On the Design of Climate Policy

INAUGURAL-DISSERTATION
zur Erlangung des akademischen Grades eines
Doktors der Wirtschaftswissenschaft
(doctor rerum politicarum)

des Fachbereichs Wirtschaftswissenschaft
der Freien Universität Berlin

vorgelegt von
Daniel Nachtigall, M.Sc.

Berlin 2017

Erstgutachter:

Prof. Dr. Ronnie Schöb

Zweitgutachter:

Prof. Dr. Robert Christian Schmidt

Tag der Disputation:

23. Juni 2017

Erklärung zu Koautoren

Die vorliegende Dissertation umfasst neben einer Einleitung (Kapitel 1) drei Forschungspapiere (Kapitel 2, 3 und 4). Die Kapitel 1, 2 und 4 sind allein verfasst worden. Kapitel 3 ist in Ko-Autorenschaft entstanden. Ko-Autor des Kapitels 3 ist Prof. Dr. Dirk Rübbelke. Für die Dissertation ist dieses Kapitel gegenüber dem gemeinsam verfassten Artikel leicht angepasst worden. Diese Veränderung verantwortet allein der Autor der vorliegenden Dissertation. Eine Liste mit Vorveröffentlichungen von Kapiteln befindet sich auf Seite 135.

Acknowledgements

This thesis would not exist without the support of several persons. First, I thank my primary supervisor Ronnie Schöb, who offered me the opportunity to pursue a PhD in economics when I was writing my Master thesis at his chair. He has always supported me despite the fact that I had chosen not to write the dissertation in his major research area of the last years. I have constantly admired his creativity, his critical thinking as well as the fact that I could always approach him to discuss the problems that had arisen during my PhD. Second, I thank my second supervisor Robert Schmidt for the constructive collaboration and his valuable comments. In fact, he had the initial idea for Chapter 4 of this thesis and substantially shaped and improved this chapter. Having many interests in common, Robert has become a good friend during the last four years.

I am indebted to Dirk Rübbelke as well as Zhongxiang Zhang for inviting me to research stays at Basque Center for Climate Change and Tianjin University. The collaboration and the exchange of ideas with both of them has always been both productive and inspiring and shaped this PhD thesis a lot. In addition, I would like to thank these institutions and all their employees for their support, feedback, and hospitality.

At Freie Universität Berlin, I am grateful to my colleagues Flora Budianto, Katja Görlitz, Clemens Hetschko, Juliane Hennecke, Katharina Jenderny, Jens Pohlmann, Merlin Penny, Malte Preuß, Christoph Skupnik and Tobias Wolf for their company during the PhD phase and for the inspiring conversations. In particular, I have always appreciated the discussions with Tobias Wolf with whom I shared the office in the last four years. I am grateful to the past and present student assistants of the Chair of International Public Economics Meike Baumheier, Tom Günther, Silva Haselon, Maria Karsten, Lukas Klingholz, Anja Mocek and Ioana Sintu for their support. Finally, I would like to thank Cordula Arlinghaus for reducing the administrative burden to a minimum and for correcting the orthographical errors of my manuscripts. Part of the correction team has also been Iris Müller, Alex Odlum, and Laura Scharfenberg, who receive my special thanks.

My thanks goes also to the colleagues of my PhD program for spending so many intensive, but rewarding hours together when preparing for the first-year exams and during our summer schools. We are all indebted to Roland Strausz and Verena Neumann for administrating our Research Training Group 1659 'Interdependencies in the regulation of markets'. I appreciate the financial support of the German Science Foundation that has enabled me to attend several conferences and workshops. I thank all the participants of conferences, seminars and workshops for their valuable feedback on the chapters of this thesis. In particular, I am grateful to Mark Schopf for his helpful comments and suggestions.

Throughout my PhD, I could always rely on the support of my family and my friends, who are the most important pillar in my life. I am indebted to Helke Seitz for always being a good listener and for her valuable advices. Last but not least, I thank my parents Bernd and Elke Nachtigall for sharing my happiness in the successful moments and for their unconditional support in the troublesome phases of the PhD. Without you, I would have never been able to finish this thesis.

Contents

List of Figures

List of Tables

List of Symbols

Chapter 2: Prices versus quantities

Symbol	**Description**
γ	Slope of the marginal utility function
$\pi(\cdot)$	Profit function of OPEC
$\pi_F(\cdot)$	Profit function of the competitive fringe
ψ	Marginal environmental damage
a	Intercept of utility function
c	Marginal extraction costs of fringe
c_q	Threshold of extraction costs for quota
c_t	Threshold of extraction costs for carbon tax
p	Oil price net of taxes
$p^o(\cdot)$	OPEC's price reaction without competitive fringe
$p^*(\cdot)$	OPEC's price reaction with competitive fringe
q	Consumer price for oil
$q(\cdot)$	Inverse demand function
t	Per unit carbon tax
t_b	Per unit base tax
t_P	Pigouvian tax rate
$\bar{t}$	Carbon tax that yields $\bar{R}$
t^o	Optimal carbon tax without competitive fringe
$t^*(\cdot)$	Optimal carbon tax with competitive fringe
$MR(\cdot)$	Marginal revenue of OPEC
R	Oil quantity
$R(\cdot)$	Demand function

Symbol	**Description**
$R_e(\cdot)$	Effective demand in case of quota
$R_F(\cdot)$	Supply function of the competitive fringe
R_{fb}	Global first best quantity of oil
R_M	Monopolistic quantity
$R^*(\cdot)$	OPEC's quantity reaction with competitive fringe
$\bar{R}$	Quota of climate coalition
$\bar{R}^*(\cdot)$	Optimal quota of climate coalition with competitive fringe
$U(\cdot)$	Utility from oil consumption
$W(\cdot)$	Welfare of climate coalition

Chapter 3: The green paradox and learning-by-doing in the renewable energy sector

Symbol	**Description**
α	Slope of marginal extraction costs curve
$\underline{\alpha}$	Minimum value of α, leading to reversal of green paradox
$\overline{\alpha}$	Maximum value of α, leading to reversal of green paradox
β	Discount factor
λ	Lagrangian multiplier
π_f	Profit of resource owner
π_r	Profit of renewable energy producer
ρ	Degree of private appropriability
a	Slope of quadratic cost function
b	Learning factor
$c(\cdot)$	Cost function of renewable energy in first period
$e(\cdot)$	General extraction cost function
m	Intercept of demand function
p	Market price for energy in first period
q	Slope of demand function for energy
r	Risk free interest rate
s	Per unit subsidy for renewable energy in first period
t	Per unit carbon tax in first period
x	Fossil fuel supply in first period
y	Renewable energy production in first period
$C(\cdot)$	Cost function of renewable energy in second period
$G(\cdot)$	General convex cost function
M	Matrix containing partial derivatives
P	Market price for energy in second period
T	Per unit carbon tax in second period
X	Fossil fuel supply in second period
$\bar{X}$	Physical stock of resources
$\tilde{X}$	Total emissions in case of economic exhaustion
Y	Renewable energy production in second period

Chapter 4: Dynamic climate policy under firm relocation

Symbol	**Description**
$\gamma(\cdot)$	Abatement cost function
$\bar{\epsilon}$	Baseline emissions
θ	Relocation costs
$\underline{\theta}$	Lower bound of relocation costs
$\bar{\theta}$	Upper bound of relocation costs
$\theta_i^j(\cdot)$	Indifference point between location plan i and j
$\kappa(\cdot)$	Investment cost function
λ	Lagrangian multiplier
μ	Lagrangian multiplier
ν	Lagrangian multiplier
$\pi_i(\cdot)$	Profit function of firm type i
$\pi_i^*(\cdot)$	Profit function of firm type i after optimal abatement decision
ψ	Marginal environmental damage
c_q	Slope of short term abatement costs
c_k	Slope of investment costs
g	Transfer in first period
k	Investment in abatement capital
$k_i^*(\cdot)$	Optimal investment in abatement capital of firm type i
p	Per unit carbon price in first period
q	Short-term abatement in first period
$q_i^*(\cdot)$	Optimal short-term abatement in first period of firm type i
A	Country A
B	Country B
G	Transfer in second period
$\overline{G}$	Upper bound for transfer in second period
P	Per unit carbon price in second period
Q	Short-term abatement in second period
$Q_i^*(\cdot)$	Optimal short-term abatement in second period of firm type i
$T_i(\cdot)$	Inter-temporal tax payments of firm type i
$W(\cdot)$	Aggregated welfare of country A
$W_i(\cdot)$	Welfare contribution of firm type i
$W_i^j(\cdot)$	Aggregated welfare in the presence of firm types i and j

Chapter 1

Introduction

1.1 The problem of climate change

According to Barack Obama climate change ‘will define the contours of this century more dramatically than any other’.[1] In fact, the latest report of the Intergovernmental Panel of Climate Change (IPCC) from 2014 states that the global mean surface temperature is expected to rise between 1.5 and 4.5°C until the end of the 21st century relative to the pre-industrial temperature. Such sharp temperature increase is unprecedented over millions of years of earth history and is associated with substantial impacts such as a rising sea level, a changing precipitation patterns and more frequent extreme weather events (IPCC 2014). These changes pose a major threat on the food security and potentially lead to massive migration of people living on the shores of the oceans due to the rising sea level (Schellnhuber 2006).

