneously indicates an individual's degree of concern with climate change and her preference for redistribution of income.[3] The voters' utility function comprises consumption utility, utility from the degree of actual redistribution relative to the individual's desired level of redistribution, and utility from climate protection. As a result, both policies affect utility over various channels at the same time: the income tax (with lump-sum revenue recycling) affects consumption utility via the direct monetary effect and utility from redistribution via its effect on the overall (post-tax) income distribution. The carbon tax, the revenue recycling of which can render it overall progressive or regressive, affects consumption utility via the monetary cost of climate protection, redistribution utility over the distributive implications of the tax, and utility from climate protection. The concept of *party-unanimity Nash equilibrium* (PUNE) from Roemer (2006) allows to take all these complex relations into account and to obtain political equilibria numerically with heterogeneous party platforms in the two-dimensional policy space. This would not be possible with a Downsian median-voter approach.

The analysis proceeds in two steps: first, the income tax is exogenously given and policy competition is one-dimensional over the level of the carbon tax. Here the numerical examples

---

[3] The assumption that environmentalism/concern for climate change and a preference for income redistribution are positively correlated is supported by a number of empirical psychological, sociological, and econometric studies. Papers like Campbell and Kay (2014), Heath and Gifford (2006), Kilbourne et al. (2002), McCright and Dunlap (2011), Rossen et al. (2015), and Ziegler (2017) find (mostly phrased in the opposite way) a positive correlation of climate change skepticism or low concern for the climate issue and a free-market ideology, aversion of government interventions in the economy, and conservatism which are associated with low income redistribution.

show that higher inequality of pre-tax income leads to a higher (lower) carbon tax in equilibrium if it is progressive (regressive). The reason is that voters prefer a higher carbon tax if it is accompanied by desired additional (progressive or regressive) redistribution on top of the fixed level of income taxation. Then, in a second step, the income tax is endogenized as the second dimension of policy competition. In this two-dimensional case a higher exogenous inequality of pre-tax income is counteracted by a higher income tax, while the average of the parties' carbon tax proposals stays virtually constant. In addition, a more progressive carbon tax revenue recycling mechanism is compensated by an according adjustment in the parties' income tax proposals, but the carbon tax proposals stay (exactly) the same. In other words, the two-dimensional nature of the political game enables a decoupling of redistribution from the average equilibrium level of climate policy. But this decoupling hinges on the assumption that the voters internalize the level of redistribution via the carbon tax relative to their desired degree of redistribution. If voters, in contrast, are myopic about the redistributive implication of the carbon tax, then an increase in inequality of pre-tax income does lead to higher (lower) proposals for a progressive (regressive) carbon tax. Thus, in this case the carbon tax revenue recycling mechanism does play a role for public climate policy support. Moreover, for both the myopic and the non-myopic case, the absolute and relative difference between the parties' carbon tax proposals and, therefore, the degree of implied policy uncertainty changes with a change in inequality of pre-tax income. For high levels of inequality a further intensification of inequality leads to more polarized party platforms. Polarization of party platforms also rises with an increase in salience of the ideological political discourse on income redistribution. Overall, more income inequality can undermine public support for climate policy, but does not have to. A progressive carbon tax revenue recycling and/or the possibility to compensate the distributional implications of a regressive carbon tax via income taxation foster climate policy support.

This chapter builds on the literature on distributive effects of environmental policies, particularly carbon taxes, to model the distributional effects of the carbon tax which feed into the political economic dynamics that are in the focus of the chapter. A large number of empirical studies find that taxes on greenhouse gas emissions, energy consumption, or industrial pollution are regressive, but well-designed schemes for revenue recycling or transfer payments can lead to an overall progressive distributional effect.[4] In the present chapter the design

---

[4] Examples for this group of papers are Robison (1985), Wier et al. (2005), Brenner et al. (2007), Kerkhof et al. (2008), Callan et al. (2009), Shammin and Bullard (2009), Bureau (2011), Ekins et al. (2011), Rausch et al. (2011),

of the tax revenue recycling mechanism also plays a central role in the political economic dynamics. In Rausch et al. (2011) and Rausch and Schwarz (2016) the regressive distributional effects of environmental taxes are driven by heterogeneous consumption patterns and factor income patterns between households. The present chapter abstracts from both channels for the sake of modelling simplicity. Instead, the distributive effect of the carbon tax in this study is driven by the revenue recycling mechanism alone, which is sufficient to create progressive and regressive distributional patterns.

Barker and Köhler (2005) and Metcalf (2009) point towards the possibility of reducing the regressive distributional effect by using the environmental tax revenues for the reduction of other distortionary taxes, e.g., on labor or capital. Such additional welfare gains from the reduction of distortive taxes, known under the term "double dividend" is analyzed in an own strand of literature from an optimal taxation perspective.[5] However, in the present version of this chapter there are no pre-existing distortions in the factor markets (due to inelastic labor supply) and no direct relation to the double-dividend effect.

In general, the present study with its national perspective does not follow the prescriptive focus of the literature on optimal taxation (which the double dividend literature is a part of), on the social cost of carbon, and on discounting. Instead, it contributes to the descriptive literature on the political economy of environmental policy, which in the real world can cause substantial deviations from the first-best ideal for many reasons. This field investigates, for instance, the influence of lobbying on national environmental policy making (cf. Heyes and Dijkstra (2002) and Oates and Portney (2003) for according literature overviews.), but also questions of strategic interaction of governments facing the possibility of losing office (cf., for instance, Voß (2015) and Schmitt (2014, chapter 4)). The present chapter extends the scarce literature which embeds environmental policy in voting models. A key difficulty of one-dimensional voting models based on environmental policy is that voting outcomes in reality are simultaneously influenced by more dominant political issues. List and Sturm (2006) approach this issue by focusing on the share of voters who determine their voting decision solely based on the secondary issue, which is environmental policy, in contrast to the majority

---

Gonzalez (2012), Chiroleu-Assouline and Fodha (2014), Jiang and Shao (2014), Mathur and Morris (2014), Williams III et al. (2015), da Silva Freitas et al. (2016), Renner (2018). Oladosu and Rose (2007) find a slightly progressive effect for a certain region.

[5] Examples in this context are Bovenberg and Mooij (1994), Babiker et al. (2003), Barrage (2018), Böhringer et al. (2016), Bento and Jacobsen (2007), and Kaplow (2012). For an overview over the double-dividend literature see Freire-González (2018).

of voters who only care for the primary issue. Therefore, their voters consider only one policy dimension at a time, instead of having truly two-dimensional preferences as in the present chapter. Also, in their study the temporal dimension is crucial – with a building up of politicians' reputation over time and the effect of term limits – for their empirical identification strategy. These temporal aspects do not play any role in my static model, as well as the econometric research dimension. McAusland (2003) employs a one-dimensional median-voter model with heterogeneous income streams from green and dirty production factors between voters and a trade component, which is absent from the present study. The factor income composition translates the environmental policy into heterogeneous monetary effects on income streams with homogeneous preferences. Moreover, the econometric study of Kahn and Matsusaka (1997) also involves a one-dimensional political reasoning. Overall, the present chapter is the first study to employ a two-dimensional voting model to simultaneously explain the degree of environmental policy (here: climate policy) and income redistribution and their interactions. The present approach gains additional value and relevance by incorporating distributional effects of the environmental policy and a preference of voters for redistribution which is correlated with their environmentalism. These aspects are all absent from previous work.

This study is also a contribution on the more general dimension of the political economy of public good provision in the face of socioeconomic inequality. But the present framework differs in a few aspects from the conventional public-good setting. A reduction of the public bad (emissions) in this case is not funded by additional taxation, e.g. of income or capital, and it is not just costly, but also creates (carbon tax) revenues. The elaboration of the implications in this direction are left for future research steps on the present study.

The present work also contributes to the literature on the application of models of two-dimensional policy competition with heterogeneous party platforms, which, to the best of my knowledge, completely relies on the PUNE concept of Roemer (2006). Roemer (1998), Roemer (1999), Roemer and van der Straeten (2005), Lee and Roemer (2006), Lee et al. (2006) all deal with redistribution as the first dimension and political ideology, xenophobia or racism as the second policy dimension. The present work extends this literature by applying the PUNE concept of two-dimensional political competition to redistribution and environmental policy with its distributive effects in the light of income inequality.

This chapter is organized as follows. In Section 4.2 the economic model is presented. Section 4.3 introduces the model of political competition based on Roemer (2006). The numerical results are presented and analyzed in Section 4.4. Section 4.5 concludes.

4.2 Model

4.2.1 Firms

Perfectly competitive firms produce a final good with a Cobb-Douglas aggregate production function

$$Q(L,E) = L^{\gamma}E^{1-\gamma} \tag{4.1}$$

with the production factors labor L and energy E. The latter contains one unit of carbon per unit of E. The labor input is numeraire (wages set to one) and its supply is inelastic (cf. Section 4.2.2). Therefore, firms maximize profits only by the choice of the energy input

$$\max_{E} \pi = p_Q Q(L,E) - L - (p_E + \kappa)E$$

with the price of the final good p_Q, the exogenous and constant energy price p_E, and the carbon tax $\kappa \in [0,\infty)$ on every unit of the energy input. The carbon tax is an endogenous outcome of political competition (cf. Section 4.3), but exogenous from the firms' perspective. With zero profits in the final goods market, final goods price p_Q reads

$$p_Q = \frac{L + (p_E + \kappa)E}{L^{\gamma}E^{1-\gamma}} \tag{4.2}$$

Substituting (4.2) into the first-order condition for energy yields

$$E = L\frac{(1-\gamma)}{\gamma(p_E+\kappa)} \quad \text{with} \quad \frac{\partial E}{\partial \kappa} = -L\frac{(1-\gamma)}{\gamma(p_E+\kappa)^2} < 0 \tag{4.3}$$

4.2.2 Households

4.2.2.1 Household Income

With the total population of the country normalized to one, there is a continuum of household types over two dimensions of heterogeneity: the individual households differ in skill level $h_i \in [0,\infty]$, which determines the household's productivity and is log-normally distributed with the mean h_μ and the median h_{med}. Households also differ with respect to their collective orientation $a_i \in [0,1]$, which can have different distributions (cf. Section 4.2.2.2). For simplicity, in the present version of the model the collective orientation a_i is uniformly distributed.

Labor Income and Income Taxation

All households inelastically supply one unit of "effort" $L_i^e = 1$ that is weighted with the skill level h_i, so that resulting household labor supply is $L_i^S = L_i^e h_i = h_i$. By aggregating over all households we obtain the equilibrium labor input, which is equal to inelastic aggregate labor supply

$$L = L^S = \int_{(a_i,h_i)} L_i^S dF(a_i, h_i) = h_\mu \tag{4.4}$$

With the wage level being equal to one, household labor supply $L_i^S = h_i$ is equal to pre-tax household income. This income is subject to a proportional income tax τ. The income tax revenues are recycled in a lump-sum fashion. Households receive payments $Rec(\kappa)$ from the recycling of carbon tax revenues, so that post-tax income is $y_i = h_i + (h_\mu - h_i)\tau + Rec(\kappa)$. In the case of lump-sum per-capita recycling each household receives $Rec(\kappa) = \kappa E(\kappa) = h_\mu \frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}$.[6] More regressive designs of revenue recycling are discussed below in the subsection "Carbon Tax Revenue Recycling". Net income is completely spent on the final good ($y_i = p_Q x_i$). Using (4.2),(4.3) and (4.4), resulting final good consumption x_i then reads

$$\begin{aligned} x_i &= y_i \frac{1}{p_Q} \\ &= y_i \frac{\gamma^\gamma (1-\gamma)^{(1-\gamma)}}{(p_E+\kappa)^{(1-\gamma)}} \\ &= (h_i + (h\mu - h_i)\tau + Rec(\kappa)) \frac{\gamma^\gamma (1-\gamma)^{(1-\gamma)}}{(p_E+\kappa)^{(1-\gamma)}} \end{aligned} \tag{4.5}$$

The income tax τ redistributes income from households with an above-average skill level ($h_i > h_\mu$) to those with a below-average skill level, leading to less post-tax inequality. For an income tax of $\tau = 1$ post-tax income would be constant across all households. Total output, however, does not change with the income tax since labor supply is inelastic. Therefore, there is also no distortion of the labor market and no according deadweight loss.

The carbon tax κ, in contrast, reduces the energy input with the contained emissions ($\frac{\partial E(\kappa)}{\partial \kappa} < 0$, cf. (4.3)) and resulting output. Since the implicit carbon intensity of the only good is constant over all households, consumption of every household decreases by the same factor. This does not yet cause a redistributive effect because every household suffers proportionally

---

[6] Since population is normalized to one, average household income h_μ is equal to aggregate income. Therefore, the aggregate carbon tax revenues $\kappa E(\kappa)$ are equal to a lump-sum per-capita payment.

to their previous income level. But, in addition, the carbon tax revenues are recycled. The net distributive effect of the carbon tax depends on the progressivity of the carbon tax recycling mechanism. With lump-sum recycling certain low-income households can even be better off after levying the carbon tax.

Carbon Tax Revenue Recycling

In principle, all sorts of distribution schemes are possible for the recycling of the carbon tax revenues. To enable more regressive distributions of revenue payments than a lump-sum per-capita recycling (for which $Rec(\kappa) = \kappa E(\kappa) = h_\mu \frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}$, as was shown above), the payments can be made proportional to an income distribution which would result from levying a hypothetical income tax τ_κ ("implicit income tax") instead of mean income h_μ:

$$Rec(\kappa) = (h_i + (h_\mu - h_i)\tau_\kappa)\frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma} \tag{4.6}$$

After substituting (4.6) into (4.5), the resulting equation can be transformed to (cf. Appendix D.1)

$$x_i = \left(1 + \frac{(1-\gamma)\kappa}{\gamma(p_E+\kappa)}\right)(h_i + (h\mu - h_i)\rho(\tau,\kappa,\tau_\kappa))\frac{\gamma^\gamma(1-\gamma)^{(1-\gamma)}}{(p_E+\kappa)^{(1-\gamma)}} \tag{4.7}$$

In doing so, the redistributive effects of the income tax and of the carbon tax can be combined into the total degree of redistribution $\rho(\tau,\kappa,\tau_\kappa)$ which results from both policy measures together. It is defined as

$$\rho(\tau,\kappa,\tau_\kappa) = \tau\left(\frac{1+\frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}\frac{\tau_\kappa}{\tau}}{1+\frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}}\right) \quad \begin{cases} > \tau & \text{for} \quad \tau_\kappa > \tau \\ = \tau & \text{for} \quad \tau_\kappa = \tau \\ < \tau & \text{for} \quad \tau_\kappa < \tau \end{cases} \tag{4.8}$$

A lump-sum recycling of carbon tax revenues corresponds to recycling payments proportional to a hypothetical income distribution which would result from an income tax of one ($\tau_\kappa = 1$), that is, a uniform distribution. As long as $\tau < \tau_\kappa = 1$, this would imply that the carbon tax is progressive relative to the post-income-tax distribution of income. If the recycling payments are proportional to the actual post-income-tax distribution of income (so that $\tau_\kappa = \tau$), then the carbon tax does not have any additional redistributive effect on top of the income tax. For

$\tau_\kappa < \tau$, the carbon tax is additionally regressive relative to the post-income-tax distribution of income.

4.2.2.2 Household Preferences

The households' utility function contains three additive terms which all play a role in driving heterogeneous political preferences:

$$\begin{aligned} u(\tau, \kappa; h_i, a_i)) &= ln(x_i(h_i; \tau, \kappa)) - \phi(a_i - \rho(\tau, \kappa, \tau_\kappa))^2 - a_i \frac{\delta}{2} E(\kappa)^2 \\ &= ln(x_i(\tau, \kappa; h_i)) - \phi(a_i - \rho(\tau, \kappa, \tau_\kappa))^2 - a_i \frac{\delta}{2} \left(\frac{h_\mu(1-\gamma)}{(p_E + \kappa)\gamma} \right)^2 \end{aligned} \tag{4.9}$$

The intuition behind the different components is explained in the following.

Consumption Utility

Consumption utility is logarithmic and concave in x_i ($\frac{\partial u_i}{\partial x_i} > 0$, $\frac{\partial^2 u_i}{\partial x_i^2} < 0$). A property of log utility is that a reduction of x_i by the same factor leads to the same absolute decrease in utility, irrespective of the income level. For this reason, the carbon tax incidence itself does not have a distributional implication despite the concavity of consumption utility, because the carbon tax hits every household with the same factor and leads to same utility decrease for all households. It is the distributional implication of the carbon tax recycling mechanism which leads to a heterogeneous effect of the carbon tax on households with different income levels.

Most empirical studies[7] find that a carbon tax is regressive. This regressivity in reality can be driven by a higher carbon intensity of the consumption bundle due to heterogeneity in final goods, by heterogeneity in factor income streams with differing carbon intensity, or by heterogeneity in the propensity to save (cf. McAusland (2003)). The modelling of heterogeneous consumption goods and savings behavior, which would require investment and a future period, is avoided here for modelling simplicity. In future work, these channels could be investigated. In the present model, it is important that the carbon tax can be made overall

---

[7] Cf. Robison (1985), Wier et al. (2005), Brenner et al. (2007), Kerkhof et al. (2008), Callan et al. (2009), Shammin and Bullard (2009), Bureau (2011), Ekins et al. (2011), Rausch et al. (2011), Gonzalez (2012), Chiroleu-Assouline and Fodha (2014), Jiang and Shao (2014), Mathur and Morris (2014), Williams III et al. (2015), da Silva Freitas et al. (2016), Renner (2018). Oladosu and Rose (2007) is an example with a small progressive effect on a regional scale.

progressive or regressive via the recycling mechanism. The design of the recycling mechanism is varied exogenously (cf. Section 4.4) and is not subject of the political debate. Otherwise, it would constitute a third policy dimension, which is beyond the scope of the present framework.

Redistributive Preference

Besides the skill level h_i, which captures socio-economic inequality, households are heterogeneous on the dimension "collective orientation" $a_i \in [0,1]$. This parameter indicates a person's degree of environmentalism, as well as her preference for redistribution or her aversion of inequality, respectively. As mentioned in the introduction, the assumption that the voter type dimension a_i in the model drives both the concern for climate change and preference for redistribution is supported by empirical studies which find a positive correlation of climate change skepticism or a non-environmentalist mindset and prevalent attitudes like free-market ideology, conservatism, and a low preference for government intervention, which are all associated with low preference for redistribution (cf. Campbell and Kay (2014), Heath and Gifford (2006), Kilbourne et al. (2002), McCright and Dunlap (2011), Rossen et al. (2015), and Ziegler (2017)).

The term $-\phi(a_i - \rho(\tau, \kappa, \tau_\kappa))^2$ expresses a Euclidian preference for redistribution or for government intervention: parameter a_i represents the desired total level of redistribution $\rho(\tau, \kappa, \tau_\kappa)$. Every deviation from this redistribution level ρ causes disutility for household i. Households with a_i close to one want to see a high level of income redistribution and low resulting inequality. These households might have the attitude that individual market incomes are more the result of a collective social effort (by relying, e.g., on public education, health-care, security, infrastructure, coworkers, etc., which are not modelled here) than just individual talent. Thus, they are sympathetic to government intervention if it helps to achieve what they perceive as greater distributive justice. In contrast, households with a low value for a_i are quite averse to redistribution of income, possibly grounded on more individualistic ethics. This implies that they are just fine with the pre-tax level of inequality or that they see government intervention as even more detrimental and, therefore, are less inclined to change market incomes.

Note, that the redistributive preference term is distinct to the person's opinion on how her personal consumption is affected by the income tax, as captured by the first log-utility term. In addition to that, the redistributive preference term comprises the person's political and social value judgments on issues like inequality, distributive justice, fairness or individualism. According to this separation, a poor person who would like the consumption increase from redistribution can at the same time dislike government intervention based on a libertarian economic value system. Or a wealthy person who would face considerable monetary losses from high income taxation might still favor it based on a more egalitarian value system.[8]

The parameter ϕ is a salience parameter which expresses the weight of the redistributive justice issue in the current political discourse. Even if people hold certain views on inequality and redistribution, the according discussion can rise or fall in importance relative to the other issues.

Climate Policy Preference

The third term $-a_i\frac{\delta}{2}E(\kappa)^2$ in the utility function (4.9) captures household i's disutility (note the negative sign) from carbon emission related climate damages. Emissions rise linearly in the equilibrium energy input $E(\kappa)$, which decreases in the carbon tax κ. Climate damages rise quadratically in emissions.

Since this term relates to households' perceived disutility from climate damages, it is secondary when and where the damages, which are not explicitly modelled, take place. What matters more for the degree of disutility is how much people care for climate damages, expressed again by the collective orientation parameter a_i.

If a_i is zero, then the person prefers a zero carbon tax, because climate damages do not hit her consumption utility directly, while the carbon tax does. The person may be neglecting damages because of spacial and temporal distance or due to a conviction that a government intervention would be even more harmful than the damages, even if climate change is undesirable.[9] A high value for a_i, i.e., close to one, means that a person cares for the full scale of climate damages or the social cost of carbon, and prefers a higher carbon tax than a person with lower a_i. The parameter δ captures the salience of the climate issue in the political debate, similar to the parameter ϕ in the case of the redistributive preference term.

---

[8] Two examples for such individuals who gained some media attention are Warren Buffett and Bill Gates (cf. Wearden, 2011 and Frank, 2016).

[9] The central idea of Campbell and Kay (2014) that people can be climate change skeptics not because of concern with the scientific argumentation itself, but because of their aversion to the solution of climate policy has a parallel in the classical public choice argument that government intervention to solve a problem is likely to be more costly than the problem itself (cf., for instance, Coase, 1960 and Buchanan and Stubblebine, 1962).

Effects of the Policies

The income tax τ affects individual utility over two channels: redistribution of income increases consumption utility of low-income individuals with $h_i < h_\mu$ and decreases consumption utility of those with $h_i > h_\mu$. At the same time, τ affects utility over the redistributive preference term. The latter also fulfills a technical function: since a majority of households has an income below the average ($h_i < h_\mu$), it would prefer an income tax of one if there was no counteracting force. Due to the redistributive preference term, the fact that many households with below-average income would like to live in a society with income taxation below 100 percent can drive the equilibrium income tax way below 100 percent. This is more consistent with empirical observations.

The carbon tax κ has three effects on utility: first, the effect on consumption utility is according to the net monetary implication of κ. The net monetary effect of κ and the recycling of the according revenues for the individual household is negative for most households, since overall output decreases with κ. A small share of households at the bottom end of the income distribution might benefit in net monetary terms if the tax recycling payment is higher than the tax-driven income reduction. Without any further benefits form κ, there would be no reason to expect a positive carbon tax in equilibrium as it reduces aggregate consumption. This benefit comes from the fact that, second, the carbon tax reduces disutility from climate damages. And third, the redistributive implication of the carbon tax affects utility over the redistributive preference term.