Global warming is caused by the greenhouse effect, according to which greenhouse gases (GHG) in the atmosphere radiate energy towards the surface, leading to a temperature increase (Ekholm 1901). The magnitude of this effect depends on the concentration of GHG in the atmosphere. GHG emissions are a by-product of economic activity and there is broad consensus among the scientific community that global warming is a man-made problem (Oreskes 2004). Mitigating climate change requires to reduce the exhaust of GHG emissions, in particular that of carbon dioxide (CO_2). Since CO_2 emissions are dispersed homogeneously throughout the atmosphere regardless of their point of origin, climate change is a global problem that requires global action.

Starting with the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, the leaders of all countries agreed to ‘stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system’ (UNFCCC 1992: Article 2). In 1997, the convention established legally binding emission reduction obligations for developed countries, so called Annex I countries, for the period from 2008 to 2012 at the third conference of the parties meeting in Kyoto (UNFCCC 1997). After the expiration of the Kyoto-protocol, the 21st conference of the parties decided unanimously to adopt the Paris Agreement, that explicitly calls for a limitation of the temperature increase to ’well below 2°C’ (UNFCCC 2015: Article

---

[1] Barack Obama’s statement at the United Nations (UN) climate change summit in 2014.

2a). After the ratification of 115 out of 197 parties, this agreement entered into force on November 4, 2016. It was celebrated as a historic success by many political leaders and leading climate scientists (Schellnhuber et al. 2016) because each country is required to put forward their best efforts, known as ’nationally determined contributions’ (NDCs) to reduce its GHG emissions beyond 2020. However, these NDCs are not sufficient to meet the 2°C target and thus can only be considered as a first step for more ambitious pledges in the future (Jeffery et al. 2015). Moreover, it remains to be seen whether countries indeed comply with their NDCs in the absence of any credible enforcement mechanism. If countries are willing to meet their pledges, these pledges will translate into national climate policies.

Economics provides valuable insights regarding the effectiveness and the efficiency of both national and global climate policy instruments (Nordhaus 2013). In particular, economics helps to inform policy makers how to achieve a given target at the lowest costs. Market-based instruments such as taxes or tradable emissions permits are, in general, adequate instruments for attaining cost efficiency. However, climate policy may be accompanied by unintended side effects such as the economically inefficient relocation of production facilities from countries with ambitious climate policy to countries with laxer regulations (Markusen et al. 1993). These side effects should be taken into account when designing efficient climate policy (Aldy et al. 2010). This thesis identifies three areas where the reaction of market participants towards climate policies provokes such unintended side effects and discusses the implications for policy makers to address these effects adequately. These areas include the relocation of firms, rent capturing by cartelized oil suppliers, and the inter-temporal extraction decision of fossil fuel owners.

The remainder of this introductory chapter introduces the economic fundamentals of climate change in Section 1.2 and illustrates to which literature strand the three main chapters of this thesis are related to. Section 1.3 reviews the relevant literature of the three main chapters in more detail, identifies the research gaps and formulates the respective research questions. Section 1.4 summarizes the contributions of this thesis and discusses the implications. In Chapter 2, 3 and 4 all topics are presented in detail.

1.2 Economics of climate change

From an economics point of view, the exhaust of GHG emissions constitutes a negative externality, i.e. an uncompensated and non-pecuniary negative impact by the economic activity of some agents on the utility or profits of other agents. Since economic agents do not account for the negative impact on others in their consumption or production decisions, externalities are one major source for market failures, implying the outcome in an unregulated market economy to be inefficient (Baumol and Oates 1988). In fact, Stern calls climate change to be the 'greatest market failure the world has ever seen' (Stern 2007, p. viii). In the presence of a market failure, a policy intervention may enhance the welfare of the society. Given that climate change is a global problem that requires global action, the implementation of climate policy in the absence of a global authority comes along with a collective action problem which will be addressed further below.

Abstracting from the collective action problem, economic theory, more precisely cost-benefit analysis, suggests that the efficient level of GHG emissions requires the aggregated marginal environmental damage to be equal to the marginal abatement costs, i.e. the additional costs to increase the abatement by one unit. Several studies have aimed at constructing the global marginal abatement cost curve by analyzing and evaluating the technological options to reduce GHG emissions (Fischer and Morgenstern 2006, Kuik et al. 2009 and McKinsey 2009). Deriving the marginal environmental damage, i.e. the Social Cost of Carbon (SCC), requires a dynamic framework because CO_2 emissions have an atmospheric lifetime of 100 years and more and thus can be characterized as a stock pollutant (Archer et al. 2009).[2] For the estimations of the SCC, economists generally employ Integrated Assessment Models (IAMs), i.e. general equilibrium models that involve several economic and non-economic sectors. Estimating the SCC has proved to be challenging due to the uncertainty regarding the exact relationship between the concentration of GHGs in the atmosphere and global warming, the translation of the temperature increase into damages as well as the monetarization and the discounting of these damages (Pizer et al. 2014).[3] Depending on the

---

[2] More precisely, Tol (2011) defines the Social Cost of Carbon as the net present value of the aggregated damages across time and space that arise due to an increase of CO_2 emissions by one ton today.

[3] Since the most severe damages from global warming will materialize only in the far future, the present costs of emitting one unit CO_2 is subject to the choice of the discount rate. There

choice of the IAM, the model assumptions and the parameter values, the estimates of the SCC vary considerably across the studies, ranging from negative SCCs to more than 1.000 USD (IPCC 2014). Assuming a pure rate of time preference of 3%, the fifth assessment report of the IPCC states an average SCC of 33 USD for studies published after the fourth assessment report, while the Environmental Protection Agency of the United States assumes a SCC of 37 USD based on an evaluation of the IAMs that have been used most frequently (IWGSCC 2013).

Once the SCC and the marginal abatement costs are derived, policy makers can implement the efficient level of GHG emissions. In general, enforcing this level by command-and-control measures is inefficient due to the informational constraints of the regulator. In contrast, market-based instruments such as taxes or tradable emission quotas can exploit the capability of markets to gather information of heterogeneous agents, leading to an efficient outcome. Pigou (1920) showed that in a decentralized economy, the first best can be achieved by implementing a per unit emissions tax that is equal to the aggregated (discounted) marginal environmental damage at the efficient level. A carbon tax equalizes the marginal abatement costs across all economic agents and thus is an efficient instrument.

Generally speaking, imposing a quota with tradable emission permits, as first suggested by Dales (1968), is equivalent to a carbon tax and may also lead to the first best (Montgomery 1972). However, the equivalence of the two instruments does not hold in all cases (Goulder and Schein 2013). These cases include, among others, interactions with other climate policies (Fischer and Preonas 2010 and Shobe and Burtraw 2012) or the presence of uncertainty (Weitzman 1974 and Murray et al. 2009). Given that more than two thirds of all GHG emissions stem from the combustion of fossil fuels such as coal, gas and oil[4], any price on CO_2 emissions necessarily affects the extraction decision of fossil fuel owners and it has been shown that market power of fossil fuel exporters also causes a discrepancy between price and quantity instruments (Berger et al. 1992). In fact, since the Organization of Petroleum Exporting Countries (OPEC) controls more than 75% of proven oil reserves, there is considerable market power in the world oil market

---

is an ongoing ethical debate about the adequate level of the discount rate, which is why most studies report the SCCs for a range of discount rates (Nordhaus 2007, Weitzman 2007 and Arrow et al. 2013).

[4] See IPCC (2014), p. 354.

(OPEC 2016). In this case, the policy maker should favor a carbon tax because the market power enables OPEC to act strategically and to set higher prices under a cap-and-trade system relative to a carbon tax (Strand 2009). Chapter 2 of this thesis analyzes this finding in more detail and asks whether this preference also holds true when the extraction costs of OPEC's competitors, e.g. the producers of shale oil, are becoming increasingly smaller due to technological progress.

The reaction of fossil fuel owners is also relevant in the absence of market power. Since fossil fuels are exhaustible resources, any tax on the carbon content affects the inter-temporal extraction decision of resource owners (Sinclair 1992). In particular, a per unit carbon tax that is rising faster than the interest rate induces resource owners to evade the increased tax burden in the future by shifting the extraction into the present (Sinn 2008b). This leads to an increase of current CO_2 emissions and accelerates global warming, which is why Sinn (2008a) calls this reaction the green paradox. Since the optimal carbon tax should be equal to the SCC in each period and most IAMs report a rising trajectory of SCCs that translates into a rising carbon price path (IPCC 2014), the green paradox may be highly relevant. Hence, analyzing the climate change problem adequately requires the use of dynamic models that enable researchers to take the reaction of fossil fuel owners into account. Chapter 3 challenges the standard result of the green paradox and asks whether this paradox also arises in the presence of a renewable energy sector that exhibits learning-by-doing.

In the absence of a global authority, a collective action problem adds to the problem of GHG emissions mitigation. The public good character of the atmosphere, in particular the non-excludability, gives rise to the free-rider problem (Arrow 2007). While the Pareto optimum demands all countries to mitigate GHG emissions, it is individually rational for each country to abstain from costly mitigation measures and benefit from the effort made by other countries. Hence, in the Nash-equilibrium, all countries under-provide the public good, which translates into socially inefficient high temperatures and damages from global warming.[5] In reality, countries do not always decide individually upon their abatement effort, but may form coalitions to act against global warming. However, the literature on international environmental agreements is rather pessimistic, finding either

---

[5] In other words, the atmosphere can be also regarded as a global commons where private use leads to over-exploitation of the common good, which is why this phenomenon is referred to as 'Tragedy of the Commons' (Hardin 1968).

that high contributions of coalition members imply small coalition sizes or that large coalition sizes are associated with contributions that are rather negligible (Carraro and Siniscalco 1993, Barrett 1994 and Finus 2008).

Despite these pessimistic results from theory, some countries or group of countries act on mitigating GHG emissions. For the Paris Agreement, Jeffery et al. (2015) report that 5 out of 32 countries in their sample made pledges that are in line with the 2°C-target, meaning that global warming is likely to remain below 2°C if all countries had committed to similar efforts. The economic literature has identified several arguments for why countries may have an incentive to act unilaterally (Edenhofer et al. 2014). For instance, implementing market-based policy instruments creates revenues which can be used to finance local infrastructure or to reduce distortionary taxes elsewhere in the economy (Goulder 1995 and Franks et al. 2015). In addition, in the presence of other distortions, reducing GHG emissions may be accompanied by co-benefits such as the reduction of local air pollution or a higher energy security (Ostrom 2010 and Pittel and Rübbelke 2008).

Unilateral climate policy may cause carbon leakage, i.e. an increase of emissions in the non-regulating countries in response to more stringent climate policy in the regulating jurisdiction, which reduces the effectiveness of environmental policy (Zhang and Baranzini 2004). One channel of carbon leakage is the investment channel according to which firms direct their investments towards countries with laxer climate regulations (IEA 2008). In the most extreme case, this involves the entire relocation of the production facilities to non-regulating countries (Babiker 2005). Chapter 4 deals with the optimal climate policy design when firms may relocate.

In total, this Section has identified three areas where implementing climate policy involves unintended reactions of market participants, which should be taken into account when designing climate policy. First, dominant fossil fuel exporters such as OPEC alter their strategic behavior depending on the choice of the market-instrument, which may lead to adverse effects on the carbon revenue of countries that implement climate policy. Second, fossil fuel owners adjust their inter-temporal extraction decision according to the carbon price path, which may lead to the green paradox. Third, domestic firms may relocate their production facilities to non-regulating countries as a response to unilateral climate policy.

1.3 Previous literature

1.3.1 Prices versus quantities: The impact of fracking on the choice of the climate policy instruments in the presence of OPEC

There is an ongoing debate on the choice of the market-based climate policy instrument, i.e. whether countries should implement a carbon tax (Pigou 1920) or a cap-and-trade system (Dales 1968). For different reasons, some scholars prefer quantities (Stavins 2008 and Keohane 2009) while others prefer prices (Nordhaus 2007 and Mankiw 2009). Even though the implications of both instruments are equivalent in most cases such as the incentives to reduce emissions, the safeguarding of international competitiveness or the distribution of the burden across industries or households, they differ in other cases (Hepburn 2006). First, the administration costs under a carbon tax are relatively lower because only those entities must be monitored where carbon enters the economy (Metcalf and Weisbach 2009). Second, in the presence of uncertainty with respect to the level of the marginal abatement costs, a carbon tax leads to lower expected social costs and thus is superior to cap-and-trade, if the slope of the marginal environmental damage curve is relatively flat and vice versa (Weitzman 1974). Third, while the emissions price is fixed for a carbon tax, it is volatile for a cap-and-trade system, implying investments in abatement technologies to become more risky and thus costly (Nordhaus 2006). Fourth, a carbon tax yields higher domestic rents if cartelized fossil fuel exporters act strategically (Berger et al. 1992). Chapter 2 analyzes the last issue in more detail.

Abstracting from the global warming externality, the literature on exhaustible resources shows within a dynamic framework that in the presence of foreign resource owners, import tariffs can be used to capture a part of exporter's resource rents, thereby increasing domestic welfare (Bergstrom 1982 and Karp and Newbery 1991). Since CO_2 emissions stem from the combustion of fossil fuels, also climate policy may serve as a means to capture resource rents from competitive foreign resource owners, implying the optimal tax rate to be above the Pigouvian tax level (Amundsen and Schöb 1999). While the supply of fossil fuels, in particular the oil market, is characterized by cartelization through OPEC, countries coordinating on climate policy can be thought of as forming a demand cartel. Hence, analyzing climate policy requires to account for the strategic interaction between both cartels (Wirl 1995). While early papers assume the demand cartel, i.e. the climate coalition, to implement a carbon tax (Rubio and Escriche 2001 and Liski and Tahvonen 2004), Wirl (2012) explicitly compares price and quantity instruments and finds that both OPEC and the climate coalition are better off when playing in prices. However, Wirl (2012) states that 'any substantial extension may render closed form solutions impossible or intractable' (Wirl 2012, p. 227), which is why static settings may be more appropriate for analyzing more complex scenarios.

In a static setting, Berger et al. (1992) analyze the reaction of a monopolistic fossil fuel exporter towards both a carbon tax and a cap-and-trade system. For a given cap, OPEC can extract the whole climate rent by marginally undercutting the quota, thereby driving the permit price to zero and leaving no revenue for the climate coalition. In contrast, a carbon tax generates some revenues, implying the climate coalition to prefer the tax over cap-and-trade. Accounting for a competitive fringe that may represent OPEC's competitors such as the shale-oil industry does not alter the qualitative result. While Berger et al. (1992) takes the emissions level of the climate coalition as given, Strand (2009) endogenizes this level, finding for the same reasons as Berger et al. (1992) that the climate coalition is better off under a carbon tax. However, Strand (2009) does not incorporate a competitive fringe into his analysis. Chapter 2 of this thesis closes this research gap by asking

1. What are the implications of declining extraction costs in the competitive fringe on the instrument choice of the climate coalition?
2. Can the climate coalition improve its welfare by implementing a dual instrument that complements a cap-and-trade system by levying a base tax?

Combining cap-and-trade with a base tax allows the climate coalition to retain some of the revenue that is captured by OPEC (Schöb 2010). However, it is not clear whether or not the dual instrument can outperform the pure price or quantity instruments in the presence of a competitive fringe.

1.3.2 The green paradox and learning-by-doing in the renewable energy sector

Due to the one-to-one relationship between the combustion of fossil fuels and the exhaust of CO_2 emissions, climate policy inevitably affects the extraction decision of fossil fuel owners. Since fossil fuels are exhaustible resources, assessing climate policy adequately requires to take the supply side into account and to link climate policy to the theory of exhaustible resources (Hotelling 1931 and Dasgupta and Heal 1979). According to this theory, resource owners choose an extraction path that maximizes the net present value of their resource stock, which leads in equilibrium to a price path that increases with the interest rate (Hotelling-rule). Pricing the carbon content of the exhaustible resources affects the optimal inter-temporal extraction decision of the fossil fuel owners (Sinclair (1992)).

Based on Long and Sinn (1985), Sinn (2008, 2012) coined the term green paradox to point out that any policy, be it a carbon tax or a subsidy for renewable energy, that disproportionally devalues the fossil fuel stock in the future, incentivizes the resource owners to extract more rapidly by shifting the extraction towards the present. This increases current CO_2 emissions and accelerates global warming, leading to more environmental damage relative to the absence of climate policy. This result relies on a set of assumptions including the existence of a unified global climate policy, positive extraction costs and the absence of a perfect substitute for fossil fuels (Sinn 2008b).

Previous and subsequent papers have modified this set of assumptions towards several directions (Ulph and Ulph 1994 and van der Ploeg and Withagen 2012). Assuming the existence of a backstop technology, i.e. a perfect substitute that supplies an unlimited amount of energy at constant marginal costs, the conclusion of Sinn (2008b) remains valid for constant marginal extraction costs of the fossil fuel suppliers (Hoel 1996 and Tahvonen 1997). However, with increasing marginal extraction costs, climate policy does not only impact the inter-temporal allocation of fossil fuels, but may also reduce the volume of the total supply, implying the resource to be exhausted economically rather than physically. This volume effect lowers the discounted environmental damage and may outweigh the potential increase of damages from accelerated global warming, in which case there is only a weak green paradox (Gerlagh 2011).