4.3 Political Competition

The model of political competition in the present framework is described in the following. It is built along the lines of the *party unanimity Nash equilibrium* (PUNE) concept of multi-dimensional political competition, as developed by Roemer (2006). The PUNE concept allows to achieve pure strategy equilibria in two-dimensional policy space $T \subset R^2$ with differentiated party platforms $t_A, t_B \in T$, in contrast to the Downsian median-voter concept. The dimensions of competition are income taxation $\tau \in [0, 1]$ and climate policy (carbon taxation $\kappa \in [0, \infty]$). The model takes the number of parties (here: two), the voter preferences (4.9), and the distribution of voter types $H \subset R^2$ as given. The model delivers as outputs the partition of the electorate in the two sets of party supporters, the two-dimensional policy platforms, and the winning probabilities for each party. A crucial element here, which also adds to realism, is that the respective party platform itself is the result of a bargaining game between two party factions: the Opportunists maximizing the probability of getting into office and the Guardians maximizing average welfare of the party supporters.

4.3.1 Definitions

The political parties take voter preferences (4.9) and the two-dimensional distribution of voter types **F**(a, h) as given. By announcing their platforms, defined by the policy vector $t_m = (\tau_m, \kappa_m)$ with $m \in \{A, B\}$, the parties A and B divide the electorate, that is, the set of all voter types H in the (a, h) space, into two sets of voters: H^A is the set of those voter types who support party A and H^B is the set of those who support party B. Every voter of the polity belongs to one, and only one, of the two sets, so that $H = H^A \cup H^B$ and $H^A \cap H^B = \varnothing$. The set of party A supporters who prefer party A's platform $t_A = (\tau_A, \kappa_A)$ given that party B proposes $t_B = (\tau_B, \kappa_B)$ is

$$\Omega(t_A, t_B) = \{(a_i, h_i) | u(t_A) > u(t_B)\}$$

The edge of the two sets of voters $\hat{a}(t_A, t_B; h_i)$ is endogenous and defined by those voters who are indifferent between the two platforms:

$$u(t_A; \hat{a}, h_i) = u(t_B; \hat{a}, h_i) \tag{4.10}$$

By definition, voters with $a_i > \hat{a}$ prefer party A's platform, and voters with $a_i < \hat{a}$ prefer party B's platform. Substituting (4.9) into (4.10) and rearranging yields

$$\hat{a}(t_A, t_B; h_i) = \tag{4.11}$$
$$\left[\ln \left[\frac{(h_i + (h_\mu - h_i)\rho(t_A, \tau_\kappa)) \left(1 + \frac{(1-\gamma)\kappa_A}{\gamma(p_E+\kappa_A)}\right)}{(h_i + (h_\mu - h_i)\rho(t_B, \tau_\kappa)) \left(1 + \frac{(1-\gamma)\kappa_B}{\gamma(p_E+\kappa_B)}\right)} \cdot \left(\frac{p_E + \kappa_B}{p_E + \kappa_A}\right)^{1-\gamma} \right] - \phi(\rho(t_A, \tau_\kappa)^2 - \rho(t_B, \tau_\kappa)^2) \right] \cdot$$
$$\left[\frac{\delta}{2} \left(\frac{(1-\gamma)h_\mu}{\gamma}\right)^2 \left(\frac{1}{(p_E + \kappa_A)^2} - \frac{1}{(p_E + \kappa_B)^2}\right) - 2\phi(\rho(t_A, \tau_\kappa) - \rho(t_B, \tau_\kappa)) \right]^{-1}$$

The curve $\hat{a}(t_A, t_B; h_i)$ divides the voter-type space in two sets which both contain approximatey half of the electorate. If one party managed to improve its voters' welfare by changing its platform, then $\hat{a}(t_A, t_B; h_i)$ would shift and thus increase the party's share of the electorate. This holds for the other party, too, so that in equilibrium, no party and no party faction can deviate from their platform without triggering a detrimental adjustment by the other party. The resulting aggregate welfare of all party A voters if the policy vector t is realized then is

$$W^A(t) = \int_{(a_i,h_i)\in H^A} u(t;a_i,h_i)\, d\mathbf{F}(a_i,h_i) = \int_0^\infty \int_{\hat{a}}^1 u(t;a_i,h_i)\, d\mathbf{F}(a_i)\, d\mathbf{F}(h_i)$$

and the aggregate welfare of the supporters of party B given the policy vector t is

$$W^B(t) = \int_{(a_i,h_i)\in H^B} u(t;a_i,h_i)\, d\mathbf{F}(a_i,h_i) = \int_0^\infty \int_0^{\hat{a}} u(t;a_i,h_i)\, d\mathbf{F}(a_i)\, d\mathbf{F}(h_i)$$

The share of party A supporters, that is, the probability measure $\mathbf{F}(\Omega(t_A,t_B))$ is a discrete number depending on the probability distribution **F**. Nevertheless, when the parties announce their policy platforms at the beginning of the election campaign, they are only certain up to a margin of error about what their share of the vote will be on election day. Without this uncertainty the winner would be known from the beginning or the chances of each party to win would be exactly $\frac{1}{2}$. In both cases, the result would be clear from the beginning and spending money on election campaigns would be pointless. So, party uncertainty about voter behavior is a vital element of realistic modelling of political competition. The parties believe that the share of voters who prefer t_A to t_B lies in a range of $[-\epsilon,+\epsilon]$ around $\mathbf{F}(\Omega(t_A,t_B))$ with a uniform probability distribution within that range. The expected probability of party A to win with platform t_A if party B plays platform t_B then reads

$$\pi(t_A,t_B) = \frac{\mathbf{F}(\Omega(t_A,t_B)) + \epsilon - \frac{1}{2}}{2\epsilon} = \frac{\int_{(a_i,h_i)\in H^A} d\mathbf{F}(a_i,h_i) + \epsilon - \frac{1}{2}}{2\epsilon}$$

As a result, each party has a probability of winning the election close to, but not exactly equal to, 50%.

4.3.2 Party Unanimity Nash Equilibrium

The PUNE equilibrium concept rests on the assumption that two types of politicians try to influence the party policy. On the one hand, the Opportunists try to maximize the party's vote share with the intention of promoting their own career. When facing a given policy platform from the respective other party their payoff functions are

$$\Pi_A^{Opp}(t_A,t_B) = \pi(t_A,t_B)$$

and

$$\Pi_B^{Opp}(t_A, t_B) = 1 - \pi(t_A, t_B)$$

respectively. On the other hand, the Guardians maximize average welfare of their constituents while neglecting the probability of actually getting into office.[10] Their payoff functions are

$$\Pi_A^{Guar}(t_A, t_B) = W^A(t_A)$$

and

$$\Pi_B^{Guar}(t_A, t_B) = W^B(t_B)$$

respectively. The two factions of party A now engage in a bargaining game in which the Guardians try to maximize their constituents' welfare while the Opportunists insist on a minimal probability of winning π_0, given that party B plays the platform t_B:

$$\max_{t \in T} W^A(t) \quad s.t. \quad \pi(t, t_B) \geq \pi_0^A \tag{4.12}$$

It would be equivalent to maximize the probability of winning while considering a lower bound to average welfare of the constituents. Party B solves the following problem in a similar way for a given platform t_A of party A:

$$\max_{t \in T} W^B(t) \quad s.t. \quad 1 - \pi(t_A, t) \geq 1 - \pi_0^B \tag{4.13}$$

Similar to Lee and Roemer (2006) and in consistence with Roemer (2006, Chapter 8) a *party unanimity Nash equilibrium* (PUNE) is defined as

(1) a partition of the type space into two party memberships $H = H^A \cup H^B$, $H^A \cap H^B = \varnothing$, a pair of numbers (π_0^A, π_0^B), and a pair of policies (t_A, t_B), such that:

(2) t_A solves problem (4.12) and t_B solves problem (4.13), and

---

[10] An additional interpretation of this behavior could be that the Guardians seek to publicly propagate their agenda, even if they end up not putting their policies into practice. In early versions of the PUNE concept, Roemer (2006) included a third faction, the Reformists, who would maximize expected welfare of their voters. Mathematically, the Reformists are redundant and the model is simpler without them.

(3) $(a_i, h_i) \in H^A \Rightarrow u(t_A; a_i, h_i) \geq u(t_B; a_i, h_i)$ and $(a_i, h_i) \in H^B \Rightarrow u(t_B; a_i, h_i) \geq u(t_A; a_i, h_i)$.

Condition (3) states that each voter prefers to continue supporting her party. Thus, endogenously formed party membership is stable. If the policy vector (t_A, t_B) is a PUNE, then neither the Opportunists, nor the Guardians can deviate from their position without making the other faction being worse off and the party platform is stable. And the same holds true for the other party. The tuple (π_0^A, π_0^B) reflects the relative bargaining power of the Opportunist faction in each party. Different degrees of relative bargaining power of the factions produce different PUNEs. Therefore, in the case that PUNEs exist, there will be a two-dimensional manifold of them in the space of $T \times T$.

Roemer (2006, Chapter 8) shows that the problem consisting of (4.12) and (4.13), which yields PUNEs as solutions, can be restated as a weighted Nash bargaining game. Thus, in party A the policy vector t is chosen which maximizes the Nash product, given that party B plays t_B:

$$\max_{t \in T} (\pi(t, t_B) - 0)^{\alpha} (W^A(t) - W^A(t_B))^{1-\alpha} \tag{4.14}$$

The according maximization problem for party B, given that party A plays t_A is

$$\max_{t \in T} ((1 - \pi(t_A, t)) - 0)^{\beta} (W^B(t) - W^B(t_A))^{1-\beta} \tag{4.15}$$

The parameters $\alpha, \beta \in [0, 1]$ denote the relative bargaining power of the Opportunists in the respective party. The numbers $((\alpha, \beta), ((1-\alpha), (1-\beta)))$ are the Nash bargaining weights of the problem. If Opportunists and Guardians do not agree on a policy platform in party A, then party B wins the election with certainty and the Opportunists' payoff is zero, while the Guardians' payoff is the average welfare in the case of enactment of party B's policy vector t_B(cf. (4.14)). The same logic holds for party B (cf. (4.15)). If there is a weighted Nash bargaining solution, then it must be PUNE. On the other hand, when there is a PUNE, then it is exactly the solution to a corresponding weighted Nash bargaining game if $ln(\pi(\cdot, t_B))$ and $ln(W^A(\cdot) - W^A(t_B))$ are concave functions on T and if $ln(1 - \pi(t_A, \cdot))$ and $ln(W^B(\cdot) - W^B(t_A))$ are concave functions on T (cf. "Assumption A" in Roemer (2006, p. 157)).

There is a convenient differential characterization of PUNEs as formulated by (4.14) and (4.15) the simplicity of which is very useful for the numerical calculation of PUNEs (cf. Roemer (2006, Section 8.4)). For the derivation see Appendix D.1.2. For a policy pair (t_A, t_B) to be a PUNE, the following equation[11] must hold for party A[12]

$$\nabla_{t_A} W^A(t_A) = -\lambda^A(t_A, t_B)\nabla_{t_A}\pi(t_A, t_B) \tag{4.16}$$

with $\lambda^A(t_A, t_B) := \frac{\alpha}{1-\alpha}\frac{\Delta W^A(t_A)}{\pi(t_A,t_B)}$; and for party B

$$\nabla_{t_B} W^B(t_B) = \lambda^B(t_A, t_B)\nabla_{t_B}\pi(t_A, t_B) \tag{4.17}$$

with $\lambda^B(t_A, t_B) := \frac{\beta}{1-\beta}\frac{\Delta W^B(t_B)}{\pi(t_A,t_B)}$. Equations (4.16) and (4.17) provide a set of $2T = 4$ equations for $2T + 2 = 6$ unknowns $(\tau_A, \tau_B, \kappa_A, \kappa_B, \alpha, \beta)$. The system of equations is numerically solvable for given Nash bargaining weights (α, β).

4.4 Climate Policy Analysis

In this section the influence of inequality of income on the equilibrium policies is analyzed. First, in Subsection 4.4.1, the income tax rate τ is exogenously given and policy competition is just one-dimensional over the carbon tax rate κ. Then, in Subsection 4.4.2, the full two-dimensional competition over both policy dimensions is examined and compared to the one-dimensional setup to carve out the interactions between the policy instruments. For the numerical illustrations, a reference parameter setting is defined and summarized in Table 4.1.

Mean income h_μ	20
Salience parameter of climate issue δ	5
Salience parameter of redistributive issue ϕ	1
Pre-tax energy price p_E	4
Party error margin ϵ	0.02
Elasticity of production w.r.t. labor γ	0.95
Elasticity of production w.r.t. energy $(1-\gamma)$	0.95

Table 4.1 : Reference parameter setting

---

[11] Note that the Del or nabla operator ∇_{t_A} indicates a derivative with respect to a vector, in this case t_A, so that $\nabla_{t_A} = \left(\frac{\partial}{\partial\tau_A}, \frac{\partial}{\partial\kappa_A}\right)$ and $\nabla_{t_B} = \left(\frac{\partial}{\partial\tau_B}, \frac{\partial}{\partial\kappa_B}\right)$.

[12] For taking the derivative of party A's winning probability $\pi(t_A, t_B)$ with respect to the vectors t_A and t_B derivatives of $\hat{a}(t_A, t_B; h_i)$ are needed. Since $\hat{a}(t_A, t_B; h_i)$ is a quite complicated function (cf. 4.11), its derivatives are taken numerically in the simulation which is the basis for the analysis section 4.4.

4.4.1 One-Dimensional Policy Competition over Climate Policy

4.4.1.1 The Role of Income Inequality and Carbon Tax Recycling

In the one-dimensional case the parties only compete over the carbon tax rate κ on every energy unit, while the income tax rate τ is exogenously given and fixed. Given the log-normally distributed skill level h_i, which is equal to pre-tax income (cf. Section 4.2.2.1), the ratio of median income to mean income $\frac{h_{med}}{h_\mu}$ is the measure for pre-income-tax inequality which is used in the following analysis. The fixed income tax leads to a certain degree of redistribution, so that post-income-tax inequality of income is lower. But, nevertheless, a decrease of $\frac{h_{med}}{h_\mu}$ increases inequality before and after levying the income tax.[13] The resulting PUNEs in one-dimensional policy competition over the carbon tax are shown in Figure 4.1 for a regressive carbon tax recycling ($\tau_\kappa = 0$), for different levels of the inequality measure $\frac{h_{med}}{h_\mu}$ and for different bargaining power parameters of the Opportunist factions $(\alpha, \beta) \in \{(0.1, 0.1), (0.5, 0.5), (0.9, 0.9)\}$.[14] Since labor is the numeraire good and wages are equal to one, the unit of the carbon tax κ in this and all the following figures must be read as "wage units/energy unit".

Party A in all cases proposes a higher carbon tax rate than party B. This is due to the definition of party A as the one which represents the voters with a collective orientation above the indifference threshold $a_i > \hat{a}(t_A, t_B; h_i)$ (cf. Section 4.3.1), who have a higher preference for climate protection and for redistribution of income than supporters of party B.

The higher the bargaining power of Opportunists in both parties, the closer are the resulting party platforms. This is not surprising since focusing mainly on the probability to win, as strongly Opportunist parties do, brings the parties closer to the median-voter logic. The most striking result is, however, that more income inequality (decreasing median income h_{med}) leads to lower carbon tax proposals of both parties in equilibrium. The reason is the regressivity of the carbon tax recycling mechanism. Recall that a recycling distribution parameter τ_κ of zero implies that the carbon tax revenues are recycled to each household proportionally to

---

[13] By assumption, "increases" or "decreases" in pre-income-tax inequality throughout the analysis imply that median income h_{med} changes while mean income h_μ stays the same. In this way, a different degree of inequality means a different distribution of an otherwise constant aggregate pre-tax income.

[14] In this and the following figures the bargaining weights of the Opportunist faction are assumed to be equal in both parties for simplicity. The case with low Opportunist bargaining weights of $\alpha, \beta = 0.1$ is always depicted with dashed curves, the case $\alpha, \beta = 0.5$ with solid curves, and the case with high Opportunist bargaining weights of $\alpha, \beta = 0.9$ with dash-dotted curves. The color blue is assigned to party A, red is assigned to party B.

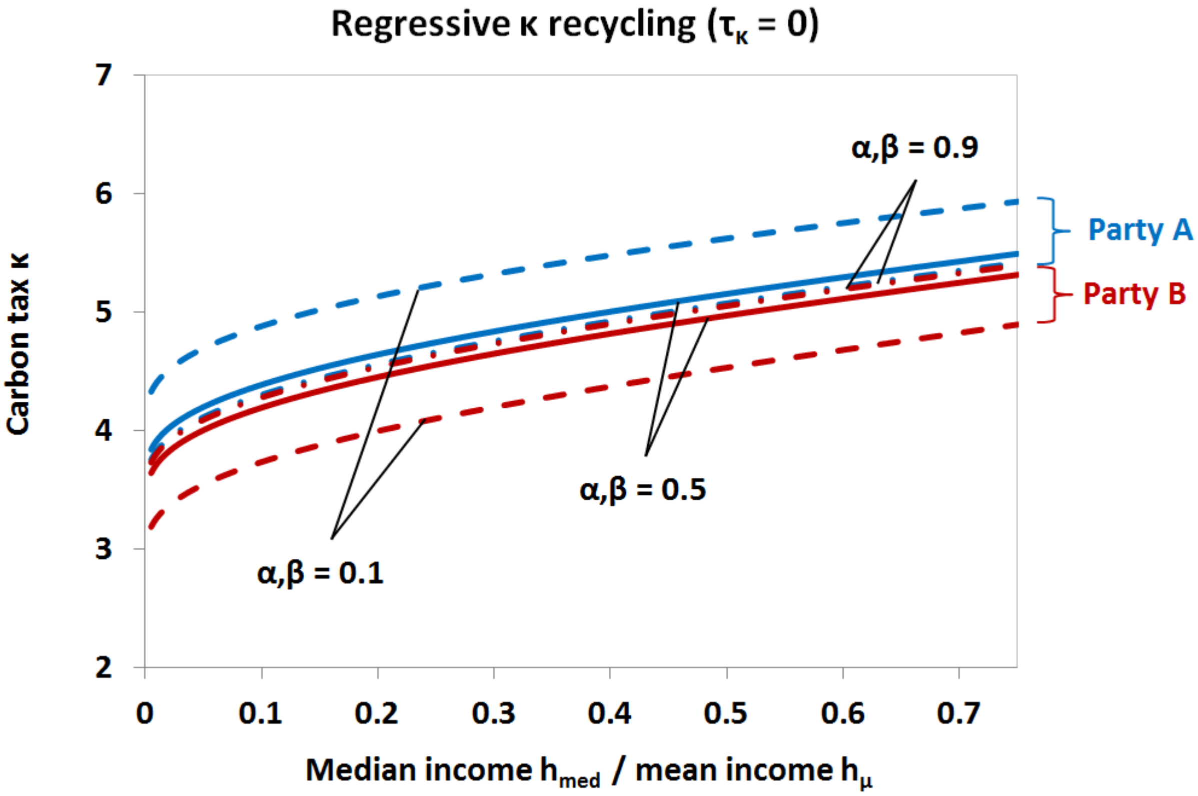

Figure 4.1 : PUNEs for one-dimensional policy competition over the carbon tax rate κ for regressive carbon tax recycling $(\tau_\kappa = 0)$ and $\tau = 0.5$.

their pre-income-tax income.[15] The distributional impact of the carbon tax in part counteracts the progressive redistribution from the (fixed) income tax. Therefore, increasing income inequality (while mean income and the income tax τ stay fixed) raises the share of voters with an income below the mean $(h_i < h_\mu)$ who have a low preference for a regressive carbon tax and strengthens their aversion against regressive policies like a carbon tax with $\tau_\kappa = 0$.

To point out the crucial role of the recycling mechanism, Figure 4.2 shows the opposite result for a progressive recycling of carbon tax revenues, that is for a distributive parameter of carbon tax recycling τ_κ equal to one. This implies, that households receive lump-sum payments.

Party A is still more environmentalist than party B and the policy proposals are more polarized if the Guardians have a higher bargaining power in the parties (that is, α, β are lower). But an increase in income inequality (in contrast to the case $\tau_\kappa = 0$) raises the preference of the

---

[15] In principle, even more regressive revenue recycling schemes are possible. But for simplicity, here the implicit redistribution parameter τ_κ is used. If τ_κ fell below zero, then some poor households would receive "negative recycling payments", which would not make sense in reality.

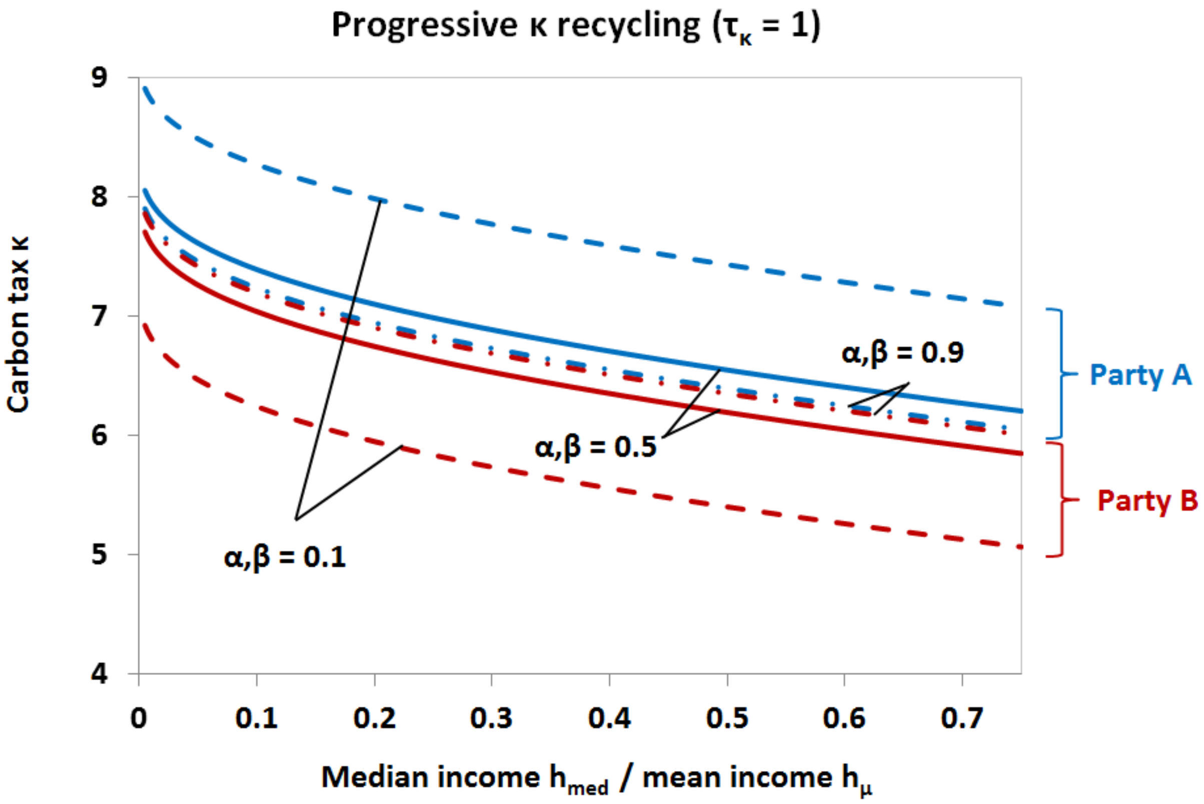

Figure 4.2 : PUNEs for one-dimensional policy competition over the carbon tax rate κ for progressive carbon tax recycling $(\tau_\kappa = 0)$ and $\tau = 0.5$.

majority of households with $h_i < h_\mu$ for a progressive carbon tax policy and also the share of households with $h_i < h_\mu$. The result is higher carbon tax proposals by both parties in equilibrium.

Polarization between the parties on climate policy is higher for a progressive carbon tax ($\tau_\kappa = 1$) than for a regressive carbon tax ($\tau_\kappa = 0$).[16] The reason is that a higher progressivity additionally benefits primarily low-income voters represented by party A at the expense of high-income voters of party B. Consequently, party A proposes a higher carbon tax and party B a lower carbon tax if the respective revenue recycling is more progressive.

4.4.1.2 The Effect of the Exogenous Income Tax Rate

The exogenously given income tax rate is an important determinant of the resulting equilibrium due to its role in the pass-through of pre-tax inequality to post-income-tax inequality. The latter ultimately affects the voters' evaluation of the distributive consequences of the carbon

---

[16] Note that the scaling of the y axis in Figures 4.1 and 4.2 is the same.

tax. Figure 4.3 demonstrates the impact of an increase in the exogenous income tax rate from $\tau = 0.5$ (grey curves) to $\tau = 0.7$ (blue and red curves) on the parties' equilibrium carbon tax proposals for different degrees of pre-tax inequality $\frac{h_{med}}{h_\mu}$. To allow a better comparison, only the curves for high bargaining power of the Opportunist factions of $\alpha, \beta = 0.9$, which are closer to the average proposals of both parties, are shown.

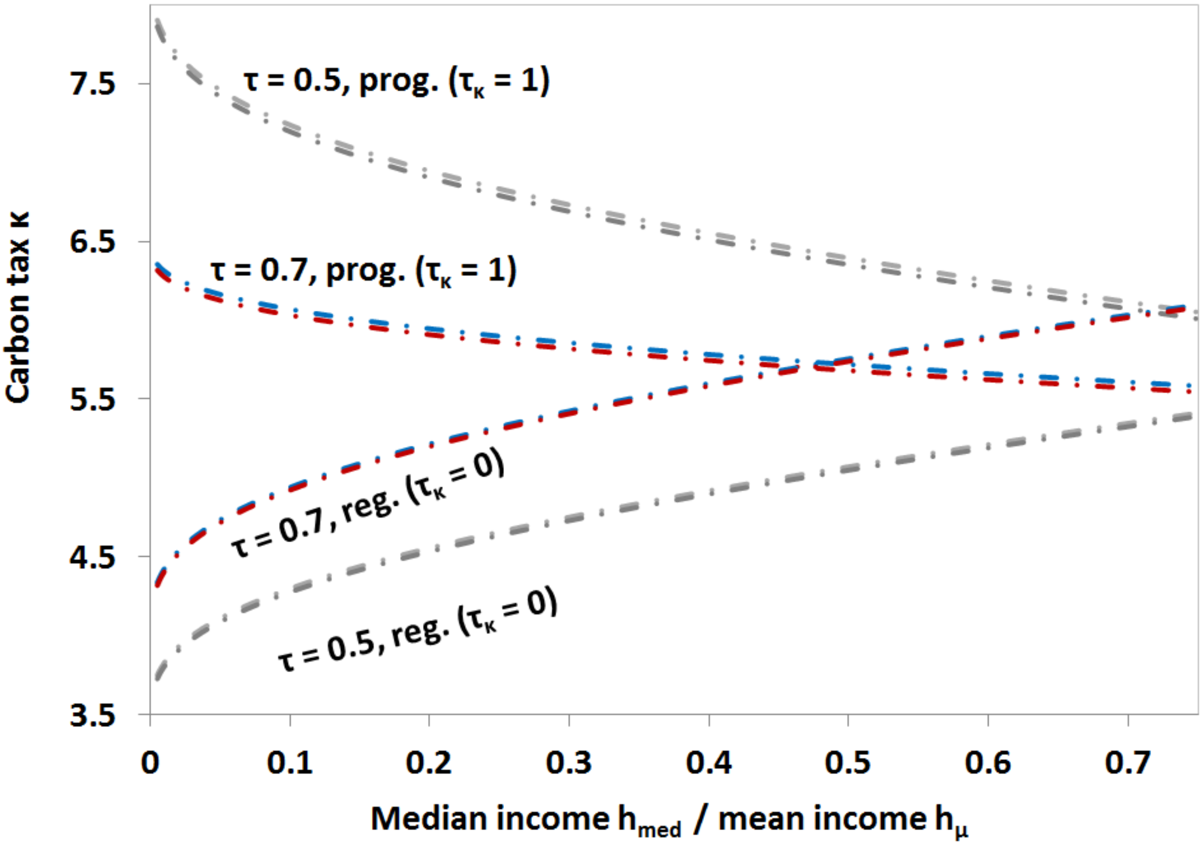

Figure 4.3 : Comparison of the parties' carbon tax proposals for different levels of pre-tax income inequality $\frac{h_{med}}{h_\mu}$ at $\tau = 0.5$ and $\tau = 0.7$ $(\alpha, \beta = 0.9)$.

The increase in the income tax rate reduces post-income-tax inequality of income and, thereby, also the perceived need for further redistribution. As a result, the voters' preference for the redistributive effect of a progressive carbon tax $(\tau_\kappa = 1)$ decreases as well, while their preference for the emission reduction effect of the carbon tax remains the same. This leads to lower equilibrium carbon tax proposals by both parties than for $\tau = 0.5$. The voter preference for a regressive carbon tax $(\tau_\kappa = 0)$, however, increases relative to $\tau = 0.5$ as the regressive distributional effect of the carbon tax is perceived as less harmful, leading to higher carbon tax proposals by both parties. Overall, the gap between carbon tax proposals in the cases of progressive and regressive revenue recycling is diminished and even reversed in sign for approximately $\frac{h_{med}}{h_\mu} > 0.48$. A reversal of the gap for low inequality of pre-tax income (high $\frac{h_{med}}{h_\mu}$) implies that a majority of the electorate perceives the exogenous tax rate of 0.7 as too high[17] and under these circumstances prefers a regressive carbon tax to a progressive one. At the inequality level corresponding to $\frac{h_{med}}{h_\mu} = 0.48$ the exogenous income tax rate of 0.7 is equal to the average desired tax rate according to the average preference of voters for redistribution (cf. "Redistributional Preference" in Subsection 4.2.2.2). Therefore, the progressive or regressive character of the carbon tax does not matter at this point and the according curves intersect. But, despite the impact of the income tax rate, the general influence of an increase in pre-tax inequality on the carbon tax proposals – positive for $\tau_\kappa = 1$, negative for $\tau_\kappa = 0$ – remains unchanged.

To sum up, voters favor a progressive carbon tax over a regressive one if it promises additional redistribution which they desire but did not yet obtain. An increase in post-tax income inequality can result from a higher pre-tax inequality or a lower income tax and raises the desire for more redistribution. This leads to higher proposals for a progressive carbon tax and lower proposals for a regressive carbon tax.

4.4.2 Two-Dimensional Policy Competition over Climate Policy and Income Tax

4.4.2.1 The Role of Income Inequality

Now the income tax rate τ is endogenized and turns into a second dimension of political competition, next to the carbon tax κ. A higher pre-tax inequality of income (that is, a lower ratio $\frac{h_{med}}{h_\mu}$) increases the share of voters with an income lower than the mean h_μ and, thus, leads to a more pronounced support for higher redistribution via the income tax and the according proposals by both parties for different levels of Opportunist bargaining power in two-dimensional policy equilibrium, as Figure 4.4 confirms.[18] The overall net effect of an exogenous increase in pre-income-tax inequality and an associated increase in redistribution via income taxation on the resulting inequality in post-income-tax (but pre-carbon-tax) income is a priori ambiguous.

At the same time, a rising inequality in pre-tax income affects the stance of both parties on climate policy, as Figure 4.5 shows. Like in the one-dimensional setup (cf. Section 4.4.1), the

---

[17] The according two-dimensional policy case (cf. Section 4.4.2) yields endogenous income tax rates between 0.58 and 0.63 at $\frac{h_{med}}{h_\mu} = 0.75$.

[18] Note, that along the curves in Figure 4.4 the equilibrium carbon tax rate changes as well.

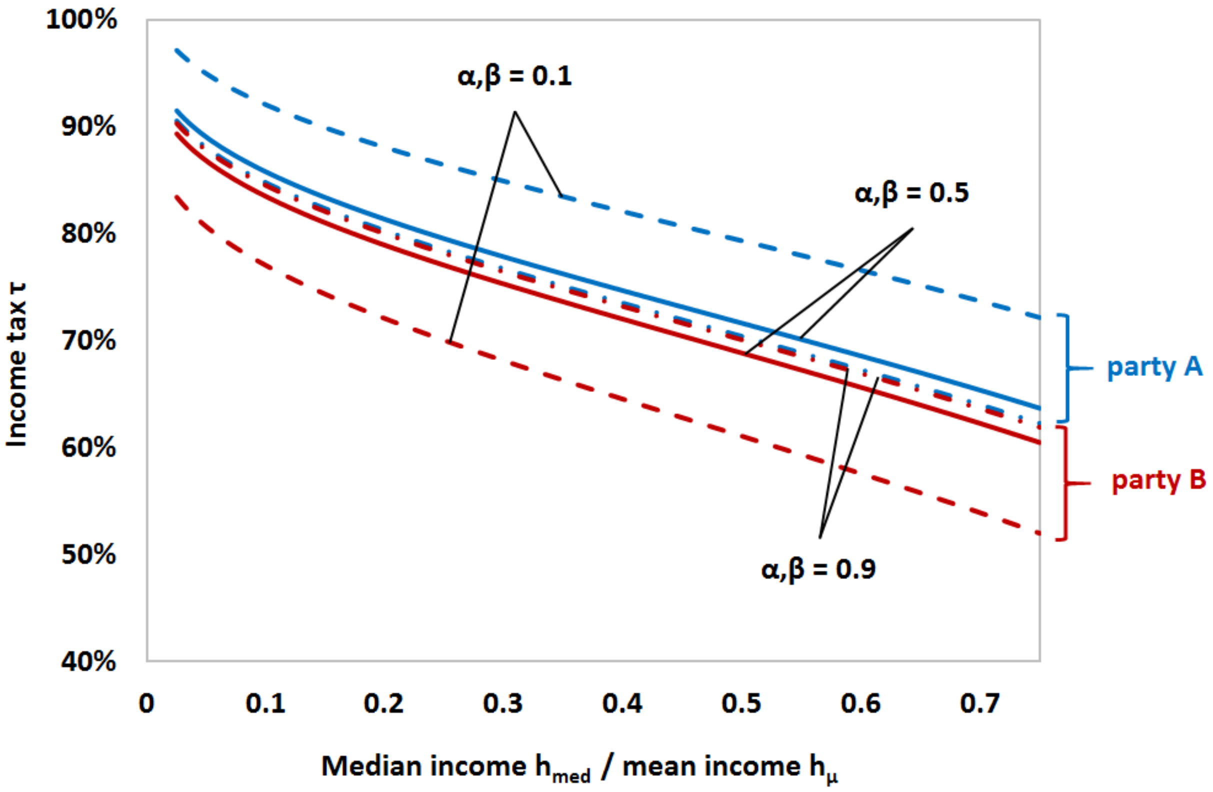

Figure 4.4 : Income tax proposals of the parties in two-dimensional competition for different levels of pre-tax income inequality $\frac{h_{med}}{h_{\mu}}$.

results are shown for three different levels of bargaining power of the respective Opportunist factions (0.1, 0.5, and 0.9).

A striking difference to the one-dimensional case with exogenous income tax is that rising inequality impacts the two party platforms in different ways: starting with low inequality (high $\frac{h_{med}}{h_{\mu}}$), an intensifying of pre-tax income inequality until approximately $\frac{h_{med}}{h_{\mu}} = \frac{8.3}{20} = 0.415$ at first reduces polarization between the two parties on the climate policy issue, that is, the difference in proposed carbon tax rates. But then, for a further rising pre-tax inequality (falling $\frac{h_{med}}{h_{\mu}}$), party polarization on the climate issue increases. The change in polarization is also stronger if the Opportunist factions have a low bargaining power, that is, if the Guardians dominate the parties.

The polarization of party platforms on the climate issue is important for the climate policy uncertainty from the perspective of risk-averse investors, e.g., in the energy sector. Even if the

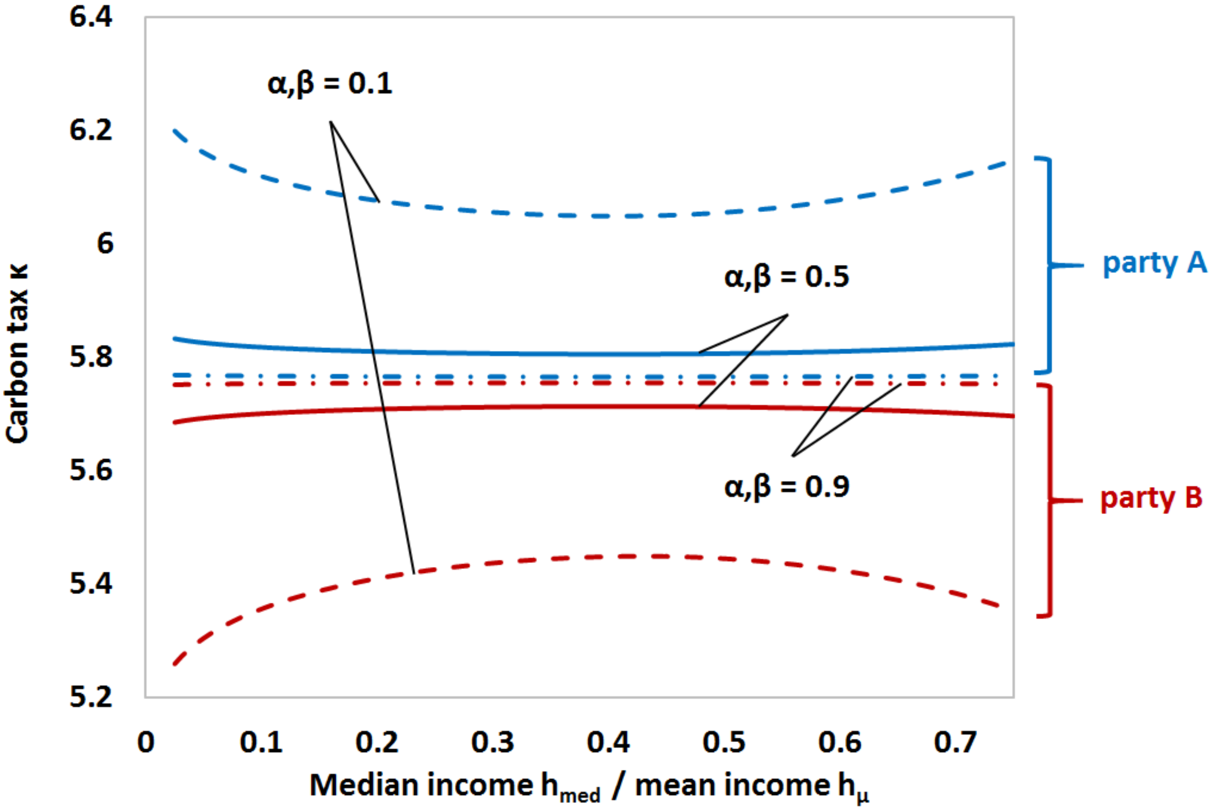

Figure 4.5 : Carbon tax proposals of the parties in two-dimensional competition for different levels of pre-tax income inequality $\frac{h_{med}}{h_{\mu}}$.

average carbon tax proposal[19] remained unaffected by changes in income inequality, a rise in climate policy uncertainty could induce risk-averse investors to invest more cautiously. In this case, a rising inequality and its effects on the climate policy proposals via the political competition dynamics could turn out as hampering the decarbonization of the economy.

At the same time with the change in polarization, the average carbon tax proposal is virtually not affected by a change in income inequality.[20] Apparently, changes in the inequality of pre-tax income are neutralized by the endogenous income tax adjustment, so that the average carbon tax proposal is not affected by any change in the voter preference in favor or against redistribution. With the income tax the voters have a policy instrument available which directly

---

[19] Each party's probability to win is close, but not exactly equal, to 50%. Therefore, the expected carbon tax in the sense of the average of carbon tax proposals weighted with the respective party's winning probability is close, but not exactly equal to, the average carbon tax proposal. For simplicity, the term "average carbon tax proposal" is used here.

[20] Calculating the actual average of the proposals shows that it is not exactly constant, but the average changes only very little (cf. Figure D.1 in Appendix D.2) with income inequality.

targets the income distribution. Therefore, they do not have to rely on the carbon tax for redistributional purposes.

Moreover, and also in contrast to the one-dimensional case (cf. Section 4.4.1), the progressive or regressive character of carbon tax recycling does not play any role for the level of the carbon tax proposals (cf. Table 4.2). With a more progressive carbon tax a lower degree of progressive redistribution is needed via the income tax to reach the same desired average level of redistribution $\rho(\tau, \kappa, \tau_\kappa)$. Therefore, income tax proposals are lower (higher) if the carbon tax is more (less) progressive, but the carbon tax proposals remain absolutely unaffected by their degree of progressivity.

	τ_A	τ_B	κ_A	κ_B
Regressive recycling ($\tau_\kappa = 0$)	79.528%	77.044%	5.8078	5.7104
Progressive recycling ($\tau_\kappa = 1$)	76.412%	73.949%	5.8078	5.7104

Table 4.2 : Comparison of equilibrium policy platforms for progressive and regressive carbon tax revenue recycling ($\alpha, \beta = 0.5$, $\frac{h_{med}}{h_\mu} = \frac{5}{20}$, other parameters as in reference case).

A characteristic feature of the present setup is that the two dimensions of voter types a_i (uniform distribution) and h_i (log-normal distribution) are not correlated. An change of the inequality of pre-tax income, therefore, changes the distribution of voters w.r.t h_i, but not w.r.t. a_i. In future research a correlation of both dimensions could be assumed. For instance, rich voters (high h_i) could, on average, exhibit a higher (or lower) collective orientation a_i. Then the implications of changes in the progressivity of carbon tax recycling or in the inequality of pre-tax income could change.

4.4.2.2 Myopia w.r.t. the Distributive Effects of the Carbon Tax

In the voter preferences as presented in Equation 4.2.2.2 (cf. Section 4.2.2) the voters have a stance on their desired degree of total redistribution $\rho(\tau, \kappa, \tau_\kappa)$ via the income tax and the carbon tax. This can be interpreted as the voters' opinion on inequality aversion, social policy, or fairness. The assumption there is that the voters fully understand and evaluate redistributional implications not only of the income tax, but also of the carbon tax. Issues like distributional justice and income inequality are usually discussed in the political debate in the context of income tax policy or social security systems. It is not obvious that voters in reality account for the overall distributional effects of environmental policy measures like a carbon tax when they are forming their opinion on the appropriate degree of the measure. However, voters can be expected to notice and care for the impact that an environmental policy has on their own income, at least once it materializes.

Therefore, the present section focuses on the changes in the previously presented results when the assumption of full understanding and internalization of the distributive nature of the carbon tax by the voters is released. Instead it is assumed that they only consider the impact of the carbon tax on their utility via the climate preference term and the consumption utility term (cf. Section 4.2.2.2), but neglect the redistributive character of the carbon tax (progressive or regressive) in the redistributive preference term: the total degree of redistribution $\rho(\tau, \kappa, \tau_\kappa)$ in the latter is substituted by the income tax rate τ only. The redistributive preference term in (4.9), thus, turns from $-\phi(a_i - \rho(\tau, \kappa, \tau_\kappa))^2$ to $-\phi(a_i - \tau)^2$. Note, that the total degree of redistribution $\rho(\tau, \kappa, \tau_\kappa)$ in the consumption utility term $ln(x_i(h_i; \tau, \kappa))$ with $x_i(h_i; \tau, \kappa)$ from (4.7) remains unchanged, because the monetary consequences of carbon tax recycling do take place even though the voters do not account for the impact on the overall distribution of income.

Under these circumstances, an increase of inequality of pre-tax income (that is, a decrease in $\frac{h_{med}}{h_\mu}$) yields again an increase in the proposed income tax rates, just as in the full internalization setting in Section 4.4.2.1.[21] Figure 4.6 shows how the impact of, e.g., an increase in pre-tax inequality on the average carbon tax proposals now changes in comparison to Figure 4.5, where it is virtually zero.

Unlike the fully informed voters of Section 4.4.2.1, the average proposal for a regressive carbon tax ($\tau_\kappa = 0$) is significantly reduced by an increase in pre-tax inequality. For a progressive carbon tax ($\tau_\kappa = 1$) the relationship appears to be non-monotonic, even when it is quite weak: when coming from a rather equal income distribution at the right of Figure 4.6, a decrease in $\frac{h_{med}}{h_\mu}$ slightly increases the average carbon tax proposal of the two parties, but then, for high levels of inequality closer to the left boundary of Figure 4.6, more inequality decreases the average carbon tax proposal. It also appears that the degree of regressivity of carbon tax recycling is no longer neutral due to the myopia assumption. Instead, a progressively designed carbon tax exhibits more public support than a regressively designed one. Furthermore,

---

[21] In fact, the income tax proposals with voters who are myopic in the described sense is slightly below the tax rates with full internalization of the distributive impact of κ if $\tau_\kappa = 0$. The reason is that the myopic voters underestimate the regressivity of the carbon tax and do not sufficiently favor an according increase in τ to compensate the regressivity of the carbon tax.