If a backstop technology is available at constant marginal cost, the use of the resource is divided into two phases. In the first phase, the economy exclusively consumes the fossil fuel until it is either physically or economically exhausted, whereas the backstop technology is used in the second phase (Heal 1976). In reality, it is observed that both renewable energy and fossil fuels are used simultaneously, so that some papers started to account for this fact by assuming increasing marginal costs of the renewable energy source (Grafton et al. 2012). Simultaneous use of both energy sources allows for incorporating learning-by-doing (LBD). Originating, inter alia, from minor technological improvements, LBD is a dynamic concept, stating that the current production costs are decreasing in the accumulated output in the past (Arrow 1962). Empirically, this relationship has proved to be stable across several industry sectors (Argote and Epple 1990). For wind and solar power, learning rates have been found to be between 5 and 35%, meaning a cost reduction of 5 to 35% for a doubling of the accumulated output (McDonald and Schrattenholzer 2001).

There are only few papers that link the theory of exhaustible resources with LBD in an alternative sector, though they do not focus on the green paradox (Tahvonen and Salo 2001 and Chakravorty et al. 2012). Chapter 3 of this thesis fills in this research gap by asking

1. How does the presence of LBD impact the extraction decision of resource owners?
2. Under which conditions does a weak and a strong green paradox arise when the future carbon price is increased or renewable energy is subsidized.

Chakravorty et al. (2011) address the first question within a time-continuous model which requires them to solve the model numerically. Despite the extensive sensitivity analysis, their solutions remain subject to the choice of the parameter values. In contrast to their approach, Chapter 3 of this thesis applies a two-period model which allows for deriving analytical solutions. In addition, Chapter 3 also evaluates subsidies for renewable energy and includes increasing marginal extraction costs.

1.3.3 Dynamic climate policy under firm relocation: The implications of phasing out free allowances

Unilateral climate policy reduces the CO_2 emissions in the regulating country, but this reduction may be counteracted by an increase of emissions in the non-regulated countries. This backlash is known as carbon leakage. According to IEA (2008), there are three major channels for carbon leakage. First, the competition channel where regulated firms face higher costs and consequently lose market shares to firms operating in unregulated jurisdictions. Second, the fossil fuel price channel according to which carbon pricing reduces the demand for fossil fuels in the regulated countries, leading to a drop of the world market prices and thus to higher demand in non-regulated countries. Third, the investment channel where climate policy alters the strategic location decision of firms towards countries with laxer environmental standards.

There is empirical evidence for the first two rather short-term channels (Felder and Rutherford 1993, Paltsev 2001 and IPCC 2014), in particular for energy-intensive industries such as steel (Fischer and Fox 2012) and cement (Demailly and Quirion 2006). The investment channel is rather long term and is related to the literature on the pollution haven effect (Copeland and Taylor 1994). While early papers find no evidence for the pollution haven effect (Brunnermeier and Levinson 2004), more recent ones report some evidence (Dong et al. 2012), indicating that environmental policy impacts the location decision of firms.

In the theoretical literature on endogenous plant location, some papers focus on the strategic interaction of governments when determining environmental regulation (Markusen et al. 1995 and Greaker 2003), while others analyze the impact of environmental regulation on the location decision of the firm (Motta and Thisse 1994 and Ulph and Valentini 1997), or normatively derive the optimal level of a predetermined set of policy instruments (Markusen et al. 1993 and Ikefuji et al. 2016). Chapter 4 of this thesis is related to the last group of papers. Measures to prevent the relocation of firms include border tax adjustments (Markusen 1975), reductions of the environmental tax (Markusen et al. 1993), tax exemptions for energy intensive firms (Hoel 1996) or localization subsidies (Mæstad 2001). In a static setting, Mæstad (2001) shows that a localization subsidy perfectly addresses the relocation of firms and thus is a necessary instrument for achieving the first best. In fact, if this subsidy was not feasible, then the regulator would set the second best emissions taxes below the marginal environmental damage in order to attenuate the negative welfare effect that arise from the relocation of firms.

A localization subsidy is formally equivalent to receiving allowances free of charge, if the number of free allowances is based on a sector-specific technology standard, as it is implemented in the European Union Emissions Trading System (EU ETS) since the beginning of the latest trading period in 2013. Martin et al. (2014) analyze the effect of allocating free allowances within the EU ETS on the relocation of firms and find that the current allocation scheme leads to a substantial overcompensation of firms. This overcompensation has prompted some stakeholders to call for a phasing out of allocating free allowances at the latest EU stakeholder consultation regarding the carbon leakage list (European Commission 2014). Chapter 4 addresses this proposal and asks

1. What are the welfare consequences of phasing out free allowances in the future?
2. What are the implications for the carbon prices?

Analyzing the impact of phasing out free allowances in the future requires, in contrast to Mæstad (2001), the use of a dynamic model as presented in Chapter 4. Schmidt and Heitzig (2014) use a dynamic model and show that allocating free allowances for a limited period of time is sufficient to avert the relocation of one firm permanently. However, they focus on the cost-minimal allocation of allowances for a given carbon price, whereas Chapter 4 explicitly derives the optimal carbon prices as a trade off between the relocation of some firms and the distortion of the abatement decisions of the remaining firms. Since the model of Schmidt and Heitzig (2014) involves only one firm, this trade off does not exist in their model.

1.4 Contribution and main results

1.4.1 Prices versus quantities: The impact of fracking on the choice of climate policy instruments in the presence of OPEC

Chapter 2 analyzes the impact of the fracking industry on the rent distribution between a dominant fossil fuel supplier such as OPEC and a climate coalition and asks how declining extraction costs of the shale oil producers impact the choice of the climate policy instrument. This question is addressed within a static model with two groups of countries: the climate coalition and OPEC (Section 2.2). While OPEC is the dominant oil producer, the climate coalition is the sole oil consumer, but also cares about global warming. Moreover, it hosts a number of small firms, i.e. the competitive fringe that produces oil at constant marginal costs higher than those of OPEC. These costs then represent an upper bound for the price that OPEC can charge and therefore impact the optimal policy of the climate coalition.

Section 2.3 shows that the optimal carbon tax of the climate coalition depends on the level of the fringe's marginal extraction costs. If these costs are high, OPEC's price setting behavior is virtually unrestricted, allowing OPEC to charge the monopolistic price. By anticipating this, the climate coalition implements a tax that does not only account for the damage from global warming, but also appropriates some of OPEC's rent. However, if the marginal extraction costs are low, then OPEC cannot charge a price higher than these costs. In this case, OPEC cannot exert its market power, causing the climate coalition to set the Pigouvian tax in order to maximize its domestic welfare.

Relative to a carbon tax, OPEC's reaction towards a fixed quota is more extreme to the extent that OPEC marginally undercuts that quota, which allows OPEC to extract a larger share of the climate rent. However, since the oil price cannot exceed the fringe's marginal extraction costs, declining costs reduce the rent extraction of OPEC and leave more revenue from selling permits for the climate coalition. Moreover, low extraction costs eventually prevent OPEC from exerting its market power, implying the climate coalition to optimally choose the quota that equals the quantity that results from implementing the Pigouvian tax.

Hence, both instruments are equivalent in this case.

In the Paris Agreement, the conference of the parties committed themselves to fixed emissions reduction targets, meaning that emissions trading schemes are likely to turn out as the predominant climate policy instrument in the future. Complementing a cap-and-trade system by levying a base tax allows the climate coalition to redistribute some rent from OPEC to the national governments. However, Section 2.4 shows that this dual instrument cannot outperform a pure carbon tax.

In summary, Chapter 2 reveals that a carbon tax weakly dominates a cap-and-trade system from the perspective of the climate coalition. However, if the marginal extraction costs of the shale oil producers are sufficiently small, both instruments are equivalent. This result is new to the literature and is the main contribution of this Chapter. In addition, the analysis suggests that if a cap-and-trade system evolves as the predominant climate policy instrument of the climate coalition, then this instrument should be complemented by a base tax.

1.4.2 The green paradox and learning-by-doing in the renewable energy sector

Chapter 3 analyzes the interactions between the energy use from the combustion of fossil fuels and from renewable energy sources, asking the questions of how learning-by-doing in the renewable energy sector impacts the extraction decision of fossil fuel owners and under which conditions climate policy elicits a weak or a strong green paradox. These questions are answered within a two-period model, where energy from fossil fuels and renewable energy are assumed to be perfect substitutes in each period (Section **??**). Renewable energy can be produced under increasing marginal costs and exhibits learning-by-doing, meaning that production costs are declining in the accumulated output of the past. Both fossil fuel owners and producers of renewable energy maximize their inter-temporal profits by choosing their current and future extraction and production quantities in the first period. Using comparative statics, Sections **??**, **??** and **??** analyze how a marginal increase of the learning factor, a subsidy for renewable energy, and a carbon tax impacts the extraction of the fossil fuel owners and thus CO_2 emissions.

Under the assumption of zero extraction costs, resource owners always exhaust the physical stock of resources entirely, meaning that there is either a strong green paradox or no green paradox at all. Section **??** shows that a higher learning factor may decrease or increase current CO_2 emissions. Initially, more effective learning lowers the production costs of renewable energy in the future, incentivizing its producers to raise future output and, by anticipating this, also the output in the present. This lowers the energy price in both periods, so that resource owners will adjust their extraction decision, depending on the relative strength of the two price reductions.

Section **??** shows that an increase of the subsidy for current renewable energy unambiguously raises the current output of renewable energy, but yields ambiguous results with respect to the change of current CO_2 emissions. On the one hand, an expansion of renewable energy in the first period leads to a drop of the current energy price and incentivizes resource owners to postpone the extraction. On the other hand, a higher output of current renewable energy reduces the production costs in the future, which increases the future output and decreases the future energy price, inducing the owners of fossil fuels to shift extraction towards the present period. If the learning factor is sufficiently high, the second effect outweighs the first one, implying current CO_2 emissions to rise in response to a marginal increase of a subsidy for renewable energy.

Raising the carbon tax in the future unambiguously increases current CO_2 emissions, meaning that the strong green paradox arises. Since this carbon tax reduces the value of fossil fuels in the future, resource owners adjust their extraction decision by shifting some extraction towards the present. However, the presence of LBD attenuates this effect because the carbon tax also leads to an increase of the energy price in the future, thereby boosting the production of renewable energy. Anticipating this, the producers of renewable energy also increase the output in the present, which lowers the current energy price and incentivizes resource owners to postpone their extraction. However, this counter-effect never outweighs the initial increase of CO_2 emissions as long as marginal extraction costs are zero.

Section **??** assumes increasing marginal extraction costs. Under this assumption, the resource stock may be exhausted economically rather than physically, implying that climate policy also has a volume effect besides affecting the inter-temporal allocation of the resource. If this is the case, an increase of the carbon tax in the future may only cause a weak green paradox, potentially leading to a rise of current CO_2 emissions, but also to a reduction of the overall emissions. More importantly, Section **??** shows that raising the future carbon tax may not cause a green paradox at all, if the slope of the marginal extraction cost curve is sufficiently flat. The reason is that resource owners respond to a future carbon tax by both lowering their total extraction and only slightly shifting extraction to the present. Moreover, taxation leads to higher energy prices, which induces renewable energy firms to increase their output not only in the future, but also in the present because of the anticipated benefits from LBD. This leads to a crowding out of energy from the combustion of fossil fuels and may outweigh the initial increase in current emissions, leading to less emissions in the present. Thus, if the slope of the marginal extraction cost curve is sufficiently flat, there is a reversal of the green paradox that has not yet been identified in the literature, implying this finding to be the main contribution of Chapter 3.

1.4.3 Dynamic climate policy under firm relocation: The implications of phasing out free allowances

Chapter 4 analyzes the consequences of phasing out the allocation of free allowances in the EU ETS in the middle term when firms can relocate to another country that does not put a price on carbon. This question is addressed within a two-period two-country model (Section 4.2), where the regulator of one country disposes of two instruments in each period: A carbon price, which may be implemented via an emissions trading scheme, and a lump-sum transfer, which is formally equivalent to allocating free allowances and is paid conditional on the firm operating in the regulating country in the respective period. While the carbon price induces firms to invest in abatement capital, the transfer aims at preventing relocation.

Section 4.3 suggests that there should be no phasing out. Since the provision of free allowances in the future perfectly addresses the relocation problem, the regulator would lose this perfect instrument if she committed to restrict the transfers in the future. Hence, the first best, i.e. setting the carbon prices equal to the marginal environmental damage and preventing all relocation by offering a sufficiently high transfer in the future, may not be feasible anymore. This result was also derived by Mæstad (2001) in a static setting.

In contrast to Mæstad (2001), the two-period model of Chapter 4 allows for analyzing the implications for the carbon price path when transfers are to be phased out in the future, i.e. in the second period. In this case, the regulator can prevent any immediate relocation by offering a high enough first period transfer. However, this may prompt some firms to play a 'take the money and run'-strategy, collecting the transfers in the first period, but relocating thereafter. In order to increase the number of firms that permanently produce in the regulating country, the regulator should raise the first period carbon price above the marginal environmental damage, reduce the second period carbon price below the marginal environmental damage, and adjust the first period transfer accordingly. Increasing the first period carbon price creates a lock-in effect, analogously to the analysis of Schmidt and Heitzig (2014). A higher first period carbon price triggers investments in abatement capital, making firms' profits less affected by the carbon price of the second period. This disproportionally benefits firms that maintain their production in the regulating country, relative to those that planned to relocate after the first period, implying the number of firms permanently producing in the regulating country to increase. However, moving the carbon prices away from the first best distorts the abatement decisions of firms. Hence, in the second best, the regulator trades-off the distortion of the abatement decision with the reduced relocation and optimally implements a declining carbon price path. This finding is new to the literature on endogenous plant location and is the main contribution of Chapter 4.

1.4.4 Overall contribution

This thesis investigates the design of climate policy in the presence of unintended side effects and has identified three areas, where these side effects are relevant: rent capturing by cartelized oil suppliers, the inter-temporal extraction decision of fossil fuel owners, and the relocation of firms in case of existing carbon price differences between countries.

This thesis shows that these negative side effects may not necessarily exist. In particular, as Chapter 3 finds, there may be no green paradox if the marginal extraction cost curve is sufficiently flat and if there is a perfect and clean substitute, that exhibits learning-by-doing. This result underlines the finding of Edenhofer and Kalkuhl (2011), who conclude that the occurrence of a ‘green paradox is limited to specific conditions’ (Edenhofer and Kalkuhl 2011, p. 2211), and adds to the list of previous findings regarding a reversal of the green paradox (Eichner and Pethig 2011, Ritter and Schopf 2014 and van der Meijden et al. 2015). In addition, the analysis of Chapter 4 reveals that even in the absence of allocating allowances free of charge, firms do not relocate as long as the relocation costs are sufficiently high. Finally, Chapter 2 shows that low extraction costs of the competitive fringe prevent OPEC from exerting its market power and thus from appropriating a large share of the climate rent. However, this only means that the negative side effects do not necessarily exist under specific conditions. In general, they are highly relevant and thus should be taken into consideration when designing climate policy instruments.

Concerning the design of climate policy and the set of policy instruments, this thesis suggests that the regulator should use a variety of different policy tools in order to address the externalities and the side effects separately. Given that the conference of the parties implemented quantity targets in the Paris Agreement, Chapter 2 shows that the sole use of quotas allows the cartelized fossil fuel owners to extract the whole climate rent. Thus, in order to prevent this welfare diminishing rent extraction, the cap-and-trade system should be accompanied by a second instrument, namely a base tax. For unilateral climate policy with mobile firms, Chapter 4 shows that the set of policy instruments should not be restricted by phasing out the allocation of free allowances because this overloads the remaining policy instrument to the extent that it needs to serve two different purposes. This requires the regulator to set the carbon tax such as to balance the gains from internalizing the damage from global warming against the loss from the relocation of firms, leading to a welfare-inferior allocation relative to the first best.

Summing up, the major insight of this thesis is that the governments should dispose over a very broad set of policy instruments in order to address each policy goal separately. This insight, also referred to as Tinbergen rule (Tinbergen 1952), does not only hold true for climate policy, but also applies for all other policy areas. Thus, reducing the set of policy instruments as proposed by the President-elect Donald Trump, who aims at eliminating regulations such as the

Clean Water Act or the Clean Power Plan, unnecessarily restrict governments' abilities to efficiently correct for market failures. If these regulations, besides its intended positive impacts, involve complementary negative side effects, then this thesis suggests to address these side effects by additional instruments rather than to forbid the regulation in the first place.

Chapter 2

Prices versus quantities: The impact of fracking on the choice of climate policy instruments in the presence of OPEC

Daniel Nachtigall

2.1 Introduction

At the climate conference in Paris 2015, the conference of the parties called for 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels' (UNFCCC 2015: Art. 2a) as suggested by the latest reports of the Intergovernmental Panel on Climate Change (IPCC 2014) and agreed to limit the exhaust of greenhouse gas emissions. As a first step of coordinated action against global warming, each country put forward country-specific emissions reduction targets. Limiting global carbon dioxide (CO_2) emissions necessarily impacts the demand for fossil fuels because the vast majority of CO_2 emissions stem from the combustion of fossil fuels. Thus, coordinated climate action by the major fossil fuel consuming countries can also be thought of as forming a climate coalition that acts as a demand cartel in the fossil fuel market. At the same time, any regulation of CO_2 emissions inevitably affects the supply of the owners of fossil fuels such as oil.