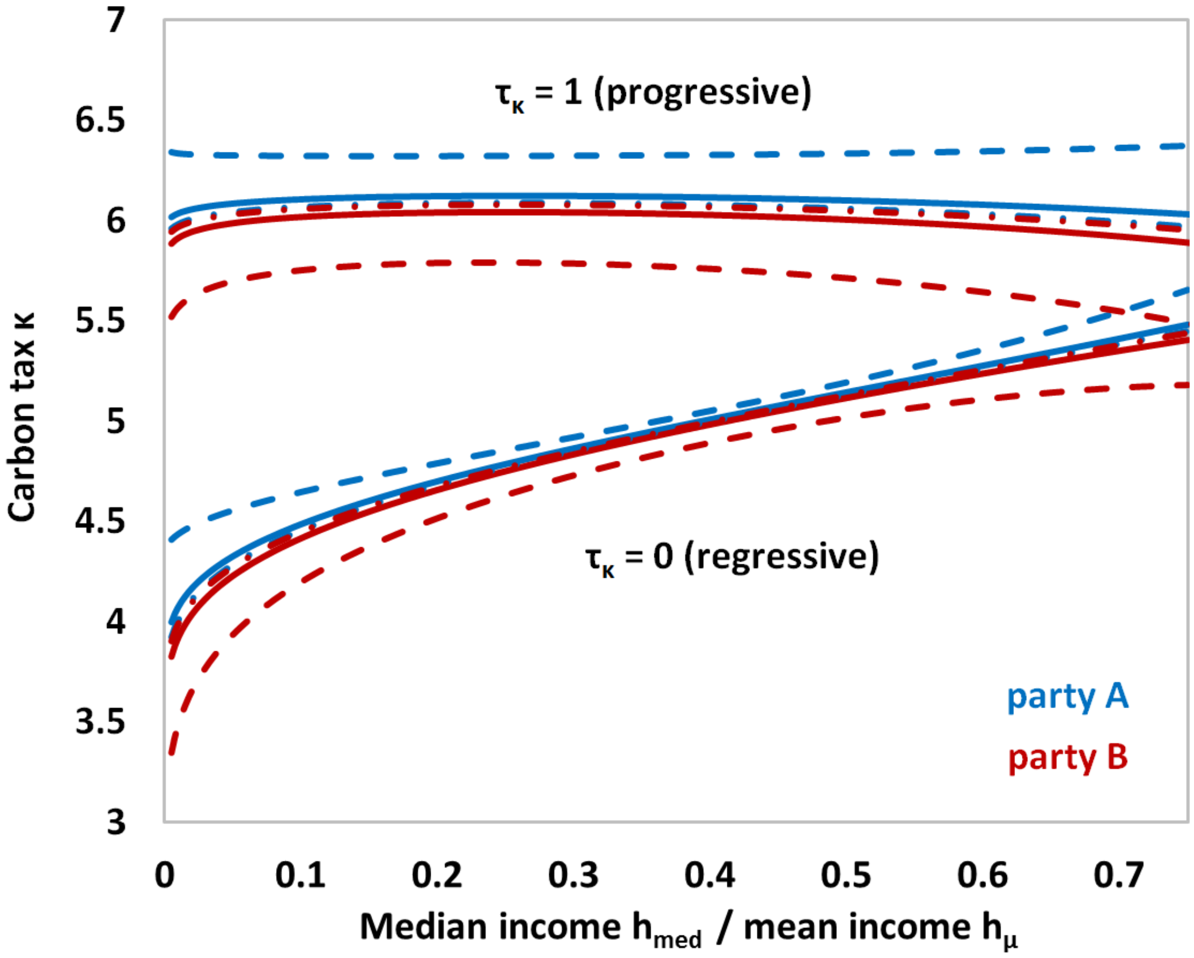

Figure 4.6 : Carbon tax proposals for voters who are myopic w.r.t. the redistributional implications of the carbon tax κ.

the advantage due to a more progressive design of carbon tax revenue recycling is more pronounced for higher levels of pre-income-tax inequality.

To sum up, even though the income tax adjusts to the increase in pre-tax inequality, the changes in inequality affect the voters' preference for the carbon tax, depending on its degree of progresivity. If the tax is regressive, then a majority of voters suffers individual monetary losses caused by its regressive character and prefers a lower carbon tax than in the case of a progressive carbon tax. If they were not myopic, they would want to compensate the regressive implication of the carbon tax via an income tax increase. But with the myopia assumption they do not account for the overall regressive distributional implication of the carbon tax and do not demand an income tax increase, thinking erroneously that their desired level of redistribution is reached. In the case of a progressive carbon tax a majority of voters enjoys additional monetary benefits from progressive revenue recycling (compared to regressive revenue recycling) without accounting for this additional progressive redistribution by choosing a lower income tax (in order to restore the average "desired" level of redistribution). In this way the carbon tax turns into a redistributive instrument without affecting the myopic people's utility over the redistributive preference term. Even if only a share of the electorate is myopic in the described sense, then this fact can also be expected to affect the equilibrium policy platforms.

4.4.2.3 Role of the Salience of the Redistribution Discourse ϕ

In this Subsection the question is raised how an increase in the salience of the political discourse on the distribution of income and the desired level of redistribution affects the PUNE outcomes. The salience of the distributional ideological issue is captured by the parameter ϕ in the term $-\phi(a_i - \rho(\tau, \kappa, \tau_\kappa))^2$, which expresses the disutility from deviations of the actual level of income redistribution from the individual's desired level (cf. Equation (4.9)). Without this ideological stance on redistribution the majority of voters with $h_i < h_\mu$ would prefer an income tax of one based only on the implications of redistribution for consumption utility. So, it reduces income taxation below one out of ideological concerns with regard to the degree of redistribution.

An increase in the salience of the related public discourse strengthens these ideological distributional concerns and can be expected to decrease the voter preference for income taxation. Figure 4.7 demonstrates this effect on the two-dimensional PUNEs for different bargaining weights of the Opportunist factions in the reference parameter setting. With the salience parameter ϕ going towards zero, income taxation in the equilibrium tends towards one. But an increasing ϕ reduces the proposed income tax rates of both parties for all relative bargaining weights. If the ideological stance on redistribution becomes so salient in voters' minds that it dominates the consumption related implications of the income tax, then the average income tax proposal approaches the average value for $a_i \in [0, 1]$, which is 0.5 for a uniform distribution of a_i.

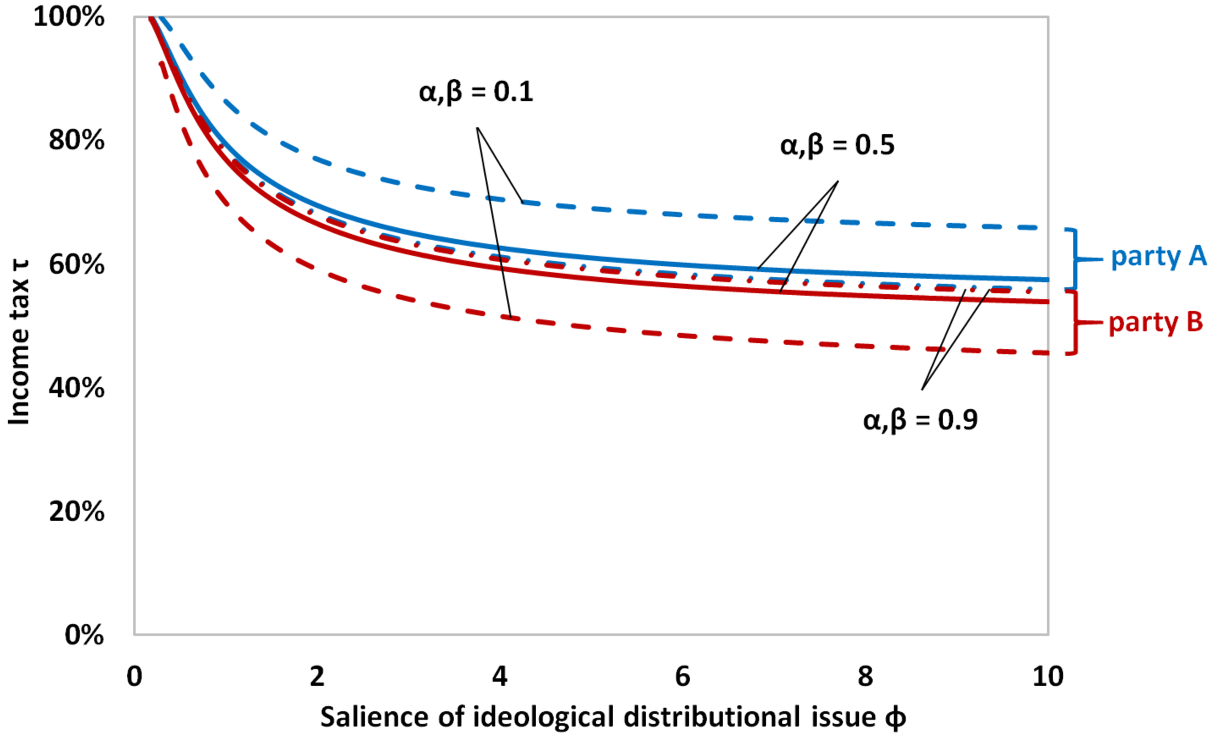

Figure 4.7 : Effect of the salience of the ideological discourse on redistribution ϕ on the equilibrium income tax proposals.

The effect of a rise in the salience parameter ϕ on the parties' simultaneous carbon tax proposals is shown in Figure 4.8. as a reaction, the polarization of the carbon tax proposals increases, particularly strongly in the range $0 < \phi < 3$, where the income tax decrease is most pronounced. This indicates that it is the rising post-income-tax inequality after the associated income tax reduction of Figure 4.7 which drives the polarization in carbon tax proposals. The result that, by leading to lower redistribution, an increase in ϕ fosters climate policy uncertainty seems to reaffirm the point from Section 4.4.2.1 that higher inequality of (pre-tax) income can raise policy uncertainty with regard to the carbon tax.

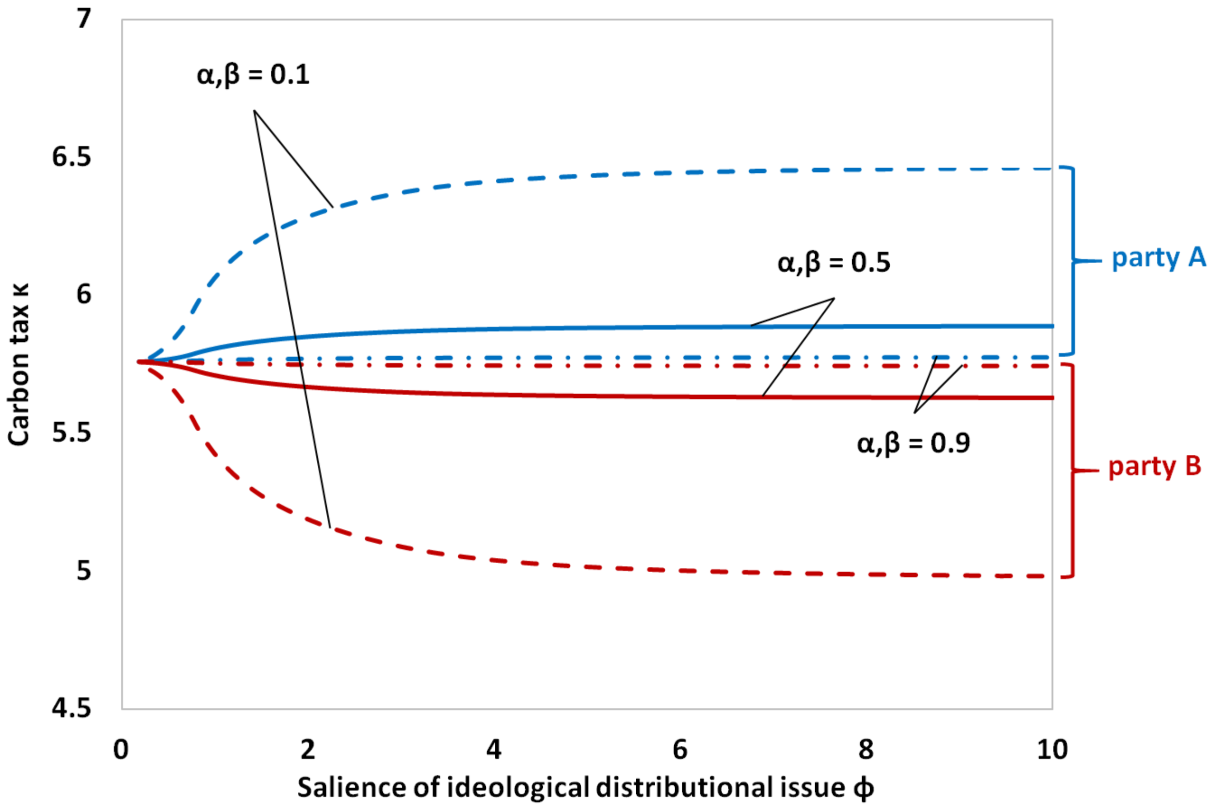

Figure 4.8 : Increase in party polarization on the climate issue with increasing salience of the redistributive discourse ϕ

4.5 Conclusion

This chapter presents the first analysis of two-dimensional political competition over a carbon tax and a proportional income tax in a static model of production with labor and carbon-intensive energy. Voter types are heterogeneous in pre-tax income and in their "collective orientation", which stands behind the individual preference for climate protection and for inequality aversion. The fact that the results differ significantly between a model version with a fixed exogenous income tax and one-dimensional political competition over the carbon tax and the full two-dimensional model emphasizes the importance of the two-dimensional approach.

In the one-dimensional case an increase in pre-tax inequality leads to higher (lower) carbon tax proposals by both parties if the carbon tax revenue recycling mechanism is progressive (regressive). In contrast, in the two-dimensional case the income tax compensates changes in inequality in pre-tax income and the average carbon tax proposal remains largely unaffected. The polarization of party platforms on the climate issue, however, changes non-monotonically with inequality of pre-tax income. For a low ratio of median income to mean income of approximately $\frac{h_{med}}{h_{\mu}} < 0.4$ the difference in the parties' carbon tax proposals increases with rising inequality. This implies that policy uncertainty, in the sense of the standard deviation from the expected value of the carbon tax, for investors in sectors heavily affected by climate policy – like renewable energy or other low-carbon technologies – can be exacerbated by rising inequality in market incomes. Party polarization and resulting policy uncertainty on the climate issue is also reinforced in the model by a higher salience of the normative discourse on the "appropriate", or individually desired, level of redistribution. This discourse reduces redistribution below 100 percent, which would result from purely monetary loss/benefit considerations of the voters, on the grounds of fairness, aversion to government intervention, distributive justice, and the like. The analysis also shows that it plays a significant role for the political equilibrium whether voters take the overall redistributive implication of the carbon tax into account in their utility function. If they are myopic in this respect, then the redistributive effect of the carbon tax is not offset by an adjustment in the income tax and changes in pre-tax inequality do affect the average carbon tax proposal, in contrast to the non-myopic case. The study reaffirms that distributive effects can play a very important role for the level of public support for climate policy measures. The way that carbon tax revenues are recycled, the way that climate policy is combined with income tax measures, the question what is taken into account in the public debate, the distribution of views on redistribution and inequality aversion, and the salience of the according public discourse are all important factors in the formation of public opinion on climate policy proposals.

The present work is only a first step in the analysis of the complex relationships between climate policy, or more general public good provision, political competition, inequality, and redistribution. The presented effects should be analyzed more in depth in future research to better understand some mechanisms, e.g. of increasing party polarization with changing pre-tax income inequality, to examine the sensitivity of the observed effects to further parameter changes, and to get closer to an empirical evaluation of the effects with real-world data. As a part of the sensitivity analysis, but also of a calibration, different distributions of the voter type parameter for "collective orientation" (uniformly distributed in this chapter) should be considered. Then also different party profiles like high redistribution/low climate policy and low redistribution/high climate policy could be possible.

A large number of extensions is possible for the presented framework: by extending the model to include elastic labor supply and, possibly, capital with capital income taxation the interaction of tax-related distortions in these factor markets and the endogenous climate policy dynamics could deliver additional insights for the debate on optimal carbon taxation and a double dividend. On this front, it could be quite insightful to establish an optimal taxation setting and to compare it with the outcome of political competition. In this way, the welfare reducing effects of different political economic aspects could be investigated. The model could also be combined with a temporal dimension to create economic growth, saving behavior, endogenous investments in green technologies, and an endogenous evolution of income inequality over time. In doing so, the feedback loop between economic processes affecting inequality, the political process which determines party platforms, and resulting decarbonization of the economy, which again creates winners and losers, could be closed to get a better understanding of the involved mechanisms. Such an extension could possibly yield a contribution to the debate on the environmental Kuznets curve. Also, the assumption of just two parties, although satisfying for the U.S., is quite restrictive for the explanation of the according political competition in other countries with proportional representation and coalition governments. Another possible future extension could aim at a combination of the present model of national political economic dynamics for a number of country blocs which are heterogeneous in income level, income distribution, and distribution of what I called "collective orientation" in this chapter with a model of international climate negotiations.

A Appendix to Chapter 1

A.1 Model Details

A.1.1 Household Capital Supply Behavior

The Euler equation (1.11) implicitly gives savings as a function of period incomes and the interest rate i_2.

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

From the total derivative of the Euler equation with respect to changes in period incomes and the interest rate, we derive the savings reactions

$$\begin{aligned}
\frac{\partial s_{1m}}{\partial y_{1m}} &= \frac{[\beta(1+i_2)]^{\frac{1}{\eta}}}{1+i_2+[\beta(1+i_2)]^{\frac{1}{\eta}}} > 0 \\
\frac{\partial s_{1m}}{\partial \pi_{2m}^{\tau}} &= \frac{\partial s_{1m}}{\partial \pi_{2m}} = -\frac{1}{1+i_2+[\beta(1+i_2)]^{\frac{1}{\eta}}} < 0 \\
\frac{\partial s_{1m}}{\partial i_2} &= -\frac{\beta u'(c_{2m})}{u''(c_{1m})+\beta(1+i_2)^2 u''(c_{2m})} + \frac{\partial s_{1m}}{\partial \pi_{2m}} s_{1m} \\
&= \frac{1}{\eta(1+i_2)} \frac{\pi_{2m}^{\tau}+(1-\eta)(1+i_2)s_{1m}}{1+i_2+[\beta(1+i_2)]^{\frac{1}{\eta}}} \gtrless 0
\end{aligned} \tag{A.2}$$

A.1.2 Aggregate Capital Supply with Homothetic Preferences

We show in the following that capital supply is a function of the resource extraction path and the interest rate i_2 only as long as we assume symmetric (and homothetic) consumption preferences. In case of an unit resource tax, the derivation is completely analogue.

Totally differentiating $K_2^s = s_{1E} + s_{1I}$ and taking into account (1.12) yields

$$dK_2^s = \frac{\partial s_{1E}}{\partial y_{1E}} dy_{1E} + \frac{\partial s_{1E}}{\partial d\pi_{2E}^{\tau}} d\pi_{2E}^{\tau} + \frac{\partial s_{1E}}{\partial i_2} di_2 + \frac{\partial s_{1I}}{\partial y_{1I}} dy_{1I} + \frac{\partial s_{1I}}{\partial \pi_{2I}^{\tau}} d\pi_{2I}^{\tau} + \frac{\partial s_{1I}}{\partial i_2} di_2$$

as $s_{1m} = s_{1m}(y_{1m}, \pi_{2m}, i_2)$ by the Euler equation (1.11) of the respective country $m = E, I$.

The changes in the period income streams in both countries can be further decomposed with respect to resource inputs, factor prices, and the carbon tax τ_2. Taking into account Equations (1.2), (1.4), and (1.5) and $\frac{\partial s_{1E}}{\partial y_{1E}} = \frac{\partial s_{1I}}{\partial y_{1I}}$ and $\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} = \frac{\partial s_{1I}}{\partial \pi^{\tau}_{2I}}$ for symmetric homothetic preferences yields

$$dK_2^s = \left[\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right] dR_2 + SE di_2$$

where we use (A.2) to derive the aggregate substitution effect:

$$\begin{aligned} SE &= \frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi_{2I}} K_2 \\ &= -\left[\frac{\beta u'(c_{2E})}{u''(c_{1E}) + \beta(1+i_2)^2 u''(c_{2E})} + \frac{\beta u'(c_{2I})}{u''(c_{1I}) + \beta(1+i_2)^2 u''(c_{2I})}\right] > 0 \end{aligned}$$

A.1.3 Comparative Statics of Conditional Market Equilibrium

To determine the sign of $\frac{dp_2}{dR_2}$, we totally differentiate the market equilibrium conditions (1.14) and (1.16), solve for the market price reactions $\frac{dp_2}{dR_2}$ and $\frac{di_2}{dR_2}$ and obtain

$$\frac{dp_2}{dR_2} = \frac{F_{2RR} - \Gamma_2 SE + F_{2KR}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1\right)}{1 - F_{2KK} SE} < 0$$

with $\Gamma_t = F_{tRR}F_{tKK} - F_{tKR}^2$, while $SE = \frac{\partial s_{1E}}{\partial i_2} + \frac{\partial s_{1I}}{\partial i_2} - \frac{\partial s_{1I}}{\partial \pi^{\tau}_{2I}} K_2$ is the aggregated substitution effect from a change in the interest rate i_2, as defined in Appendix A.1.2. The negative sign unambiguously holds as $F_{2RR} < 0$, $F_{2KK} < 0$, and $\Gamma_2 > 0$ due to the concavity of the production technology, $F_{2KR} > 0$ due to the complementarity of production factors, and $SE > 0$ as shown in Appendix A.1.2, as well as $\frac{\partial s_{1E}}{\partial \pi_{2E}} < 0$, and $\frac{\partial s_{1E}}{\partial y_{1E}} > 0$ according to (1.12). This also implies that the general equilibrium change in the interest rate

$$\frac{di_2}{dR_2} = \frac{F_{2KR} + F_{2KK}\left(\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial \pi_{2E}} p_1\right)}{1 - F_{2KK} SE} > 0$$

is unambiguously positive. Using the total derivative of (1.13), derived in Appendix A.1.2, substituting for $\frac{di_2}{dR_2}$ yields

$$\frac{dK_2}{dR_2} = \frac{\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KR} SE}{1 - F_{2KK} SE} \tag{A.3}$$

The denominator captures the feedback effect of a change in the second-period capital stock on savings incentives. A higher capital stock K_2 decreases, ceteris paribus, the marginal productivity of capital due to the concavity of the production technology (1.3) and thus the interest rate i_2 in capital market equilibrium, which induces households to substitute savings for present consumption. Recall that the income effects induced in both countries by this decrease in the interest rate exactly offset each other in case of symmetric and homothetic consumption preferences. Due to the concavity of the production technology and the positive substitution effect SE, the denominator is unambiguously positive.

A.1.4 Equilibrium Capital Accumulation with Symmetric Preferences

From (A.3) we know that

$$\frac{dK_2}{dR_2} = \frac{\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 - \frac{\partial s_{1E}}{\partial y_{1E}} p_1 + F_{2KR} SE}{1 - F_{2KK} SE}$$

where $SE = \frac{\partial s_{1E}}{\partial y_{1E}} \frac{c_{1E}+c_{1I}}{\eta(1+i_2)}$, as derived in Section A.1.2. Since the denominator is unambiguously positive, the sign of the capital reaction depends solely on the numerator. From the final goods market equilibrium and the symmetric Euler equation (1.11) it follows that

$$c_{1E} + c_{1I} = F_1 + K_1 - K_2 = \frac{c_{2E} + c_{2I}}{[\beta(1+i_2)]^{\frac{1}{\eta}}} = \frac{F_2 + K_2}{[\beta(1+i_2)]^{\frac{1}{\eta}}}$$

Moreover, since $\frac{\partial s_{1E}}{\partial y_{1E}} = -\frac{\partial s_{1E}}{\partial \pi_{2E}} [\beta(1+i_2)]^{\frac{1}{\eta}}$ from (1.12), we can rearrange the numerator and conclude that capital accumulation will react negatively to a shift of resources to the future period if

$$\frac{\partial s_{1E}}{\partial \pi_{2E}} p_2 \left\{ 1 + [\beta(1+i_2)]^{\frac{1}{\eta}} \frac{p_1}{p_2} - \frac{1}{\eta\sigma} \frac{i_2(F_2+K_2)}{F_2(1+i_2)} \right\} < 0$$

and therefore if

$$\frac{1+i_2}{\theta_{2K}+i_2} \left\{ 1 + [\beta(1+i_2)]^{\frac{1}{\eta}} \frac{p_1}{p_2} \right\} > \frac{1}{\sigma\eta}$$

Since the left side is greater than unity ($\theta_{2K} < 1$), this implies that $\sigma\eta \geq 1$ is a sufficient condition for $\frac{dK_2}{dR_2} < 0$.[1]

---

[1] The elasticity of substitution measures how easily capital and oil can be substituted in production. It thus also captures how strongly capital demand reacts to a change in resource input. The intertemporal elasticity of

A.2 The Monopolist's Second-Order Condition

Consider the maximization problem of the omniscient benevolent monopolist (1.21).

$$\begin{aligned}\max U(c_{1E}, c_{2E}) &= u(c_{1E}) + \beta u(c_{2E})\\ &= u[p_1 R_1 + (1+i_1)s_{0E} - s_{1E}] + \beta u[\tilde{p}_2 R_2 + (1+i_2)s_{1E}]\end{aligned}$$

The omniscient monopolist is aware that

$$\begin{array}{lll} p_t = F_{tR}(K_t, R_t) & \text{with } \dfrac{dp_2}{dR_2} = \dfrac{\partial p_2}{\partial R_2} + \dfrac{\partial p_2}{\partial K_2}\dfrac{dK_2}{dR_2} & \text{from (1.19)}\\ i_t = F_{tK}(K_t, R_t) & \text{with } \dfrac{di_2}{dR_2} = \dfrac{\partial i_2}{\partial R_2} + \dfrac{\partial i_2}{\partial K_2}\dfrac{dK_2}{dR_2} & \text{from (1.20)}\\ K_1 \text{ given} & & \\ K_2 = K_2(R_2) & & \text{from (A.3)}\\ s_{1E} = s_{1E}(y_{1E}, \pi_{2E}, i_2) & \text{with } \dfrac{ds_{1E}}{dR_2} = -\dfrac{\partial s_{1E}}{\partial y_{1E}}\dfrac{\partial y_{1E}}{\partial R_1} + \dfrac{\partial s_{1E}}{\partial \pi_{2E}}\dfrac{d\pi_{2E}}{dR_2} + \dfrac{\partial s_{1E}}{\partial i_2}\dfrac{di_2}{dR_2} & \end{array}$$

Additionally taking into account the budget constraints (1.9) and (1.10) and the resource constraint (1.2) reduces (1.21) to a one-dimensional optimization problem. Thus, for the necessary first-order condition, we obtain

$$\begin{aligned}\frac{dU}{dR_2} = u'(c_{1E})&\left[\underbrace{\left(p_1 + \frac{\partial p_1}{\partial R_1}R_1 + \frac{\partial i_1}{\partial R_1}s_{0E}\right)}_{MV_1}\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right]\\ &+ \beta u'(c_{2E})\left[\underbrace{\tilde{p}_2 + \frac{d\tilde{p}_2}{dR_2}R_2 + \frac{di_2}{dR_2}s_{1E}}_{MV_2^{\tau}} + (1+i_2)\frac{ds_{1E}}{dR_2}\right] \overset{!}{=} 0\end{aligned}$$

---

substitution, in turn, indicates how sensitive households' savings and, therefore, capital supply are to changes in the interest rate i_2. Thus, intuitively, if $\sigma > \frac{1}{\eta}$, shifting resources to the second period lowers the resource price, and thereby capital demand, to such an extent that the strong reduction in capital demand outweighs the incentive to increase savings derived from the complementarity-driven rise in the interest rate i_2.

where $u'(c_{tE}) = \frac{\partial u}{\partial c_{tE}}$ holds. The second-order condition for a (local) welfare maximum then reads

$$\begin{aligned}\frac{d^2U}{(dR_2)^2} = u''(c_{1E})\left[MV_1\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right]^2 + u'(c_{1E})\left[\frac{\partial MV_1}{\partial R_1}\left(\frac{dR_1}{dR_2}\right)^2 - \frac{d^2s_{1E}}{(dR_2)^2}\right]\\ + \beta u''(c_{2E})\left[MV_2^\tau + (1+i_2)\frac{ds_{1E}}{dR_2}\right]^2\\ + \beta u'(c_{2E})\left[\frac{dMV_2^\tau}{dR_2} + \frac{di_2}{dR_2}\frac{ds_{1E}}{dR_2} + (1+i_2)\frac{d^2s_{1E}}{(dR_2)^2}\right]\end{aligned} \tag{A.4}$$

where

$$\begin{aligned}\frac{\partial MV_1}{\partial R_1} &= 2\frac{\partial p_1}{\partial R_1} + \frac{\partial^2 p_1}{(\partial R_1)^2}R_1 + \frac{\partial^2 i_1}{(\partial R_1)^2}s_{0E}\\ \frac{dMV_2^\tau}{dR_2} &= 2\frac{d\tilde{p}_2}{dR_2} + \frac{d^2\tilde{p}_2}{(dR_2)^2}R_2 + \frac{d^2 i_2}{(dR_2)^2}s_{1E} + \frac{di_2}{dR_2}\frac{ds_{1E}}{dR_2}\end{aligned}$$

From the savings decision of the representative household, we know that the Euler equation

$$\frac{u'(c_{1E})}{\beta u'(c_{2E})} = 1 + i_2$$

holds in the optimal equilibrium outcome. This implies, on the one hand, that the necessary first-order condition of the monopolist's utility maximization problem (1.21)

$$-u'(c_{1E})\left[p_1 + \frac{\partial p_1}{\partial R_1}R_1 + \frac{\partial i_1}{\partial R_1}s_{0E}\right] + u'(c_{2E})\left[\tilde{p}_2 + \frac{d\tilde{p}_2}{dR_2}R_2 + \frac{di_2}{dR_2}s_{1E}\right] = 0$$

can be reduced to the modified Hotelling rule (1.22), i.e.,

$$(1+i_2)MV_1 = MV_2^\tau$$

On the other hand, we can also conclude that for any extraction path in the conditional market equilibrium the Euler equation has to hold. Thus, from the total derivative of the Euler equation with respect to R_2 we obtain

$$u''(c_{1E})\left[MV_1\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right] = \beta u'(c_{2E})\frac{di_2}{dR_2} + \beta(1+i_2)u''(c_{2E})\left[MV_2^\tau + (1+i_2)\frac{ds_{1E}}{dR_2}\right]$$

This allows us to substitute the first term in (A.4) and, upon rearranging, arrive at

$$\begin{aligned}
\frac{d^2U}{(\partial R_2)^2} = & \left[MV_1\frac{dR_1}{dR_2} - \frac{ds_{1E}}{dR_2}\right]\left[\beta u'(c_{2E})\frac{di_2}{dR_2} + \beta(1+i_2)u''(c_{2E})\left(MV_2^{\tau} + (1+i_2)\frac{ds_{1E}}{dR_2}\right)\right] \\
& + \beta u'(c_{2E})\left[(1+i_2)\frac{\partial MV_1}{\partial R_1}\left(\frac{dR_1}{dR_2}\right)^2 + \frac{dMV_2^{\tau}}{dR_2}\right] + \beta u'(c_{2E})\frac{di_2}{dR_2}\frac{ds_{1E}}{dR_2} \\
& + \beta u''(c_{2E})\left[MV_2^{\tau} + (1+i_2)\frac{ds_{1E}}{dR_2}\right]^2 \\
= & \, \beta u'(c_{2E})\left[(1+i_2)\frac{\partial MV_1}{\partial R_1} + MV_1\frac{dR_1}{dR_2}\frac{di_2}{dR_2} + \frac{dMV_2^{\tau}}{dR_2}\right]
\end{aligned}$$

For a welfare maximum we must have $\frac{d^2U}{(dR_2)^2} < 0$ and therefore, since $\beta u'(c_{2E}) > 0$,

$$(1+i_2)\frac{\partial MV_1}{\partial R_1} + MV_1\frac{dR_1}{dR_2}\frac{di_2}{dR_2} + \frac{dMV_2^{\tau}}{dR_2} < 0$$

Given that $\frac{dR_1}{dR_2} = -1$ by the resource constraint, this also implies that

$$\frac{d[(1+i_2)MV_1]}{dR_2} - \frac{dMV_2^{\tau}}{dR_2} = (1+i_2)\frac{\partial MV_1}{\partial R_1}\frac{dR_1}{dR_2} + \frac{di_2}{dR_2}MV_1 - \frac{dMV_2^{\tau}}{dR_2} > 0$$

B Appendix to Chapter 2

B.1 Conditional Market Equilibrium with Exploration Investments

We derive and define the modified conditional market equilibrium completely analogue to Section 1.2.3 and Appendices A.1.1, A.1.2, A.1.3 but take into account that, by setting $R_1 = S_1(X) - R_2$, first period resource supply now may either change due to a change in R_2, which represents a pure intertemporal reallocation of resources (for given exploration efforts), or due to a change in exploration efforts (for a given R_2). Moreover, since exploration expenditures X directly reduce first period income in country E, the budget constrain (1.9) is modified accordingly. Thus, aggregate capital supply is function of intertemporal resource allocation represented by R_2 for a given X and of exploration efforts.

Overall, proceeding along the lines of the standard setting but consequently separating the influences of R_2 for given X and vice versa, we observe that the second period capital stock in conditional market equilibrium is now a function of R_2 and X with

$$\begin{aligned} dK_2 &= \frac{\left(\frac{\partial s_{1E}}{\partial \pi^{\tau}_{2E}} \tilde{p_2} - \frac{\partial s_{1e}}{\partial y_{1E}} p_1 + F_{2KR} \cdot SE\right)}{1 - F_{2KK} SE} dR_2 + \frac{\partial s_{1E}}{\partial y_{1E}} \frac{\left(p_1 S_1'(X) - 1\right)}{1 - F_{2KK} SE} dX \\ &= \left.\frac{dK_2}{dR_2}\right|_X dR_2 + \left.\frac{dK_2}{dX}\right|_{R_2} dX \end{aligned}$$

where we use the notation $\left.\frac{dK_2}{dR_2/dX}\right|_{R_2/X}$ to indicate that the respective variable is held constant. While $\left.\frac{dK_2}{dR_2}\right|_X$ is already known from Appendix A.1.3, the second term $\left.\frac{dK_2}{dX}\right|_{R_2}$ captures the effect of increase in exploration efforts on the aggregate capital stock K_2 for a given second period resource supply R_2. As indicated by the numerator, this effect derives from the first period profits or resource income from a marginal increase in exploration expenditures which needs not be positive. Thus, $\left.\frac{dK_2}{dX}\right|_{R_2}$ is of ambiguous sign, in general.

B.2 Proofs

Proof of Proposition 2.1:

To derive the comparative statics (2.3), we totally differentiate (2.1) with respect to R_2 and τ_2 taking into account $dR_1 = -dR_2$ by (1.2) and (1.17), (1.18), (1.19), and (1.20).

For the denominator, we have

$$\frac{d[(1+i_2)MV_1]}{dR_2} - \frac{dMV_2^{\tau}}{dR_2} = \frac{di_2}{dR_2}MV_1 - (1+i_2)\frac{dMV_1}{dR_1} - \frac{dMV_2^{\tau}}{dR_2} > 0$$

along the equilibrium supply path as shown in Appendix (A.2).[1]

The numerator, in contrast, is generally of ambiguous sign and captures the direct effect of a marginal increase in the second period's resource tax on the Hotelling condition (2.1) for the initially, that is, before the tax increase, optimal resource supply path.

Proof of Proposition 2.2:

We know that $\frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2} > 0$ and $\frac{d[(1+i_2)MV_1]}{dR_2} - \frac{dMV_2^{\tau}}{dR_2} > 0$ always hold (cf. Section 2.3.1 and Appendix A.2). If marginal oil revenue is negative, so that $-MR_2 > 0$, then

$$\frac{dR_2^*}{d\tau_2} = \frac{-MR_2 + \frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2}}{\frac{d[(1+i_2)MV_1]}{dR_2} - \frac{dMV_2^{\tau}}{dR_2}} > 0$$

must always hold. □

Proof of Proposition 2.3:

Proof by contradiction. We label the numerator of (2.3) as $M := -MR_2 + \frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2}$. Since the denominator must be positive for any tax rate as long as we restrict the analysis to utility-maximizing resource extraction policies, we consider only the numerator.

$$sgn(M) = sgn\left(\frac{dR_2^*}{d\tau_2}\right) \tag{B.1}$$

M depends on the tax rate only indirectly via the resource supply path because the second-period capital stock K_2 and market prices i_2 and p_2 are functions of the resource supply path only (see (A.3), (1.19), and (1.20)): $M = M(R_2)$. M is not directly a function of the future tax rate τ_2: $M \neq M(R_2, \tau_2)$. $\Rightarrow$ $sgn(M)$ is a function of R_2, but not directly of τ_2. Assume M is

---

[1] More generally, the positive sign also implies that the familiar Hotelling arbitrage consideration will lead the monopolist to the equilibrium outcome (at least locally).

not monotonous. ⇒ There are two tax rates $\tau_{2,a}, \tau_{2,b}$ for which the monopolist chooses the same optimal extraction path

$$R_2^*(\tau_{2,a}) = R_2^*(\tau_{2,b}) \tag{B.2}$$

and for which, according to (B.1), it holds that

$$sgn(M(R_2^*(\tau_{2,a}))) \neq sgn(M(R_2^*(\tau_{2,b})))$$

⇒ From (B.2) follows

$$sgn(M(R_2^*(\tau_{2,a}))) \neq sgn(M(R_2^*(\tau_{2,a})))$$

↯□.

B.3 Share of Oil Expenditures in GDP

Figure B.1 shows the share of oil expenditures in GDP for the U.S. and for all OECD countries except the U.S. The expenditure share of oil remained below 10% for the whole data range. The data for U.S. oil consumption (EIA 2016b) and oil prices (EIA 2016a) comes from the United

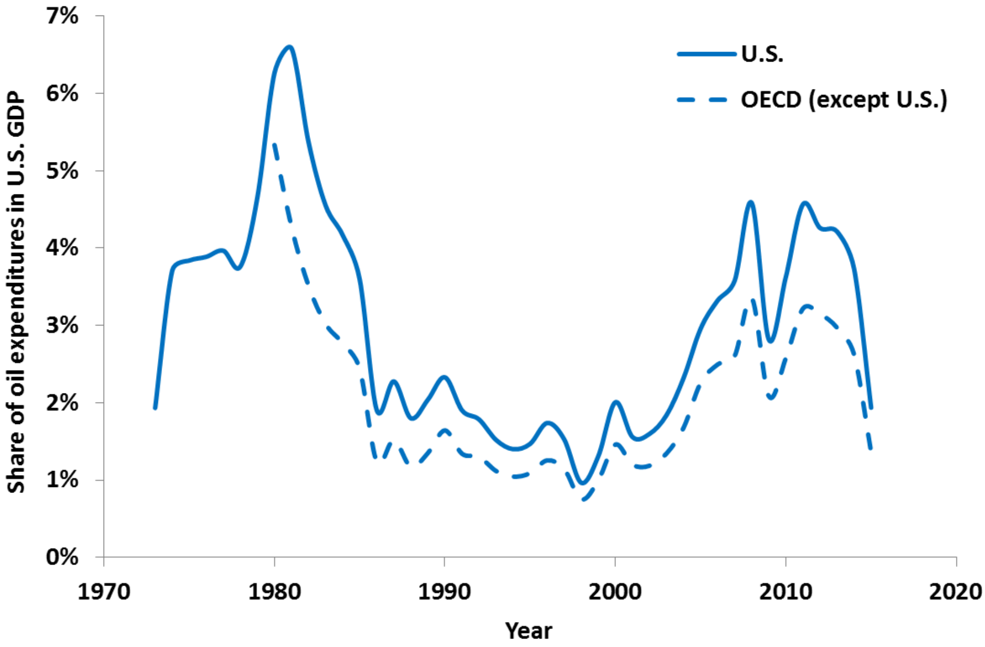

Figure B.1 : Share of oil expenditures in GDP for U.S. and non-U.S. OECD countries.

States Energy Information Administration. GDP data for the U.S. come from the databank of the Federal Reserve Bank St. Louis (FRED 2016b). Oil consumption of OECD countries from (OECD 2016b), global oil prices (for OECD countries) (FRED 2016a), and GDP of OECD countries (OECD 2016a). Although different countries became additional OECD members over time, the data considers the ones which were OECD members in 2015 for the whole period of 1980 until 2015.

B.4 The Effect of the Elasticity of Substitution on the Postponement Condition

By increasing σ for a given intertemporal elasticity of substitution $\frac{1}{\eta}$, in general, $\frac{dK_2}{dR_2} < 0$ is more likely, but this implies that not only the left side but also the right side of the postponement condition (2.5) may increase in σ. To resolve this ambiguity and to investigate whether acceleration of extraction becomes more likely with a higher elasticity of substitution, we now consider the behavior of the right side in the limiting case $\sigma \to \infty$.

For $\sigma \to \infty$, the CES production technology (1.3) becomes linear[2] 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, the resource supply path continues to influence the capital market equilibrium via capital *supply* because a shift in the resource supply path, ceteris paribus, transfers aggregate income from one period to the other, and households adapt their savings, that is, aggregate capital supply. Since in the limiting case $\sigma \to \infty$ the extraction profile no longer has a direct complementarity-driven influence on the interest rate and therefore can no longer induce a substitution effect, the endogeneity of the future capital stock is entirely dependent on this income transfer from

---

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

the first to second period. We therefore have[3]

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

Since $p_t = F_{tR} = \lambda$ and $i_t = F_{tK} = \gamma$ for the linear production technology in the limiting case $\sigma \to \infty$ and since the savings reactions are just functions of the interest rate i_2 and the preference parameters by (A.2), we conclude that $|\frac{dK_2}{dR_2}|$[4] is bounded from above for $\sigma \to \infty$. Since $\theta_{2R} < 1$ and $\theta_{2K} < 1$ by definition, and $|i_2\frac{\partial s_{1E}}{\partial\pi^{\tau}_{2E}}| < 1$ by (A.2), the right side of postponement condition (2.5) is also bounded from above.

B.5 Unit Tax without Exploration Costs

Figure B.2 shows the zones of acceleration and postponement of oil extraction as a reaction to climate policy for the case of a unit tax on oil without any exploration costs over the two main parameters of the production structure, the elasticity of factor substitution σ and the productivity parameter of oil λ. This figure is the counterpart to figure 2.1 (cf. Section 2.4) which depicts the case of an ad-valorem tax. The red shaded area, where the marginal value of oil would fall below zero if the monopolist was forced to extract the whole oil stock, is identical for both types of taxes since it is determined by the pre-policy state $\tau = t = 0$. For the unit tax, the border line between the acceleration zone and the postponement zone (solid dark blue curve) embraces a smaller area than for the ad-valorem tax (cf. bleached light-blue curve). But for the most part of the area with $\lambda < 0.1$ and $\sigma < 1$ the monopolist postpones extraction due to the climate policy, like for the ad-valorem tax. On the one hand, the fact that for a unit tax the term $-MR_2$ in the numerator of (2.3) is substituted by -1 in the most cases reduces the inclination to accelerate extraction. On the other hand, the term $\frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial\pi_{2E}}\frac{\partial\pi^{\tau}_{2E}}{\partial\tau_2}$ in the numerator of (2.3) also changes with the switch from an ad-valorem tax to a unit tax,

---

[3] Regarding the denominator, note that $F_{2KK} = 0$ for a linear production technology. Moreover, 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 (1.7) and (1.9) and $i_2 = F_{2K} = \gamma$. Together, this implies that $\lim_{\sigma\to\infty} F_{2KK}SE = 0$.

[4] In fact, we get by (A.2)

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

as $\lambda < 1$.

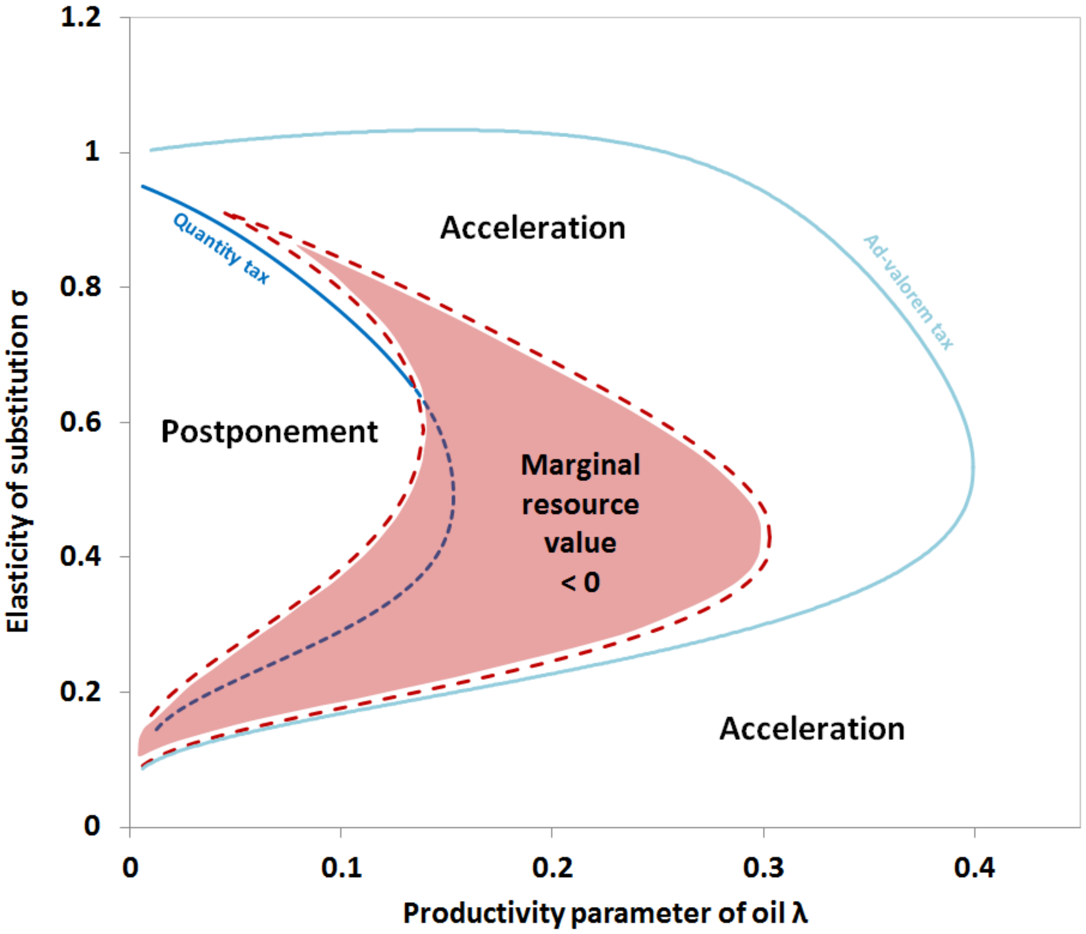

Figure B.2 : Zones of acceleration and postponement of extraction over the elasticity of factor substitution σ and the productivity parameter of oil λ for a unit tax.

also affecting the postponement/acceleration zones. The border line between the two zones for the unit tax in part cuts through the parameter area with a negative marginal resource value. Strictly speaking, here the model setup without exploration costs reaches its limits as the monopolist has a clear rationale to leave a part of the stock in the ground. Therefore, the border line of the zones is dashed.