The oil market is characterized by the market power of the extractors, where the Organization of the Petroleum Exporting Countries (OPEC) accounts for almost half of the world's oil production and nearly 75% of proven oil reserves, leaving OPEC as the dominant player in the oil market. Given the market power of OPEC and the formation of the demand cartel by the Paris Agreement, the market structure in the oil market can be characterized as a bilateral monopoly. Under this market structure, previous papers find that the climate coalition is strictly better off under a carbon tax than under a cap-and-trade system. However, OPEC is not the sole supplier of oil, but faces increasing competition due to the evolution of the shale oil industry. Even though the extraction costs of shale oil are still much higher than those of OPEC's conventional oil, technological progress in the shale oil industry has dramatically decreased the extraction costs within the last years. This paper explores the consequences of declining extraction costs of OPEC's competitors on the rent distribution between the climate coalition and OPEC as well as the implications for the choice of the climate policy instrument.

The commitment to fixed emissions reduction targets in the Paris Agreement indicate that cap-and-trade may turn out as the predominant climate policy instrument. In fact, many countries, among which there are major emitters of CO_2, such as the European Union, China and some U.S. states, have already launched or are planning to launch emissions trading schemes. However, the economics literature predominantly favors a carbon tax over cap-and-trade for various reasons (see Goulder and Schein 2013 for a recent review). One reason for this preference is the existence of market power in the oil market, first explored by Berger et al. (1992). Accounting for OPEC's dominant role with respect to its competitors within a competitive fringe model, Berger et al. (1992) analyze OPEC's reaction towards carbon taxes and quotas for a given level of CO_2 emissions. Strand (2009) endogenizes the level of CO_2 emissions for both instruments, but does not incorporate fossil fuel producers other than OPEC. This paper fills the research gap between both papers by deriving the optimal level of CO_2 emissions (in contrast to Berger et al. 1992) and accounting for the impact of the competitive fringe (in contrast to Strand 2009) on the choice of the policy instrument.

Following Berger et al. (1992) and Strand (2009), the research question is answered within a static setting, where the two players, i.e. the climate coalition and OPEC, strategically interact with each other due to their dominant roles in the oil market. The shale oil industry is assumed to have positive constant marginal extraction costs higher than those of OPEC. The extraction costs then represent an upper bound for the oil price that OPEC can charge. If these costs are declining, so does the upper bound, which ultimately limits the price setting behavior of OPEC and thus impacts the optimal climate policy of the climate coalition.

Given the market power of OPEC, its reaction towards climate policy differs between a carbon tax and a fixed quota, which is why the climate coalition generally prefers one instrument over the other. In particular, as pointed out by Berger et al. (1992), OPEC's reaction towards a fixed quota is to marginally undercut that quota, which drives the permit price to zero and leaves no revenue for the climate coalition. This result also holds true in this paper as long as the fringe's marginal extraction costs are sufficiently high. For low extraction costs, OPEC still marginally undercuts the quota, but can capture only a part of the climate rent because the oil price is limited by the fringe's extraction costs.

Relative to a quota, a carbon tax generates positive revenue for the government and thus is welfare-superior for the climate coalition in general. However, low extraction costs of the fringe prevent OPEC from charging the monopolistic price and from exerting its market power. By anticipating this, the climate coalition optimally implements the Pigouvian tax in the first place and it turns out that the price and quantity instruments are equivalent in this case. However, for high extraction costs, the climate coalition strictly prefers the carbon tax, implying price regulation to weakly dominate quantity regulation. Complementing the quantity regulation by a base tax, as proposed by Schöb (2010), allows the climate coalition to retain some of the carbon revenue, but cannot outperform the pure price regulation.

2.1.1 Related literature

In a dynamic setting, early papers focused on using import tariffs to capture exporter's resource rents starting with Bergstrom (1982) and Karp and Newbery (1991).[1] More recently, several papers have discussed climate policy as a means to capture foreign resource rents (Wirl 1995, Wirl and Dockner 1995, Amundsen and Schöb 1999, Rubio and Escriche 2001, Liski and Tahvonen 2004 and Eisenack et al. 2012). Wirl (2012) explicitly compares price and quantity strategies within a dynamic game between a climate coalition and OPEC and finds that both players are better off under the price strategy. Karp et al. (2015) extends this model by incorporating a non-strategic third country that also consumes oil, but does not belong to the climate coalition. Even this small extension renders the analysis intractable, preventing any closed-form solutions and forcing the authors to solve the problem numerically. Hence, some authors have started using static settings in order to analyze more complex scenarios such as the incorporation of a competitive fringe.

Berger et al. (1992) were the first to analyze the reaction of a dominant oil supplier towards price and quantity instruments while accounting for a competitive fringe. In the absence of the fringe, OPEC's best reaction towards a fixed quota is to marginally undercut that quota, thereby extracting the whole climate rent and leaving no carbon revenue for the climate coalition. In contrast, a carbon tax generates some revenue for the importing countries, which is why it is welfare-superior to a cap-and-trade system. Incorporating a competitive fringe

---

[1] Keutiben (2014) analyzes the impact of a competitive fringe of oil suppliers on the optimal import tariff and finds that the presence of competitors enhances the ability of the importer to capture the exporter's resource rent.

that supplies oil at increasing marginal extraction costs causes the residual demand to turn downwards, forcing OPEC to reduce its price. However, the effective demand in the case of quantity regulation remains perfectly inelastic at the quota, which allows OPEC to charge a higher price relative to a carbon tax, implying a carbon tax to continue to be preferred by the importing countries. While Berger et al. (1992) compare price and quantity regulation for an exogenously given level of oil consumption, the present paper derives the welfare-optimal oil quantities for each policy instrument and contrasts the respective welfare levels.

Strand (2009) endogenizes the oil consumption by maximizing the climate coalition's welfare, but does not incorporate a competitive fringe into his analysis. As in Berger et al. (1992), quantity regulation allows OPEC to capture the whole climate rent. Anticipating this, the climate coalition may find it optimal to reduce the quota to zero. A marginal increase of the quota starting at zero increases the utility from oil consumption, but this welfare gain is entirely captured by OPEC. Since the permit price is zero, the climate coalition suffers a welfare loss due to the additional damage from global warming. However, raising the quota beyond zero may eventually improve the climate coalition's welfare because it forces OPEC to reduce its oil price in order to capture the climate rent, which finally leads to an increase of the consumer surplus. If the consumer surplus outweighs the damage from global warming, then the climate coalition optimally implements a positive quota equal to the quantity that an unregulated monopolist would choose. Any quota beyond that quantity is ineffective because OPEC would optimally reduce its supply accordingly. Since a cap-and-trade system does not generate any revenue, whereas a carbon tax leaves some revenue for the climate coalition, Strand (2009) concludes that price regulation strictly dominates quantity regulation.

In order to retain some revenue from the cap-and-trade system, Schöb (2010) proposes to complement the quota by a base tax. He finds that this dual instrument enables the climate coalition to generate the same revenue as from implementing a carbon tax. In contrast to Schöb (2010), the present paper derives the optimal level of oil consumption while accounting for a competitive fringe.

The remainder of the paper is organized as follows. Section 2.2 presents the model that is used to analyze the research question. Section 2.3 compares a carbon tax with a cap-and-trade system and works out the impact of the competitive fringe on the choice of the climate policy instrument. In Section 2.4, the dual instrument that complements the quantity regulation with a base tax is analyzed. Finally, Section 2.5 discusses the results and concludes.

2.2 The model

Following Berger et al. (1992) and Strand (2009), I set up a static model. Even though the extraction of fossil fuels is inherently a dynamic problem, which requires dynamic solution techniques, I take the warning of Wirl (2012) seriously, who states that 'any substantial extension may render closed form solutions impossible or intractable' (Wirl 2012, p. 227). Moreover, a static setting may be appropriate as long as the analysis covers the medium run, i.e. the next 20 to 30 years. There are two groups of countries: the climate coalition and a cartelized group of fossil fuel exporters such as OPEC. OPEC is assumed to be the dominant oil producer, whereas the climate coalition as a demand cartel is the sole oil consumer, but also hosts a number of small firms that extract oil at higher marginal costs than OPEC.

The timing of the game is the following. First, the climate coalition chooses the policy instrument and sets the level of the carbon tax or the quota respectively. Second, OPEC moves by determining its exporter price or its quantity. This timing reflects the fact that international climate negotiations that involve many countries take much more time than the coordination of a small subgroup of fossil fuel exporting countries that have already been cooperating for several years.[2] Third, the competitive fringe determines its extraction amount. The problem is solved via backwards induction.