B.6 Sensitivity Analysis for Further Parameters

B.6.1 Initial Factor Endowments K_1 and $\bar{S}$

The results of the numerical simulation in Figure B.3 show that the initial endowments of capital and oil can affect the direction of the extraction shift. Obviously, changes in (relative) factor endowments are closely related to the basic logic of Section 2.4.1. The scarcity of oil compared to the other production factors heavily affects the policy reaction of the extraction path. A higher initial resource endowment leads to a lower marginal product and to a lower marginal resource revenue (cf. numerator of (2.3)). The resulting tax-induced losses in resource rents are lower. This reduces the incentive to accelerate extraction and makes postponement of extraction more likely (cf. Figure B.3). The same scarcity reasoning explains the effect of a decrease in capital endowment K_1: a lower initial capital endowment K_1 of the world economy decreases the resource's marginal revenue and marginal productivity and, thus, makes postponement of extraction more likely. This suggests that we can expect a different supply-side reaction to a credible threat of climate policy today than at some other point in the past or the future with proceeding depletion of the oil stock and capital accumulation over time.

The parameter λ can be seen as a scaling parameter for the marginal revenue of oil and the according acceleration incentive. This is the reason why changes in both factor endowments are more pronounced at higher values of the productivity parameter of oil λ.[5]

The distribution of initial capital asset endowments can in principle also affect the policy reaction. If the exporting country's share in the capital endowment is higher, then its capital asset motive in the present is reinforced more than the one in the future. Therefore, present extraction is higher and equilibrium values of all model variables differ. Unfortunately, if the initial equilibrium before introduction of a climate policy is different, a comparison of reactions to climate policy under various distributions of capital endowment becomes analytically intractable. The numerical simulation in Figure B.4, however, shows that a higher share of country E in the (constant) global capital asset endowment increases the area of extraction postponement. We see that the distribution of the capital endowment is almost irrelevant for the policy outcome for more realistic parameter settings of $\lambda < 0.1$. But this also implies that transfer payments from the importing to the exporting countries as part of a climate policy agreement would be neither detrimental, nor beneficial for the result of postponement of oil extraction.

---

[5] Due to decreasing returns to scale with respect to (K, R), but constant returns to scale with respect to (K, R, L), in final goods production, higher capital endowments can lead to scenarios in which there is no longer positive capital accumulation as households more and more tend to consume and save out of the given stock, which rises linearly in capital endowments (cf. $c_{1E} + c_{1I} + K_2 = F_1 + K_1$).

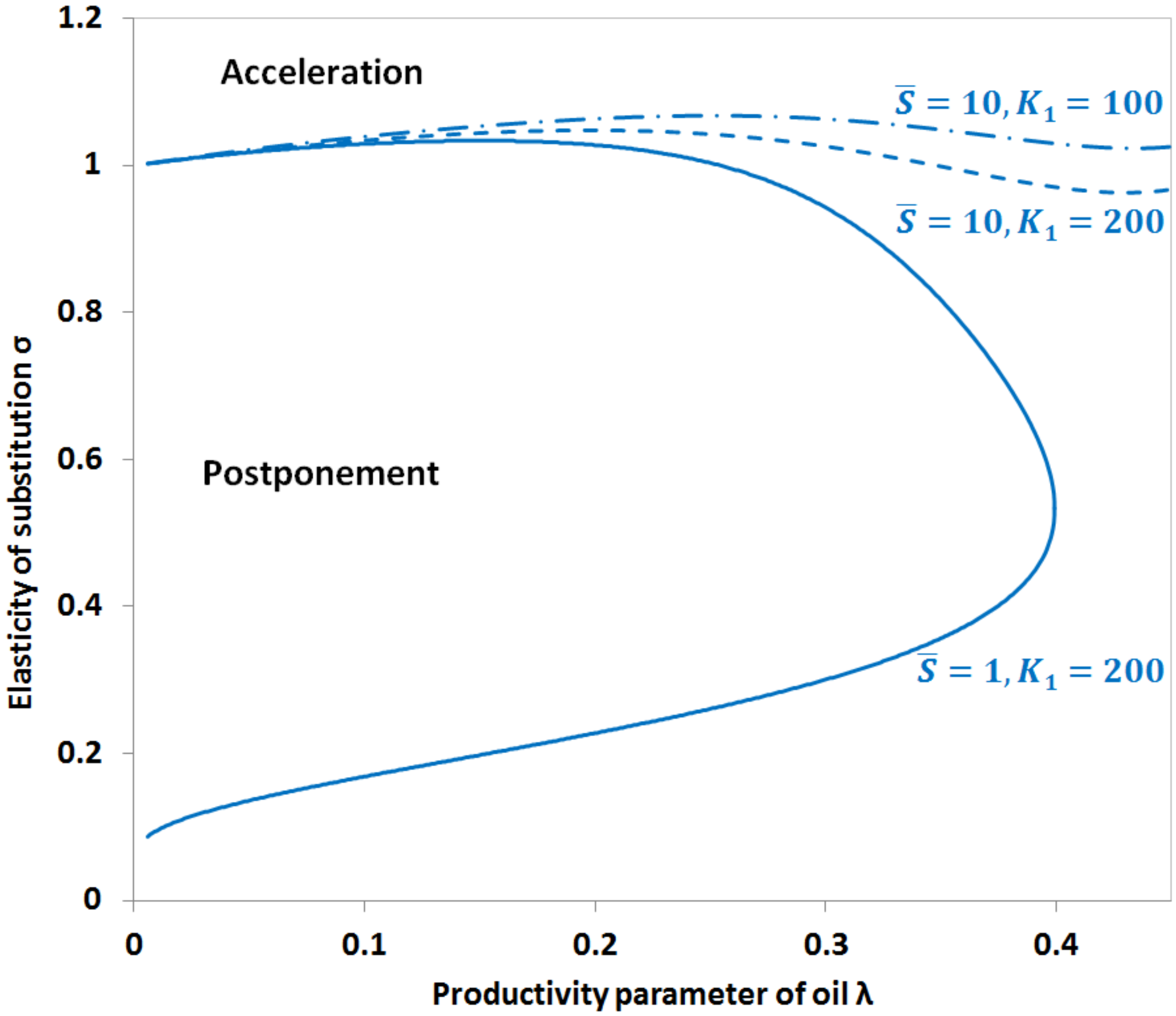

Figure B.3 : Influence of the initial capital endowment K_1 and the resource endowment $\bar{S}$ on the borderline between the acceleration and the postponement area ($\beta = 0.3, \eta = 2, \frac{s_{0E}}{K_1} = 0.1$).

B.6.2 Household Preferences

The households' preference parameters β and η also affect the extraction reaction to a future tax increase. Figure B.5 illustrates the role of the utility discount factor β. A lower β, indicating higher impatience, reinforces the savings reaction to the tax increase and the according income loss in the second period $\frac{\partial s_{1m}}{\partial \pi^{\tau}_{2m}}$ (cf. (1.12)). This increases the probability of extraction postponement. This effect is more pronounced at higher values of the productivity parameter of oil λ: the tax-induced income loss and the according savings adjustment are higher when a higher productivity parameter of oil λ leads to a higher marginal product and a higher income share of oil.

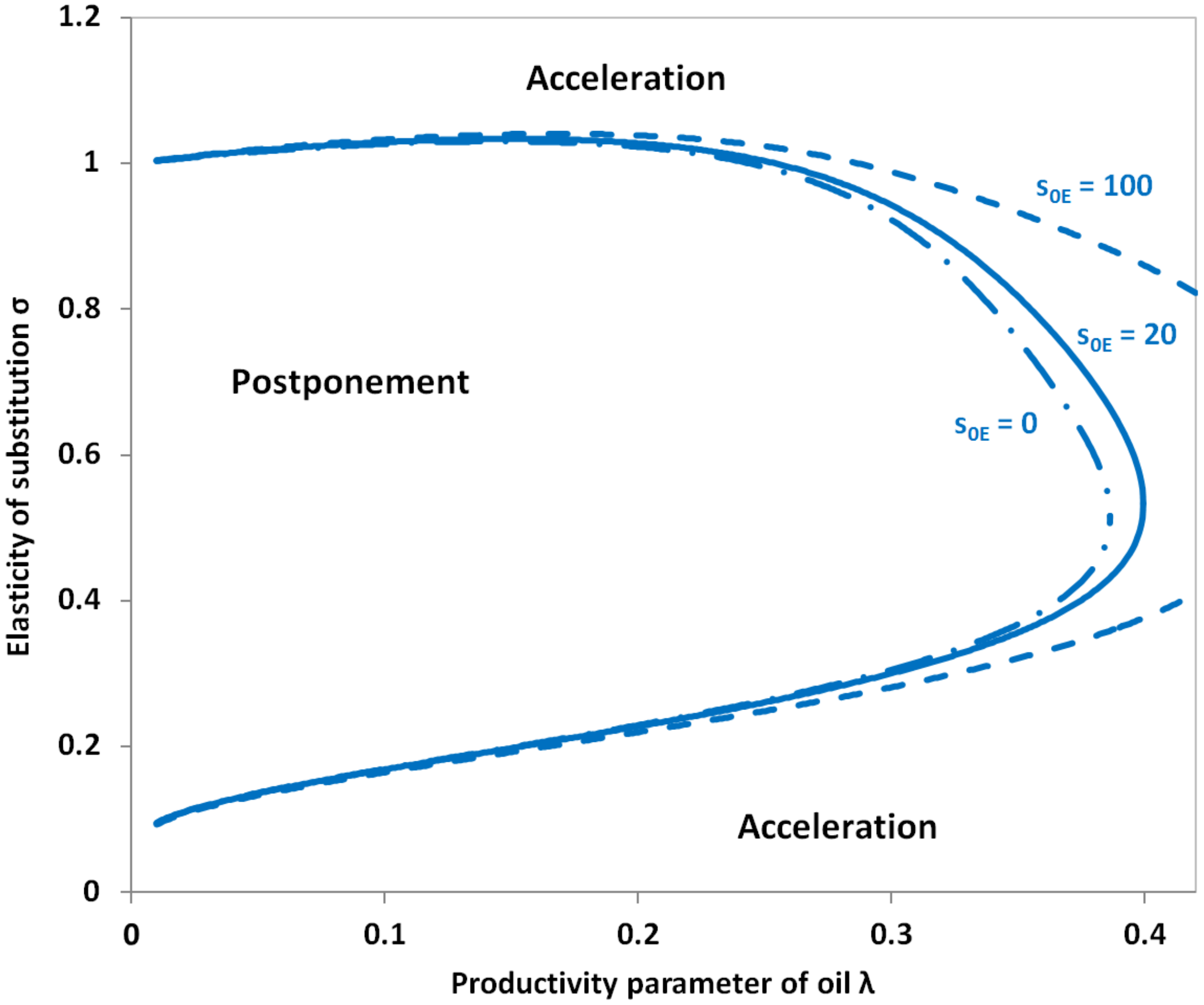

Figure B.4 : Influence of the amount of capital assets of country E s_{0E} on the boundary between acceleration and postponement of extraction ($\beta = 0.3$, $\eta = 2$, $K_1 = 200$, $\bar{S} = 1$).

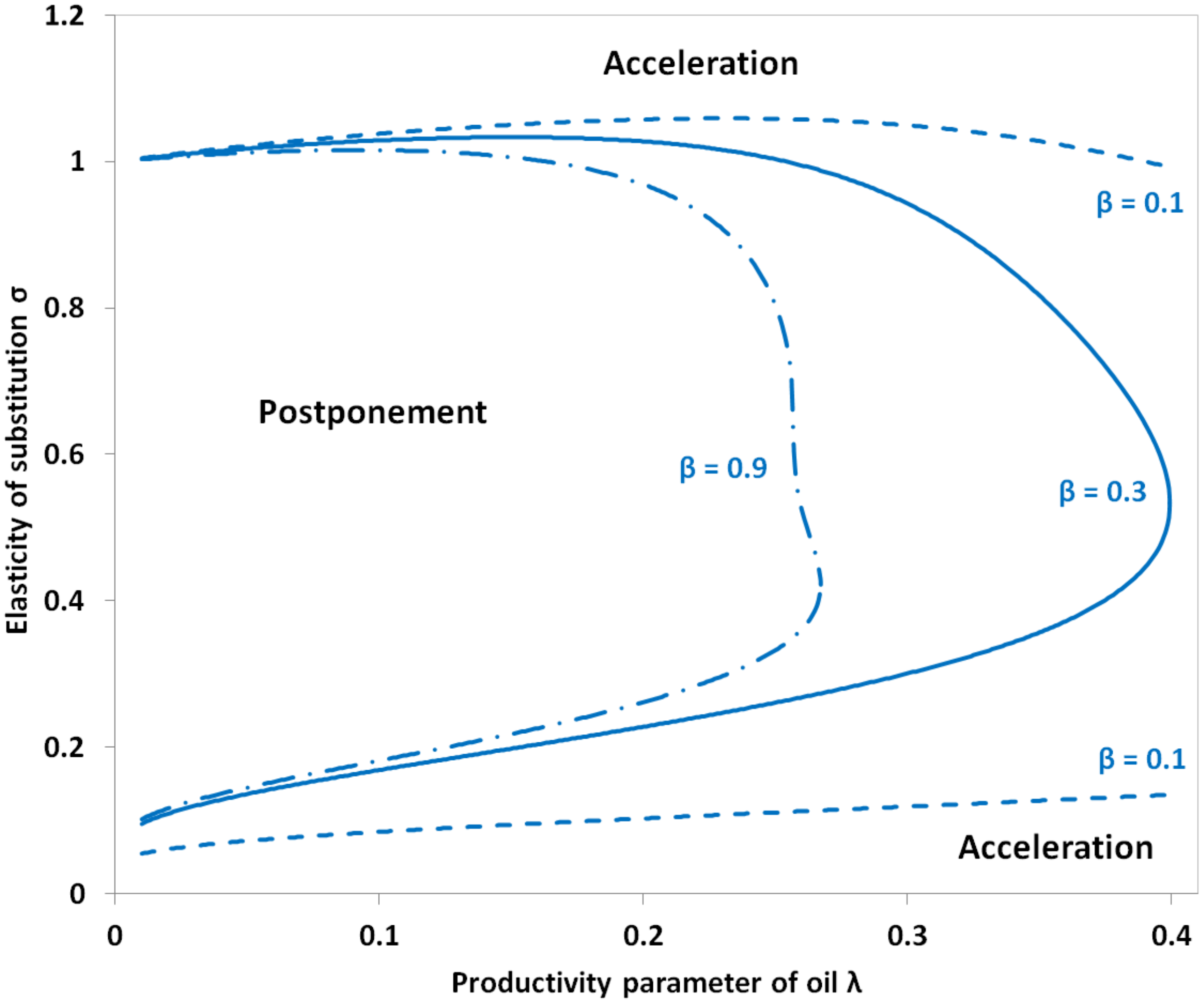

Figure B.5 : Influence of the utility discount factor β on the boundary between acceleration and postponement of extraction ($\eta = 2$, $K_1 = s_{0E} + s_{0I} = 20 + 180 = 200$, $\bar{S} = 1$).

The second preference parameter η, which indicates the curvature of the utility function and whose inverse $\frac{1}{\eta}$ is the elasticity of intertemporal substitution, also affects the strength and the sign of the savings reaction to the tax-induced income loss in the future. In Figure B.6, a higher value of η leads to a stronger future capital asset motive and makes postponement of extraction more likely in the case of higher substitution elasticites σ. But the opposite is the case for lower values of σ. The absolute value of the savings reaction to an income loss $\frac{\partial s_{1m}}{\partial \pi^{\tau}_{2m}}$ (cf. (A.2) in the Appendix) is higher for higher values of η. But the pre-policy equilibrium is different with a different η, as well. This leads to similar analytical difficulties as in the previous Section B.6.1. Although the influence of η depends on other model parameters, the result that extraction is postponed for reasonable parameter ranges like $\lambda < 0.1$ and $0.2 < \sigma < 0.9$ remains rather robust.

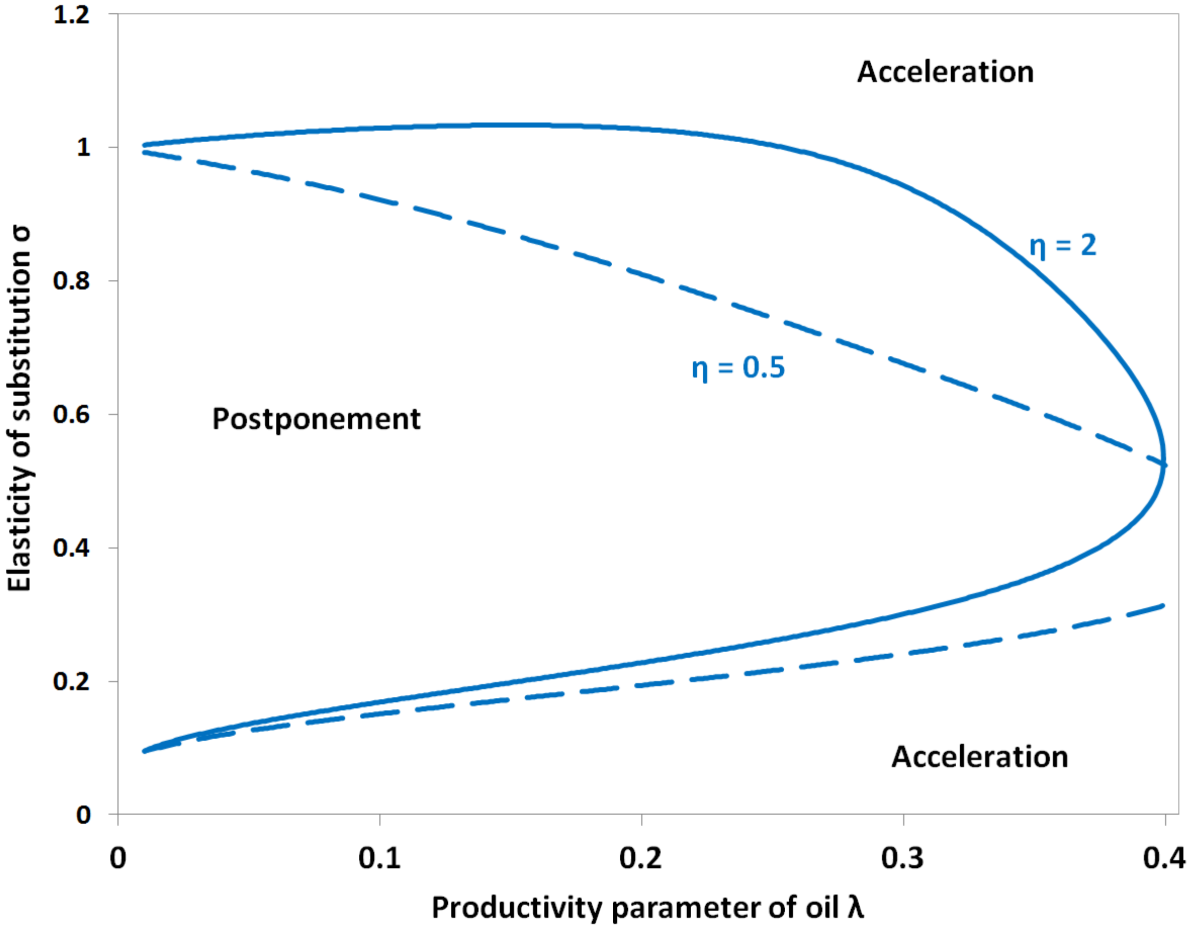

Figure B.6 : Influence of the elasticity of intertemporal substitution $\frac{1}{\eta}$ on the boundary between acceleration and postponement of extraction ($\beta = 0.3$, $K_1 = s_{0E} + s_{0I} = 20 + 180 = 200$, $\bar{S} = 1$).

C Appendix to Chapter 3

C.1 Numerical Analysis

C.1.1 CAFE Compliance without Urban Adjustment (Step 1)

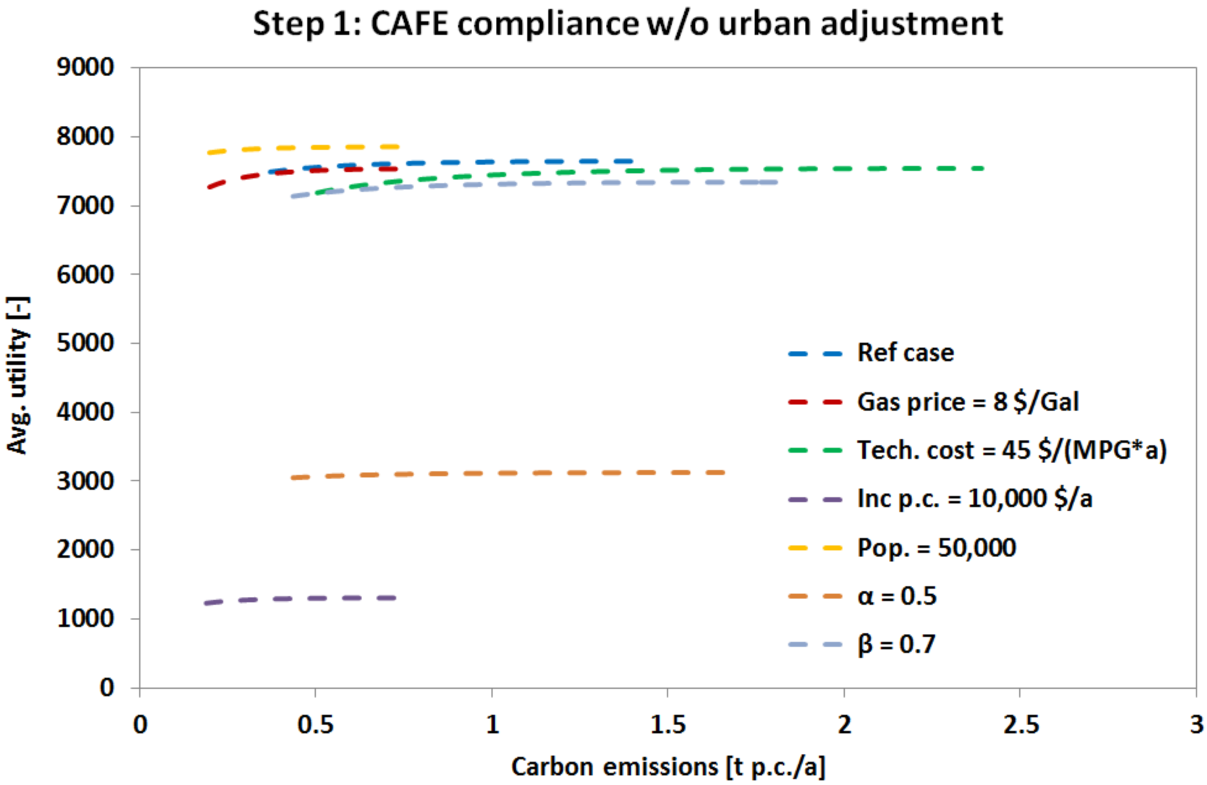

Figure C.1 : Reduction of average utility with emission reductions for CAFE compliance case without urban adjustment for the reference case and some deviating parameters

The blue curve represents the reference case, while the others represent cases where one parameter is changed relative to the reference case. All the curves start at the right end, but in different points, because the different parameter settings lead to different initial states. With tightening CAFE standards the city moves to the left along the respective curve towards lower average emissions per capita, but also towards lower average utility levels. The purple curve of the case with a lowered household income of $10,000\frac{\$}{a}$ is way below the other graphs and not visible in the figure. The shape of the curves seems to vary considerably. But looking at

Figure 3.2, where we have normalized average utility and per-capita emission reductions, we see that the overall pattern is fairly similar.

C.1.2 Welfare Effects of Urban Adjustment (Step 2)

With a Cobb-Douglas utility function and constant prices utility scales linearly with available income. Here, a constant housing price curve $p_0(x)$ from before the policy intervention is assumed (the price of the numeraire composite good is 1). To approximate the average change in available household income due to the effect of the change in distances x and vehicle efficiency $mpg(x)$ in the expansion of step 2, the average commuting distance before ($x_{\varnothing\, comm,1}$) and after the expansion ($x_{\varnothing\, comm,2}$) and the average vehicle efficiency before ($mpg_{\varnothing\, comm,1}$) and after the expansion ($mpg_{\varnothing\, comm,2}$) are considered. Starting with average utility after step 1 ($u_{\varnothing\, 1,CAFE}$) and substituting available income after the mentioned income shock for available income before yields an approximated utility level $u_{\varnothing,comm,2}$ of a hypothetical average household.

$$u_{\varnothing,comm,2} = u_{\varnothing\, 1,CAFE} \frac{(y - t(mpg_{\varnothing\, comm,1})x_{\varnothing\, comm,2} - v(mpg_{\varnothing\, comm,2}))}{(y - t(mpg_{\varnothing\, comm,1})x_{\varnothing\, comm,1} - v(mpg_{\varnothing\, comm,1}))} \tag{C.1}$$

The fact that the housing price adjustment which is not considered in this exercise is the logical reason for the increase in commute x and in vehicle mileage mpg is ignored here. The resulting difference between the states before and after the income shock are a proxy for the average vehicle related component of the total (negative) welfare effect of urban expansion:

$$\Delta u_{2,veh} = u_{\varnothing\, 1,CAFE} - u_{\varnothing,comm,2}$$

To capture the according proxy for the average housing related component of the welfare effect of urban expansion we take the difference between the final utility level in equilibrium after the full housing price adjustment $u_{2,CAFE}$ and the approximated average utility level calculated in (C.1) $u_{\varnothing,comm,2}$:

$$\Delta u_{2,hou} = u_{2,CAFE} - u_{\varnothing,comm,2}$$

Figure C.2 visualizes $\Delta u_{2,veh}$ and $\Delta u_{2,hou}$ relative to the welfare cost of compliance of step 1 ($\Delta u_{1,CAFE}$). The difference of the two welfare effect components is the magnitude of the negative net effect of the urban expansion of welfare that is shown in Figure 3.4.

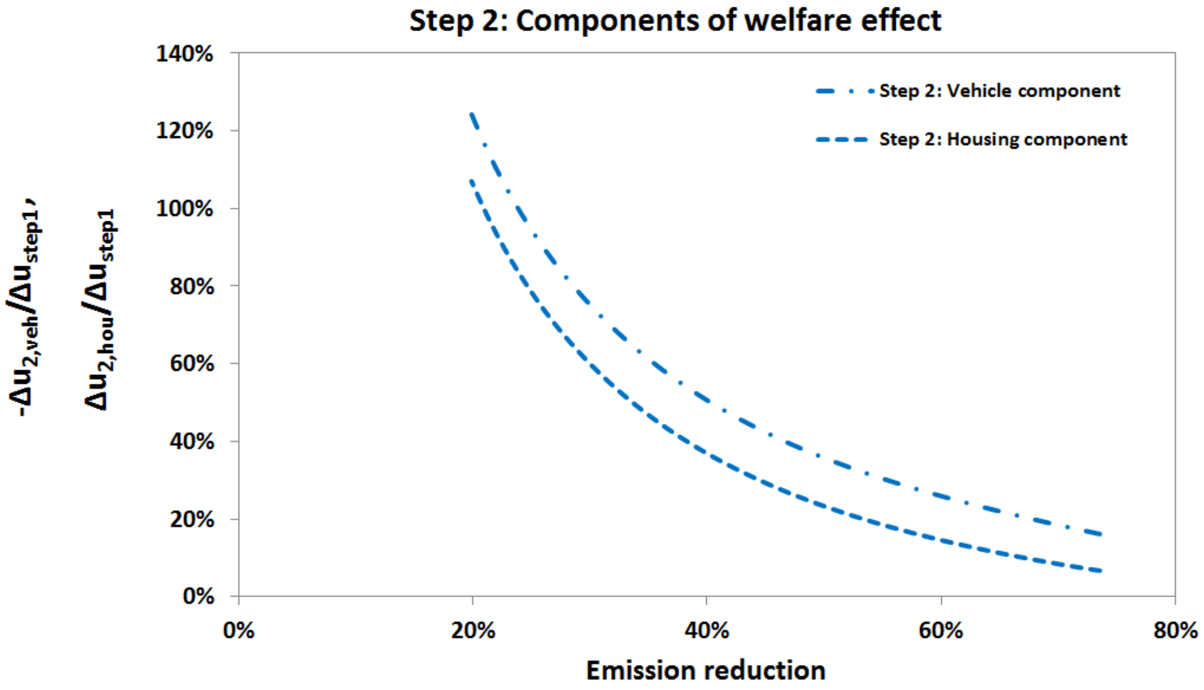

Figure C.2 : Components of the welfare effect of urban adjustment (step 2) for CAFE policy

Both, the housing related component and the vehicle related component have a significant magnitude between 10 percent and 120 percent of $\Delta u_{1,CAFE}$. Although this is just a rough exercise, the order of magnitude of the components is visualized. If one of the components in a possible future empirical study is left out of the picture resulting estimates for the welfare effect of urban adjustment due to CAFE standards could be highly biased.

D Appendix to Chapter 4

D.1 Model Derivations

D.1.1 Total degree of redistribution

The sum of carbon tax revenues $\kappa E(\kappa)$ is recycled proportionally to the income distribution which would result from an income tax of τ_κ. The according formulation of $Rec(\kappa)$ from (4.6) is substituted into (4.5), which yields

$$\left[h_i + (h\mu - h_i)\tau + \underbrace{(h_i + (h_\mu - h_i)\tau_\kappa)\frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}}_{Rec(\kappa)} \right] \frac{\gamma^\gamma(1-\gamma)^{(1-\gamma)}}{(p_E+\kappa)^{(1-\gamma)}} =$$

$$\left[h_i \left(1 + \frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}\right) + (h_\mu - h_i)\tau \left(1 + \frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}\frac{\tau_\kappa}{\tau}\right)\right] \frac{\gamma^\gamma(1-\gamma)^{(1-\gamma)}}{(p_E+\kappa)^{(1-\gamma)}} =$$

$$\left(1 + \frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}\right) \left[h_i + (h_\mu - h_i)\, \underbrace{\tau \left(\frac{1 + \frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}\frac{\tau_\kappa}{\tau}}{1 + \frac{\kappa(1-\gamma)}{(p_E+\kappa)\gamma}} \right)}_{\rho(\tau,\kappa,\tau_\kappa)} \right] \frac{\gamma^\gamma(1-\gamma)^{(1-\gamma)}}{(p_E+\kappa)^{(1-\gamma)}}$$

with the total degree of redistribution $\rho(\tau, \kappa, \tau_\kappa)$.

D.1.2 Differential Formulation of PUNE

This differential formulation of PUNE is taken from Roemer (2006). In the case of party A, the weighted Nash bargaining game is defined by a maximization of the Nash product, as stated in (4.14) in Section 4.3.2

$$\max_{t \in T} (\pi(t, t_B) - 0)^\alpha (W^A(t) - W^A(t_B))^{1-\alpha}$$

Applying logs yields

$$\max_{t \in T} \, \alpha \, ln(\pi(t, t_B)) + (1-\alpha) \, ln(\Delta W^A(t))$$

with $\Delta W^A(t) = W^A(t) - W^A(t_B)$. For maximization, the gradient w.r.t. the policy vector t is taken and set to zero

$$\frac{\alpha}{\pi(t,t_B)}\nabla_t\pi(t,t_B) + \frac{(1-\alpha)}{\Delta W^A(t)}\nabla_t W^A(t) = 0$$
$$\nabla_t W^A(t) = -\frac{\alpha}{1-\alpha}\frac{\Delta W^A(t)}{\pi(t,t_B)}\nabla_t\pi(t,t_B)$$

Defining $\lambda^A(t,t_B) = \frac{\alpha}{1-\alpha}\frac{\Delta W^A(t)}{\pi(t,t_B)}$ yields the equation

$$\nabla_t W^A(t) = -\lambda^A(t,t_B)\nabla_t\pi(t,t_B)$$

In the same way, the according maximization problem for party B from (4.15)

$$\max_{t\in T}((1-\pi(t_A,t)) - 0)^{\beta}(W^B(t) - W^B(t_A))^{1-\beta}$$

can be transformed to

$$\nabla_t W^B(t) = \lambda^B(t_A,t)\nabla_t\pi(t_A,t)$$

with $\lambda^B(t_A,t) = \frac{\beta}{1-\beta}\frac{\Delta W^B(t)}{\pi(t_A,t)}$

D.2 Climate Policy Analysis

In the case of two-dimensional policy competition a variation of the inequality of pre-tax income $\frac{h_{med}}{h_\mu}$ is taken care of by the income tax τ. The carbon tax proposals of the parties remain largely unaffected for the three examined bargaining weights of the Opportunist factions in both parties.

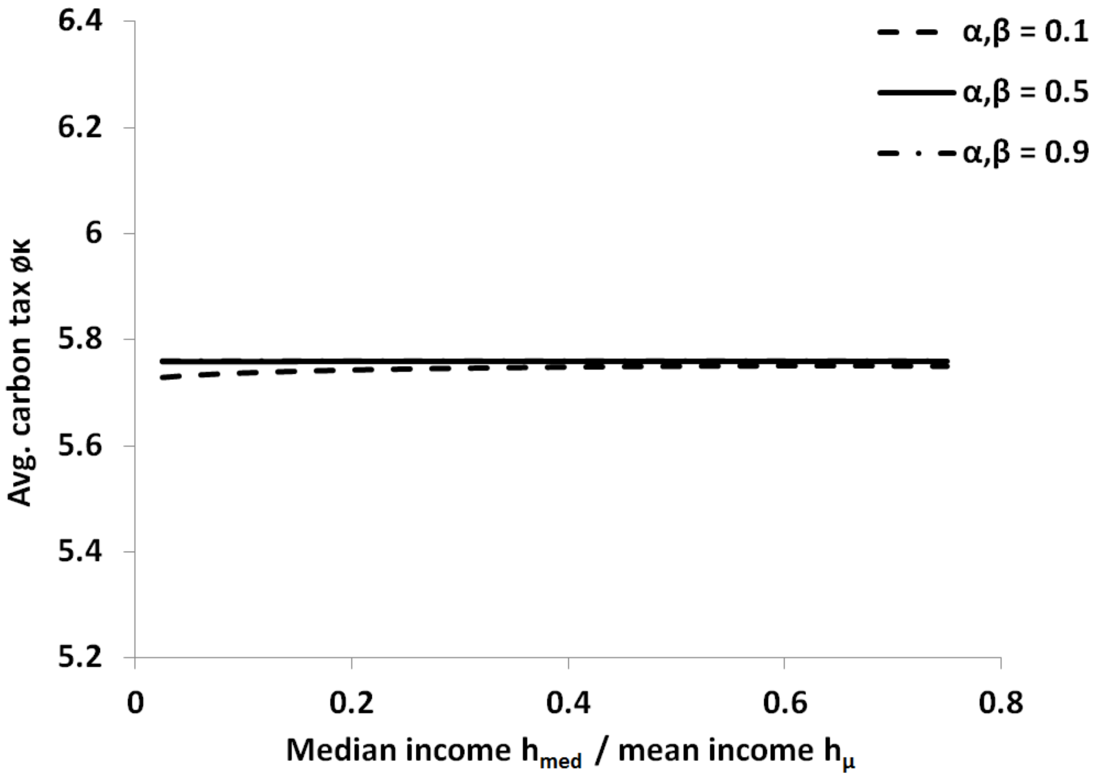

Figure D.1 : Average carbon tax proposals for two-dimensional PUNEs at the reference parameter setting (cf. Table 4.1)

Bibliography

Abdul-Hamid, Omar, Adedapo Odulaja, Ramadan Janan, Angela Agoawike, and Alvino-Mario Fantini (2013). *OPEC Annual Statistical Bulletin 2013*. Vienna. URL: `https://www.opec.org/opec_web/static_files_project/media/downloads/publications/ASB2013.pdf`.

Alonso, William (1977). *Location and land use: Toward a general theory of land rent*. 6. printing. Cambridge/Mass.: Harvard Univ. Press.

Anas, Alex and Hyok-Joo Rhee (2007). "When are urban growth boundaries not second-best policies to congestion tolls?" *Journal of Urban Economics* 61 (2), pp. 263–286.

Anderson, Soren T. and James M. Sallee (2011). "Using loopholes to reveal the marginal cost of regulation: The case of fuel-economy standards". *The American Economic Review* 101 (4), pp. 1375–1409.

Andrade de Sá, Saraly and Julien Daubanes (2016). "Limit pricing and the (in)effectiveness of the carbon tax". *Journal of Public Economics* 139, pp. 28–39.

Anthoff, David, Richard S. J. Tol, and Gary W. Yohe (2009). "Risk aversion, time preference, and the social cost of carbon". *Environmental Research Letters* 4 (2), p. 24002.

Austin, David and Terry Dinan (2005). "Clearing the air: The costs and consequences of higher CAFE standards and increased gasoline taxes". *Journal of Environmental Economics and Management* 50 (3), pp. 562–582.

Babiker, Mustafa H., Gilbert E. Metcalf, and John Reilly (2003). "Tax distortions and global climate policy". *Journal of Environmental Economics and Management* 46 (2), pp. 269–287.

Barker, Terry and Jonathan Köhler (2005). "Equity and ecotax reform in the EU: Achieving a 10 per cent reduction in CO2 emissions using excise duties". *Fiscal Studies* 19 (4), pp. 375–402.

Barrage, Lint (2018). "Optimal dynamic carbon taxes in a climate-economy model with distortionary fiscal policy". *Review of Economic Studies* (forthcoming).

Bento, Antonio M. and Mark Jacobsen (2007). "Ricardian rents, environmental policy and the 'double-dividend' hypothesis". *Journal of Environmental Economics and Management* 53 (1), pp. 17–31.

Berk, Istemi and Hakan Yetkiner (2014). "Energy prices and economic growth in the long run: Theory and evidence". *Renewable and Sustainable Energy Reviews* 36, pp. 228–235.

Böhringer, Christoph, Nicholas Rivers, and Hidemichi Yonezawa (2016). “Vertical fiscal externalities and the environment”. *Journal of Environmental Economics and Management* 77, pp. 51–74.

Bonanno, Giacomo (1990). “Equilibrium theory with imperfect competition”. *Journal of Economic Surveys* 4 (4), pp. 297–328.

Bovenberg, A. Lans and Ruud A. de Mooij (1994). “Environmental levies and distortionary taxation”. *The American Economic Review* 84 (4), pp. 1085–1089.

Brenner, Mark, Matthew Riddle, and James K. Boyce (2007). “A Chinese sky trust? Distributional impacts of carbon charges and revenue recycling in China”. *Energy Policy* 35 (3), pp. 1771–1784.

Brueckner, Jan K. (2007). “Urban growth boundaries: An effective second-best remedy for unpriced traffic congestion?” *Journal of Housing Economics* 16 (3–4), pp. 263–273.

Buchanan, James M. and Wm Craig Stubblebine (1962). “Externality”. *Economica* 29 (116), pp. 371–384.

Bureau, Benjamin (2011). “Distributional effects of a carbon tax on car fuels in France”. *Energy Economics* 33 (1), pp. 121–130.

Burke, Paul J. and Shuhei Nishitateno (2013). “Gasoline prices, gasoline consumption, and new-vehicle fuel economy: Evidence for a large sample of countries”. *Energy Economics* 36, pp. 363–370.

Callan, Tim, Sean Lyons, Susan Scott, Richard S.J. Tol, and Stefano Verde (2009). “The distributional implications of a carbon tax in Ireland”. *Energy Policy* 37 (2), pp. 407–412.

Calvo, Guillermo and Ronald Findlay (1978). “On the optimal acquisition of foreign capital through investment of oil export revenues”. *Journal of International Economics* 8 (4), pp. 513–524.

Campbell, Troy H. and Aaron C. Kay (2014). “Solution aversion: On the relation between ideology and motivated disbelief”. *Journal of Personality and Social Psychology* 107 (5), pp. 809–824.

Central Intelligence Agency (2014). *CIA World Factbook*. URL: `https://www.cia.gov/library/publications/the-world-factbook/`.

Chan, Nathan W. and Kenneth Gillingham (2015). “The microeconomic theory of the rebound effect and its welfare implications”. *Journal of the Association of Environmental and Resource Economists* 2 (1), pp. 133–159.

Chiroleu-Assouline, Mireille and Mouez Fodha (2014). “From regressive pollution taxes to progressive environmental tax reforms”. *European Economic Review* 69, pp. 126–142.

Coase, Ronald H. (1960). "The problem of social cost". *The Journal of Law & Economics* 3, pp. 1–44.

Cunado, Juncal and Fernando Perez de Gracia (2014). "Oil price shocks and stock market returns: Evidence for some European countries". *Energy Economics* 42, pp. 365–377.

Curuk, Malik and Suphi Sen (2015). "Oil trade and climate policy". *CESifo Working Paper Series* (5285).

da Silva Freitas, Lucio Flavio, Luiz Carlos de Santana Ribeiro, Kênia Barreiro de Souza, and Geoffrey John Dennis Hewings (2016). "The distributional effects of emissions taxation in Brazil and their implications for climate policy". *Energy Economics* 59, pp. 37–44.

Dasgupta, Partha S. and Geoffrey M. Heal (1979). *Economic theory and exhaustible resources*. Cambridge Economic Handbooks. Cambridge: Cambridge University Press.

Davenport, Coral (2018). *Trump Administration unveils its plan to relax car pollution rules*. New York. URL: `https://www.nytimes.com/2018/08/02/climate/trump-auto-emissions-california.html`.

Dempsey, Judith A. and Andrew J. Plantinga (2013). "How well do urban growth boundaries contain development? Results for Oregon using a difference-in-difference estimator". *Regional Science and Urban Economics* 43 (6), pp. 996–1007.

Di Maria, Corrado, Ian Lange, and Edwin van der Werf (2014). "Should we be worried about the green paradox? Announcement effects of the Acid Rain Program". *European Economic Review* 69, pp. 143–162.

Eichner, Thomas and Rüdiger Pethig (2011). "Carbon leakage, the green paradox, and perfect future markets". *International Economic Review* 52 (3), pp. 767–805.

Ekins, Paul, Hector Pollitt, Jennifer Barton, and Daniel Blobel (2011). "The implications for households of environmental tax reform (ETR) in Europe". *Ecological Economics* 70 (12), pp. 2472–2485.

Energy Information Administration (2016a). *Online data base - U.S. crude oil composite acquisition cost by refiners*. 2016. URL: `http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=R0000____3&f=A` (visited on 12/02/2016).

Energy Information Administration (2016b). *Online data base - U.S. product supplied of crude oil and petroleum products*. 2016. URL: `http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MTTUPUS2&f=A` (visited on 12/02/2016).

Energy Information Administration (2018). *How much carbon dioxide is produced from burning gasoline and diesel fuel?* URL: `https://www.eia.gov/tools/faqs/faq.php?id=307&t=11` (visited on 08/02/2018).

Federal Reserve Bank St. Louis (2016a). *Economic data base - Global price of APSP crude oil*. https://fred.stlouisfed.org/series/POILAPSPUSDA. 2016. URL: `https://fred.stlouisfed.org/series/POILAPSPUSDA` (visited on 12/02/2016).

Federal Reserve Bank St. Louis (2016b). *Economic data base - U.S. gross domestic product*. https://fred.stlouisfed.org/series/FYGDP. 2016. URL: `https://fred.stlouisfed.org/series/FYGDP` (visited on 12/02/2016).

Fischer, Carolyn and Ramanan Laxminarayan (2005). "Sequential development and exploitation of an exhaustible resource: do monopoly rights promote conservation?" *Journal of Environmental Economics and Management* 49 (3), pp. 500–515.

Fouquet, Roger (2014). "Long-run demand for energy services: Income and price elasticities over two hundred years". *Review of Environmental Economics and Policy* 8 (2), pp. 186–207.

Frank, Robert (2016). *Bill Gates calls for higher capital gains taxes*. Ed. by CNBC. URL: `https://www.cnbc.com/2016/05/02/bill-gates-calls-for-higher-capital-gains-taxes.html` (visited on 09/13/2018).

Freire-González, Jaume (2018). "Environmental taxation and the double dividend hypothesis in CGE modelling literature: A critical review". *Journal of Policy Modeling* 40 (1), pp. 194–223.

Frondel, Manuel, Jörg Peters, and Colin Vance (2008). "Identifying the rebound: evidence from a German household panel". *Energy Journal* 29 (4), pp. 145–163.