3. Stage: Competitive fringe

The competitive fringe represents small competitive firms, operating in the shale-oil industry. All firms take the resource price net of taxes p as given and are assumed to have the same constant marginal extraction costs $c > 0$. They maxi-

---

[2] Alternatively, one could think of OPEC having coordinated already in the pre-Paris period. The Paris agreement then establishes the climate coalition and sets its long-term policy, while OPEC reacts accordingly.

mize their profits $\pi_F(R) = pR - cR$ by choosing the optimal amount of extraction R and the supply function reads

$$R_F(p) = \begin{cases} \infty & \text{if} \quad p > c \\ [0, \infty] & \text{if} \quad p = c \\ 0 & \text{if} \quad p < c. \end{cases} \tag{2.1}$$

2. Stage: OPEC

As a dominant player in the oil market, OPEC decides upon its extraction before all other firms move, taking the policy of the climate coalition as given. For simplicity, the marginal extraction costs of OPEC are normalized to zero, reflecting the fact that OPEC's extraction costs are still far below those of its competitors.[3] In contrast to the climate coalition, OPEC does not care about the damage from global warming caused by the combustion of fossil fuels. Let p be the net resource price, t be the price of carbon (either tax or permit price), $q = p + t$ be the consumer price and $R(q)$ as well as $q(R)$ be the (inverse) demand for oil, then the profits of OPEC read

$$\pi(p, t) = pR(p + t) \quad \text{and} \quad \pi(R, t) = (q(R) - t)R. \tag{2.2}$$

As will be shown in the next section, OPEC's profit maximizing strategy depends on the choice of the policy instrument of the climate coalition.

1. Stage: Climate coalition

The climate coalition is the sole consumer of oil. The utility of the representative consumer is characterized by declining marginal utility. In order to obtain closed-form solutions, I follow Strand (2009) and assume the utility to be linear-quadratic with

$$U(R) = aR - (1/2)\gamma R^2, \tag{2.3}$$

which leads to a linear demand function. Taking the consumer price for oil $q = p + t$ as given, the representative consumer maximizes her utility and the

---

[3] In fact, marginal extraction costs of OPEC are not zero, but positive ranging from 3 USD/barrel (bbl) for Saudi Arabia to 20 USD/bbl for Venezuela and are far below the marginal extraction costs of shale-oil, which are estimated to be around 70 USD/bbl according to Knoema (2014).

demand function as well as the inverse demand function are given by

$$\max_R U(R) - qR \;\Leftrightarrow\; q(R) = a - \gamma R \;\Leftrightarrow\; R(q) = (1/\gamma)(a - q). \tag{2.4}$$

The climate coalition experiences damage from global warming that arises from the combustion of fossil fuels. For simplicity, the combustion of one unit of oil is assumed to emit one unit of CO_2, causing a constant marginal environmental damage of ψ. This reflects the basic characteristics of climate change in the medium term. In the following, I assume $\psi < a$, meaning that the marginal environmental damage is lower than the marginal utility of the first unit of oil.

Social welfare of the climate coalition is based on a national concept, consisting of the consumer surplus, the tax revenues of the government and the environmental damage. The welfare function is given by

$$W(R, p) = aR - (1/2)\gamma R^2 - pR - \psi R, \tag{2.5}$$

where the tax payments of the consumers and the tax revenues for the government cancel out. The global welfare maximum, i.e. the maximum of the joint welfare of the climate coalition and OPEC, is given by $R_{fb} = (1/\gamma)(a - \psi)$. However, due to the opposing incentives of the climate coalition and OPEC, the first-best will not be achieved as long as the players do not cooperate when choosing their policies. In principle, the climate coalition may maximize its national welfare either by a price or a quantitiy instrument. However, the reaction of OPEC is different in both cases as will be seen in the next section.

2.3 Comparing climate policy instruments

This section compares a carbon tax with a cap-and-trade system. As a reference case, let us first turn to the analysis without the competitive fringe as in the model of Strand (2009).

2.3.1 Prices versus quantities without a competitive fringe

In the absence of the competitive fringe, there is a standard Stackelberg game, in which the climate coalition is the Stackelberg leader and OPEC the Stackelberg follower. The choice of the climate policy instrument alters the effective demand and therefore OPEC's reaction in the second stage. For a carbon tax, OPEC faces the inverse demand function $q(R)$, so that the marginal revenue reads

$$\frac{\partial \pi(R,t)}{\partial R} = MR(R,t) = a - t - 2\gamma R. \tag{2.6}$$

The unregulated monopolist chooses a profit maximizing quantity of $R_M = (1/2\gamma)a$. The effective demand in case of a quota $\bar{R}$ is given by

$$R_e(q,\bar{R}) = \begin{cases} R(q) & \text{if} \quad q \geq q(\bar{R}) \\ \bar{R} & \text{if} \quad q < q(\bar{R}). \end{cases} \tag{2.7}$$

Figure 2.1 contrasts OPEC's reaction towards both instruments when the climate coalition would like to implement a quantity of $\bar{R} < R_M$.

Figure 2.1: OPEC's reaction towards price and quantity instruments

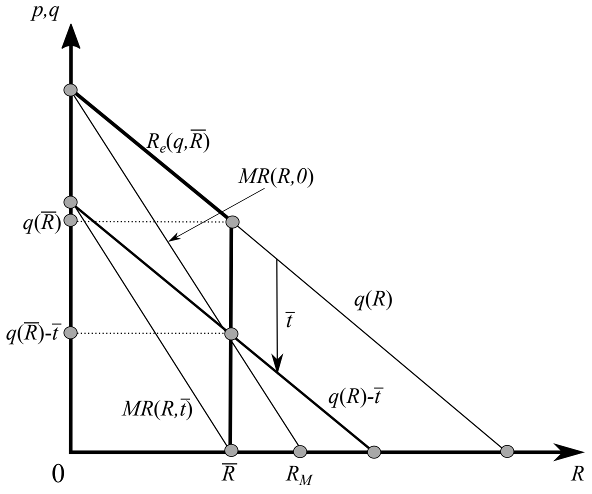


Figure 2.1 depicts the inverse demand function $q(R)$, the inverse demand function less the tax $q(R) - \bar{t}$, the marginal revenues $MR(R,0)$ and $MR(R,\bar{t})$, the effective demand function $R_e(q,\bar{R})$, the quantity of the unregulated monopolist R_M and the quota $\bar{R} < R_M$. Imposing a quota causes the effective demand function for OPEC to be kinked at $(\bar{R},\ q(\bar{R}))$ so that OPEC's optimal reaction

is to supply $\bar{R}$ at a price $q(\bar{R})$. OPEC cannot sell more than $\bar{R}$, even if it was to reduce its price. Raising the price above $q(\bar{R})$ is also not optimal because the marginal revenue exceeds the marginal costs (zero) for all $\bar{R} < R_M$. Charging a price of $q(\bar{R})$ drives the permit price to zero, implying the climate coalition to generate no revenue and OPEC to extract the whole climate rent.

If the climate coalition was to impose $\bar{R}$ by a carbon tax, it would need to implement a tax level of $\bar{t}$, so that OPEC's marginal revenue equals its marginal costs at $\bar{R}$. Facing the carbon tax $\bar{t}$, OPEC optimally charges an oil price of $q(\bar{R}) - \bar{t}$, meaning that the consumer price $q(\bar{R})$ and thus the climate rent is divided between OPEC and the climate coalition. Thus, implementing $\bar{R}$ by a carbon tax generates a positive tax revenue equal to $\bar{t}\bar{R}$ for the climate coalition.

Formally, OPEC's best response when facing a carbon tax reads

$$\max_p \pi(p,t) = pR(p+t) \;\Leftrightarrow\; p^o(t) = (1/2)(a-t). \tag{2.8}$$

OPEC's optimal oil price negatively depends on the level of the carbon tax. In the first stage, the climate coalition maximizes its welfare, taking OPEC's and the consumer's reaction into account. The optimal carbon tax reads

$$\max_t W(R(p^o(t)+t), p^o(t)) \;\Leftrightarrow\; t^o = \psi + (1/3)(a-\psi). \tag{2.9}$$

The optimal carbon tax t^o is higher than the Pigouvian tax $t_P = \psi$ because the climate coalition does not only internalize the environmental damage, but also appropriates some of OPEC's monopolistic rent by raising the tax above the Pigouvian level.