Frondel, Manuel, Nolan Ritter, and Colin Vance (2012). "Heterogeneity in the rebound effect: Further evidence for Germany". *Energy Economics* 34 (2), pp. 461–467.

Frondel, Manuel and Colin Vance (2013). "Energy efficiency: Don't belittle the rebound effect". *Nature* 494 (7438), p. 430.

Fujita, Masahisa (1990). *Urban economic theory: Land use and city size*. 1. paperback ed. Cambridge: Cambridge Univ. Press.

Gaitan, Beatriz, Richard S. J. Tol, and Hakan Yetkiner (2006). "The Hotelling's rule revisited in a dynamic general equilibrium model". In: *Proceedings of the conference on human and economic recourses*. Ed. by Oguz Esen and Ayla Ogus, pp. 213–238.

Gerlagh, Reyer (2011). "Too much oil". *CESifo Economic Studies* 57 (1), pp. 79–102.

Gillingham, Kenneth, Matthew J. Kotchen, David S. Rapson, and Gernot Wagner (2013). "Energy policy: The rebound effect is overplayed". *Nature* 493 (7433), pp. 475–476.

Gillingham, Kenneth, David Rapson, and Gernot Wagner (2016). "The rebound effect and energy efficiency policy". *Review of Environmental Economics and Policy* 10 (1), pp. 68–88.

Gonzalez, Fidel (2012). "Distributional effects of carbon taxes: The case of Mexico". *Energy Economics* 34 (6), pp. 2102–2115.

Grafton, Quentin R., Tom Kompas, and Ngo Van Long (2012). “Substitution between biofuels and fossil fuels: Is there a green paradox?” *Journal of Environmental Economics and Management* 64 (3), pp. 328–341.

Greene, David L. (1992). “Vehicle use and fuel economy: How big is the ’rebound’ effect?” *Energy Journal* 13 (1), pp. 117–143.

Greene, David L. (2012). “Rebound 2007: Analysis of U.S. light-duty vehicle travel statistics”. *Energy Policy* 41, pp. 14–28.

Greene, David L., James R. Kahn, and Robert C. Gibson (1999). “Fuel economy rebound effect for U.S. household vehicles”. *Energy Journal* 20 (3), p. 1.

Habla, Wolfgang (2016). “The green paradox and interjurisdictional competition across space and time”. *University of Gothenburg Working Papers in Economics* (No. 668). (Visited on 08/08/2016).

Hamilton, James D. (1983). “Oil and the macroeconomy since World War II”. *Journal of Political Economy* 91 (2), pp. 228–248.

Hamilton, James D. (2009). “Understanding crude oil prices”. *Energy Journal* 30 (2), pp. 179–206.

Hamilton, James D. (2013). “Oil prices, exhaustible resources, and economic growth”. In: *Handbook on Energy and Climate Change*. Ed. by Roger Fouquet. Cheltenham, UK and Northampton, MA, USA: Edward Elgar, pp. 29–57.

Hassler, John, Per Krusell, and Conny Olovsson (2010). “Oil monopoly and the climate”. *American Economic Review: Papers & Proceedings* 100 (2), pp. 460–464.

Heath, Yuko and Robert Gifford (2006). “Free-market ideology and environmental degradation: The case of belief in global climate change”. *Environment and Behavior* 38 (1), pp. 48–71.

Heitzig, Jobst, Kai Lessmann, and Yong Zou (2011). “Self-enforcing strategies to deter free-riding in the climate change mitigation game and other repeated public good games”. *Proceedings of the National Academy of Sciences*.

Henderson, J. Vernon (1985). *Economic theory and the cities*. 2nd ed. Studies in urban economics. Orlando, Fla.: Academic Press.

Heyes, Anthony and Bouwe Dijkstra (2002). “Interest groups and the demand for environmental policy”. In: *The international yearbook of environmental and resource economics 2001/2002*. Ed. by Tom Tietenberg and Henk Folmer. Cheltenham: Edward Elgar.

Higgins, Matthew, Thomas Klitgaard, and Robert Lerman (2006). “Recycling petrodollars”. *Current Issues in Economics and Finance* 12 (9).

Hillman, Arye L. and Ngo Van Long (1985). “Monopolistic recycling of oil revenue and intertemporal bias in oil depletion and trade”. *Quarterly Journal of Economics* 100 (3), pp. 597–624.

Hoel, Michael (1981). “Resource extraction by a monopolist with influence over the rate of return on non-resource assets”. *International Economic Review* 22 (1), p. 147.

Hughes, Jonathan E., Christopher R. Knittel, and Daniel Sperling (2008). “Evidence of a shift in the short-run price elasticity of gasoline demand”. *Energy Journal* 29 (1), pp. 113–134.

Jacobsen, Mark R. (2011). “Fuel economy, car class mix, and safety”. *The American Economic Review* 101 (3), pp. 105–109.

Jacobsen, Mark R. (2013). “Evaluating US fuel economy standards in a model with producer and household heterogeneity”. *American Economic Journal: Economic Policy* 5 (2), pp. 148–187.

Jacobsen, Mark R. and Arthur A. van Benthem (2015). “Vehicle scrappage and gasoline policy”. *The American Economic Review* 105 (3), pp. 1312–1338.

Jensen, Svenn, Kristina Mohlin, Karen Pittel, and Thomas Sterner (2015). “An introduction to the green paradox: The unintended consequences of climate policies”. *Review of Environmental Economics and Policy* 9 (2), pp. 246–265.

Jiang, Zhujun and Shuai Shao (2014). “Distributional effects of a carbon tax on Chinese households: A case of Shanghai”. *Energy Policy* 73, pp. 269–277.

Kahn, Matthew E. and John G. Matsusaka (1997). “Demand for environmental goods: Evidence from voting patterns on California initiatives”. *The Journal of Law & Economics* 40 (1), pp. 137–174.

Kang, Wensheng, Ronald A. Ratti, and Kyung Hwan Yoon (2014). “The impact of oil price shocks on U.S. bond market returns”. *Energy Economics* 44, pp. 248–258.

Kaplow, By Louis (2012). “Optimal control of externalities in the presence of income taxation”. *International Economic Review* 53 (2), pp. 487–509.

Kerkhof, Annemarie C., Henri C. Moll, Eric Drissen, and Harry C. Wilting (2008). “Taxation of multiple greenhouse gases and the effects on income distribution: A case study of the Netherlands”. *Ecological Economics* 67 (2), pp. 318–326.

Kilbourne, William E., Suzanne C. Beckmann, and Eva Thelen (2002). “The role of the dominant social paradigm in environmental attitudes: A multinational examination”. *Journal of Business Research* 55 (3), pp. 193–204.

Kilian, Lutz (2009). “Not all oil price shocks are alike: Disentangling demand and supply shocks in the crude oil market”. *American Economic Review* 99 (3), pp. 1053–1069.

Kilian, Lutz and Bruce Hicks (2013). "Did unexpectedly strong economic growth cause the oil price shock of 2003–2008?" *Journal of Forecasting* 32 (5), pp. 385–394.

Kilian, Lutz and Daniel P. Murphy (2014). "The role of inventories and speculative trading in the global market for crude oil". *Journal of Applied Econometrics* 29 (3), pp. 454–478.

Kim, Jinwon (2012). "Endogenous vehicle-type choices in a monocentric city". *Regional Science and Urban Economics* 42 (4), pp. 749–760.

Kim, Jinwon (2016). "Vehicle fuel-efficiency choices, emission externalities, and urban sprawl". *Economics of Transportation* 5, pp. 24–36.

Klier, Thomas and Joshua Linn (2012). "New-vehicle characteristics and the cost of the Corporate Average Fuel Economy standard". *The RAND Journal of Economics* 43 (1), pp. 186–213.

Klier, Thomas and Joshua Linn (2013). "Fuel prices and new vehicle fuel economy—Comparing the United States and Western Europe". *Journal of Environmental Economics and Management* 66 (2), pp. 280–300.

Klier, Thomas and Joshua Linn (2016). "The effect of vehicle fuel economy standards on technology adoption". *Journal of Public Economics* 133, pp. 41–63.

Langer, Ashley, Vikram Maheshri, and Clifford Winston (2017). "From gallons to miles: A disaggregate analysis of automobile travel and externality taxes". *Journal of Public Economics* 152, pp. 34–46.

Lee, Woojin and John E. Roemer (2006). "Racism and redistribution in the United States: A solution to the problem of American exceptionalism". *Journal of Public Economics* 90 (6-7), pp. 1027–1052.

Lee, Woojin, John Roemer, and Karine van der Straeten (2006). "Racism, xenophobia, and redistribution". *Journal of the European Economic Association* 4 (2-3), pp. 446–454.

Li, Shanjun, Joshua Linn, and Erich Muehlegger (2014). "Gasoline taxes and consumer behavior". *American Economic Journal: Economic Policy* 6 (4), pp. 302–342.

Linn, Joshua (2016). "The rebound effect for passenger vehicles". *Energy Journal* 37 (2), pp. 257–288.

List, John A. and Daniel M. Sturm (2006). "How elections matter: Theory and evidence from environmental policy". *The Quarterly Journal of Economics* 121 (4), pp. 1249–1281.

Long, Ngo Van (2015). "The green paradox in open economies: Lessons from static and dynamic models". *Review of Environmental Economics and Policy* 9 (2), pp. 266–284.

Long, Ngo Van and Frank Stähler (2014). "Resource extraction and backstop technologies in general equilibrium". In: *Climate policy and nonrenewable resources: The green paradox* *and beyond*. Ed. by Karen Pittel, Frederick van der Ploeg, and Cees Withagen. CESifo seminar series. Cambridge and Mass: The MIT Press, pp. 151–170. ISBN: 0262027887. DOI: 10.7551/mitpress/9780262027885.003.0007.

Long, Ngo Van and Frank Stähler (2016). "General equilibrium effects of green technological progress". *Environmental and Resource Economics*, pp. 1–8.

Marz, Waldemar and Johannes Pfeiffer (2015a). "Petrodollar recycling, oil monopoly, and carbon taxes: Update March 2018". *IFO Working Paper* (No. 204) (2015).

Marz, Waldemar and Johannes Pfeiffer (2015b). "Resource market power and levels of knowledge in general equilibrium". *IFO Working Paper* (No. 197) (2015).

Massari, Stefania and Marcello Ruberti (2013). "Rare earth elements as critical raw materials: Focus on international markets and future strategies". *Resources Policy* 38 (1), pp. 36–43.

Mathur, Aparna and Adele C. Morris (2014). "Distributional effects of a carbon tax in broader U.S. fiscal reform". *Energy Policy* 66, pp. 326–334.

McAusland, Carol (2003). "Voting for pollution policy: The importance of income inequality and openness to trade". *Journal of International Economics* 61 (2), pp. 425–451.

McCright, Aaron M. and Riley E. Dunlap (2011). "The politicization of climate change and polarization in the American public's views of global warming, 2001-2010". *The Sociological Quarterly* 52 (2), pp. 155–194.

Metcalf, Gilbert E. (2009). "Designing a carbon tax to reduce U.S. greenhouse gas emissions". *Review of Environmental Economics and Policy* 3 (1), pp. 63–83.

Mills, Edwin S. (1967). "An aggregative model of resource allocation in a metropolitan area". *The American Economic Review* 57 (2), pp. 197–210.

Moussavian, Mohammed and Larry Samuelson (1984). "On the extraction of an exhaustible resource by a monopoly". *Journal of Environmental Economics and Management* 11 (2), pp. 139–146.

Muth, Richard F. (1969). *Cities and housing*. Chicago: University of Chicago press.

National Highway Traffic Safety Administration (2010). *Final regulatory impact analysis: Corporate Average Fuel Economy for MY 2012-MY 2016 Corporate Average Fuel Economy for MY 2012-MY 2016 passenger cars and light trucks*. Ed. by NHTSA. URL: https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/cafe_2012-2016_fria_04012010.pdf.

National Research Council (2015). *Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles*. Washington, DC: The National Academies Press. DOI: 10.17226/21744. URL: https://www.nap.edu/catalog/21744/cost-effectiveness-and-deployment-of-fuel-economy-technologies-for-light-duty-vehicles.

Nordhaus, William (2015). “Climate clubs: Overcoming free-riding in international climate policy”. *American Economic Review* 105 (4), pp. 1339–1370.

Nordhaus, William D. (2010). “Economic aspects of global warming in a post-Copenhagen environment”. *Proceedings of the National Academy of Sciences* 107 (26), pp. 11721–11726.

Oates, Wallace E. and Paul R. Portney (2003). “Chapter 8 - The political economy of environmental policy”. In: *Handbook of environmental economics : environmental degradation and institutional responses*. Ed. by Karl-Göran Mäler and Jeffrey R. Vincent. Vol. 1. Elsevier, pp. 325–354. DOI: `10.1016/S1574-0099(03)01013-1`.

Oladosu, Gbadebo and Adam Rose (2007). “Income distribution impacts of climate change mitigation policy in the Susquehanna River Basin economy”. *Energy Economics* 29 (3), pp. 520–544.

Organisation for Economic Cooperation and Development (2014). *World energy outlook 2014*. Paris: OECD Publishing.

Organisation for Economic Cooperation and Development (2016a). *Online data base - Gross domestic product*. 2016. URL: `https://data.oecd.org/gdp/gross-domestic-product-gdp.htm` (visited on 12/02/2016).

Organisation for Economic Cooperation and Development (2016b). *Online data base - Total oil demand*. 2016. URL: `http://stats.oecd.org/BrandedView.aspx?oecd_bv_id=oil-data-en&doi=data-00474-en` (visited on 12/02/2016).

Organisation for Economic Cooperation and Development and International Labour Organization (2015). *The labour share in G20 economies*. Paris. URL: `https://www.oecd.org/g20/topics/employment-and-social-policy/The-Labour-Share-in-G20-Economies.pdf` (visited on 11/11/2016).

Ostrom, Elinor (2010). “A multi-scale approach to coping with climate change and other collective action problems”. *Solutions* 1, pp. 27–36.

Packey, Daniel J. and Dudley Kingsnorth (2016). “The impact of unregulated ionic clay rare earth mining in China”. *Resources Policy* 48, pp. 112–116.

Parry, Ian W. H., Margaret Walls, and Winston Harrington (2007). “Automobile externalities and policies”. *Journal of Economic Literature* 45 (2), pp. 373–399.

Pothen, Frank (2018). “Dynamic market power in an exhaustible resource industry. The case of rare earth elements”. *The World Economy* (forthcoming).

Rausch, Sebastian, Gilbert E. Metcalf, and John M. Reilly (2011). “Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households”. *Energy Economics* 33, S20–S33.

Rausch, Sebastian and Giacomo A. Schwarz (2016). “Household heterogeneity, aggregation, and the distributional impacts of environmental taxes”. *Journal of Public Economics* 138, pp. 43–57.

Renner, Sebastian (2018). “Poverty and distributional effects of a carbon tax in Mexico”. *Energy Policy* 112, pp. 98–110.

Robison, H. David (1985). “Who pays for industrial pollution abatement?” *Review of Economics & Statistics* 67 (4), p. 702.

Roemer, John E. (1998). “Why the poor do not expropriate the rich: An old argument in new garb”. *Journal of Public Economics* 70 (3), pp. 399–424.

Roemer, John E. (1999). “The democratic political economy of progressive income taxation”. *Econometrica* 67 (1), pp. 1–19.

Roemer, John E. (2006). *Political competition: Theory and applications*. 1. paperback ed. Cambridge, Mass.: Harvard Univ. Press.

Roemer, John E. and Karine van der Straeten (2005). “Xenophobia and the size of the public sector in France: A politico-economic analysis”. *Journal of Economics* 86 (2), pp. 95–144.

Rossen, Isabel L., Patrick D. Dunlop, and Carmen M. Lawrence (2015). “The desire to maintain the social order and the right to economic freedom: Two distinct moral pathways to climate change scepticism”. *Journal of Environmental Psychology* 42, pp. 42–47.

Sallee, James M., Sarah E. West, and Wei Fan (2016). “Do consumers recognize the value of fuel economy? Evidence from used car prices and gasoline price fluctuations”. *Journal of Public Economics* 135, pp. 61–73.

Schmitt, Alex (2014). *Beyond Pigou: Climate change mitigation, policy making and distortions*. Vol. 85. Institute for International Economic Studies Monograph Series. Stockholm: Stockholms Universitet.

Shammin, Md Rumi and Clark W. Bullard (2009). “Impact of cap-and-trade policies for reducing greenhouse gas emissions on U.S. households”. *Ecological Economics* 68 (8), pp. 2432–2438.

Sinn, Hans-Werner (2008). “Public policies against global warming: A supply side approach”. *International Tax and Public Finance* 15 (4), pp. 360–394.

Small, Kenneth A. and Kurt van Dender (2007). “Fuel efficiency and motor vehicle travel: The declining rebound effect”. *Energy Journal* 28 (1), pp. 25–51.

Smulders, Sjak, Yacov Tsur, and Amos Zemel (2012). “Announcing climate policy: Can a green paradox arise without scarcity?” *Journal of Environmental Economics and Management* 64 (3), pp. 364–376.

Solow, Robert M. (1974). “The economics of resources or the resources of economics”. *American Economic Review* 64 (2), p. 1.

Sovereign Wealth Fund Institute (2016). *Sovereign wealth fund rankings*. URL: `http://www.swfinstitute.org/fund-rankings/` (visited on 08/02/2016).

Statista (2018). *OPEC’s share of total global crude oil production from 2009 to 2017*. Ed. by Statista. Hamburg. URL: `https://www.statista.com/statistics/292590/global-crude-oil-production-opec-share/` (visited on 08/18/2018).

Stern, David I. and Astrid Kander (2012). “The role of energy in the industrial revolution and modern economic growth”. *Energy Journal* 33 (3).

Stiglitz, Joseph (1974). “Growth with exhaustible natural resources: Efficient and optimal growth paths”. *Review of Economic Studies* 41, pp. 123–137.

Stiglitz, Joseph E. (1976). “Monopoly and the rate of extraction of exhaustible resources”. *American Economic Review* 66 (4), p. 655.

Tullock, Gordon (1979). “Monopoly and the rate of extraction of exhaustible resources: Note”. *American Economic Review* 69 (1), pp. 231–233.

Turnbull, Geoffrey K. (2004). “Urban growth controls: Transitional dynamics of development fees and growth boundaries”. *Journal of Urban Economics* 55 (2), pp. 215–237.

United Nations Framework Convention on Climate Change (2016). *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015 - Addendum: Part two: Action taken by the Conference of the Parties at its twenty-first session*. URL: `https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf` (visited on 09/13/2018).

van der Meijden, Gerard, Frederick van der Ploeg, and Cees Withagen (2015). “International capital markets, oil producers and the green paradox”. *European Economic Review* 76, pp. 275–297.

van der Ploeg, Frederick (2015). “Second-best carbon taxation in the global economy: The green paradox and carbon leakage revisited”. *CEPR Discussion Paper* No. 10549.

van der Ploeg, Frederick and Cees Withagen (2012a). “Is there really a green paradox?” *Journal of Environmental Economics and Management* 64 (3) (2012), pp. 342–363.

van der Ploeg, Frederick and Cees Withagen (2012b). “Too much coal, too little oil”. *Journal of Public Economics* 96 (1–2) (2012), pp. 62–77.

van der Ploeg, Frederick and Cees Withagen (2015). “Global warming and the green paradox: A review of adverse effects of climate policies”. *Review of Environmental Economics and Policy* 9 (2), pp. 285–303.

van der Werf, Edwin and Corrado Di Maria (2011). “Unintended detrimental effects of environmental policy: The green paradox and beyond”. *CESifo Working Paper Series* (3466).

Voß, Achim (2015). “How disagreement about social costs leads to inefficient energy-productivity investment”. *Environmental and Resource Economics* 60 (4), pp. 521–548.

Waldman, Peter (2016). “Deputy Crown Prince Mohammed bin Salman is preparing Saudi Arabia for the end of oil”. *Bloomberg Businessweek* (4/25/2016).

Walker, Brian, Scott Barrett, Stephen Polasky, Victor Galaz, Carl Folke, Gustav Engström, Frank Ackerman, Ken Arrow, Stephen Carpenter, Kanchan Chopra, Gretchen Daily, Paul Ehrlich, Terry Hughes, Nils Kautsky, Simon Levin, Karl-Göran Mäler, Jason Shogren, Jeff Vincent, Tasos Xepapadeas, and Aart de Zeeuw (2009). “Looming global-scale failures and missing institutions”. *Science* 325 (5946), p. 1345.

Wearden, Graeme (2011). *Warren Buffett calls for higher taxes for US super-rich*. Ed. by The Guardian. URL: `https://www.theguardian.com/business/2011/aug/15/warren-buffett-higher-taxes-super-rich` (visited on 09/13/2018).

West, Jeremy, Mark Hoekstra, Jonathan Meer, and Steven L. Puller (2017). “Vehicle miles (not) traveled: Fuel economy requirements, vehicle characteristics, and household driving”. *Journal of Public Economics* 145, pp. 65–81.

Wier, Mette, Katja Birr-Pedersen, Henrik Klinge Jacobsen, and Jacob Klok (2005). “Are CO2 taxes regressive? Evidence from the Danish experience”. *Ecological Economics* 52 (2), pp. 239–251.

Williams III, Roberton C., Hal Gordon, Dallas Burtraw, Jared C. Carbone, and Richard D. Morgenstern (2015). “The initial incidence of a carbon tax across income groups”. *National Tax Journal* 68 (1), pp. 195–213.

World Bank Group (2016). *World DataBank - World development indicators*. URL: `http://databank.worldbank.org/data/reports.aspx?source=2&series=NY.GDP.PETR.RT.ZS&country=#advancedDownloadOptions` (visited on 11/11/2016).

Zhou, Baolu, Zhongxue Li, and Congcong Chen (2017). “Global potential of rare earth resources and rare earth demand from clean technologies”. *Minerals* 7 (11), p. 203.

Ziegler, Andreas (2017). “Political orientation, environmental values, and climate change beliefs and attitudes: An empirical cross country analysis”. *Energy Economics* 63, pp. 144–153.

Curriculum Vitae

Waldemar Marz
born 12/15/1985 in Tomsk

Since 02/2019	PostDoc, Center for Energy, Climate and Resources, ifo Institute, Munich
05/2013 – 01/2019	Ph.D., Economics (Dr. oec. publ.), LMU, Munich Junior Economist, Center for Energy, Climate and Resources, ifo Institute, Munich
09/2017 – 12/2017	Visiting Assistant in Research Department of Forestry and Environmental Studies, Yale University
03/2012 – 04/2013	Research Assistant, Chair for Energy Economy and Application Technology, Technical University of Munich
10/2009 – 07/2013	Bachelor of Science, Economics, Ludwig-Maximilians-Universität, Munich
10/2005 – 11/2011	Diploma, Energy and Process Technology Technical University of Munich and Universidad de Málaga
06/2004	Abitur Gymnasium bei St. Anna, Augsburg