Regarding quantity regulation, OPEC's price reaction towards a fixed quota $\bar{R}$ can be summarized by

$$p^o(\bar{R}) = \begin{cases} q(\bar{R}) & \text{if} \quad \bar{R} \leq R_M \\ q(R_M) & \text{if} \quad \bar{R} > R_M. \end{cases} \tag{2.10}$$

For any $\bar{R} > R_M$, OPEC optimally reduces its supply to R_M, thereby making $\bar{R}$ redundant. The climate coalition takes OPEC's behavior into account when determining the optimal quota. The welfare function reads

$$W(\bar{R}, p^o(\bar{R})) = \begin{cases} (1/2)\gamma\bar{R}^2 - \psi\bar{R} & \text{if} \quad \bar{R} \leq R_M \\ (1/2)\gamma R_M^2 - \psi R_M & \text{if} \quad \bar{R} > R_M. \end{cases} \tag{2.11}$$

Note that $(1/2)\gamma\bar{R}^2 - \psi\bar{R}$ is a convex function, implying the welfare maximum to be a corner solution. Intuitively, marginally increasing the quota from $\bar{R} = 0$ increases the utility from oil consumption, but this welfare gain is entirely captured by OPEC. Since the permit price and thus the carbon revenue is zero, the climate coalition suffers a welfare loss due to the increased damage from global warming.[4] However, a marginal increase of the quota at any $0 < \bar{R} < R_M$ requires OPEC to reduce its oil price in order to capture the climate rent, causing the consumer surplus to increase and turning the marginal welfare effect positive eventually. Consequently, the climate coalition either chooses the quota to be zero or to be R_M.[5]

In summary, the welfare of the climate coalition under quantity regulation is strictly lower than that under price regulation because a quota allows OPEC to capture the whole climate rent.[6] This result was already pointed out by Strand (2009). However, this conclusion may not hold true in the presence of small competitive oil suppliers.

2.3.2 The impact of the competitive fringe

Carbon taxes

In the absence of the competitive fringe, OPEC can always charge its optimal price $p^o(t) = (1/2)(a - t)$. However, the small competitors may restrict OPEC's price setting behavior to the extent that they prevent OPEC from setting $p^o(t)$ if their marginal extraction costs are below that price, i.e. if $c < (1/2)(a - t)$. In this case, OPEC would face no demand at $p^o(t)$ because the competitors would

---

[4] Formally, we have $\frac{\partial(1/2)\gamma\bar{R}^2 - \psi\bar{R}}{\partial\bar{R}}\big|_{\bar{R}=0} = -\psi < 0$.

[5] While a zero quantity implies a welfare of zero, R_M leads to $W(R_M, p^o(R_M)) = (1/8\gamma)(a - 4\psi)a$, meaning that the climate coalition prefers R_M as long as $a - 4\psi \geq 0$.

[6] To see this, compare equations (B.1) and (B.4) in the appendix and note that equation (B.1) is strictly positive by assumption.

supply oil at a lower price c.[7] Anticipating this, OPEC optimally reduces its price to c, implying the best reaction to be

$$p^*(t) = \begin{cases} (1/2)(a-t) & \text{if} \quad c \geq (1/2)(a-t) \\ c & \text{if} \quad c < (1/2)(a-t). \end{cases} \tag{2.12}$$

This function alters the welfare maximization problem of the climate coalition from equation (2.9) by substituting $p^*(t)$ for $p^o(t)$. As before, when the climate coalition anticipates OPEC to set $p^*(t) = (1/2)(a-t)$, i.e. when the fringe's extraction costs are sufficiently high, it is welfare-optimal to implement t^o. However, for low extraction costs, OPEC cannot charge the monopolistic price and the climate coalition anticipates OPEC to choose $p^*(t) = c$. Since OPEC cannot exert its market power, the climate coalition is unable to capture some of OPEC's rent by setting the carbon tax strategically, implying the welfare-optimal tax to be the Pigouvian tax t_P. For moderate extraction costs, i.e. for $c \in [(1/3)(a-\psi); (1/2)(a-\psi)]$, I show in the Appendix that there are two equilibria so that the climate coalition can either implement t_P or t^o. The welfare-maximizing taxation strategy finally depends on the fringe's extraction costs and is reported in Proposition 1.

Proposition 1
Let $c_t \equiv (1/3)(3-\sqrt{3})(a-\psi)$. *Depending on the marginal extraction costs of the competitors* c, *the climate coalition's optimal tax strategy is given by*

$$t^*(c) = \begin{cases} t_P = \psi & \textit{if} \quad c \leq c_t \\ t^o = \psi + (1/3)(a-\psi) & \textit{if} \quad c > c_t. \end{cases} \tag{2.13}$$

Proof. See Appendix. □

The intuition behind Proposition 1 is the following. Choosing $t^o > \psi$ reduces the total oil consumption and therefore the consumer surplus excessively, but enables the climate coalition to appropriate some monopolistic rent. Since t^o does not depend on the size of c, a decline of the marginal extraction costs does

---

[7] Graphically, the existence of the small competitors alter OPEC's marginal revenue to the extent that the marginal revenue equals c as long as the net oil price $q(R) - t$ is above c and drops to $MR(R, t)$ afterward.

not affect the tax level and thus the welfare of this strategy. In contrast, setting the Pigouvian tax perfectly internalizes the environmental damage and induces OPEC to charge a price of c. A decline of c then shifts a part of OPEC's profits to the consumers of the climate coalition. This increases the consumer surplus and thus the climate coalition's welfare, implying the implementation of the Pigouvian tax to become relatively more attractive as c decreases.

The interpretation of Proposition 1 is straightforward. As the marginal extraction costs of OPEC's competitors decline, e.g. due to technological progress in the shale-oil industry, the climate coalition may eventually switch from a rent-extraction strategy to a pure Pigouvian strategy when maximizing its welfare. In fact, the extraction costs of the major shale-oil fields almost halved between the years 2014 and 2016 according to Rystad Energy (2016). Thus, if the climate coalition was to use a carbon tax, it would become more likely that the climate coalition imposes the Pigouvian tax that does not contain a rent extraction element.

Quantity regulation

As in the case of taxation, the existence of the competitive fringe limits OPEC's price setting behavior. OPEC's reaction for a given quota $\bar{R}$ is illustrated in Figure 2.2.

Figure 2.2: OPEC's price reaction in the presence of a competitive fringe

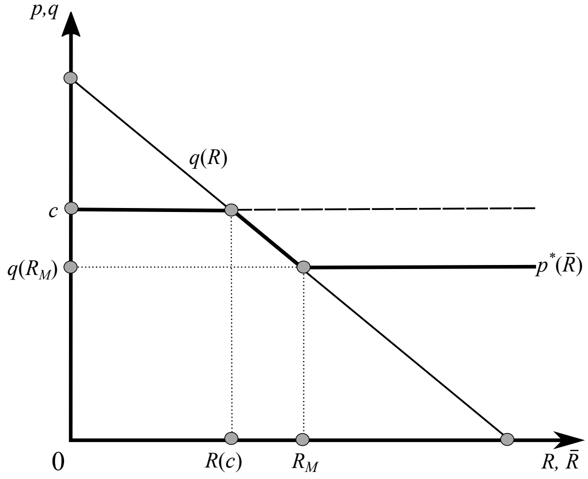


Figure 2.2 illustrates the inverse demand function $q(R)$, the supply function of the competitive fringe $c > q(R_M)$ and OPEC's optimal price $p^*(\bar{R})$. The reaction of OPEC towards an emissions cap $\bar{R}$ can be divided into three intervals. As in equation (2.10), for $\bar{R} > R_M$, OPEC reduces its supply to the quantity R_M, leading to an exporter price of $q(R_M)$. If $\bar{R} \in [R(c), R_M]$, then OPEC marginally undercuts the quota, which drives the permit price to zero and implies the exporter price to be $q(\bar{R})$. For $\bar{R} < R(c)$, OPEC also marginally undercuts $\bar{R}$ and would like to set $q(\bar{R})$, but cannot do so because in this interval, the competitive fringe prevents OPEC from charging $q(\bar{R}) > c$. Hence, OPEC's profit maximizing strategy is to supply $\bar{R}$ at a price of c. This implies the permit price to be $q(\bar{R}) - c > 0$ in this interval, leaving some carbon revenue for the climate coalition.

If the marginal extraction costs were below $q(R_M)$, OPEC would optimally charge a price of c for all $\bar{R}$. In summary, OPEC's price setting behavior is characterized by

$$p^*(\bar{R}) = \begin{cases} q(\bar{R}) & \text{if} \quad \bar{R} \in [R(c), R_M] \text{ and } c \geq q(R_M) \\ q(R_M) & \text{if} \quad \bar{R} > R_M \text{ and } c \geq q(R_M) \\ c & \text{else,} \end{cases} \tag{2.14}$$

while the corresponding quantities are given by

$$R^*(\bar{R}) = \begin{cases} R_M & \text{if} \quad \bar{R} > R_M \text{ and } c \geq q(R_M) \\ \bar{R} & \text{else.} \end{cases} \tag{2.15}$$

The climate coalition takes the price and quantity setting behavior of OPEC into account and maximizes

$$\max_{\bar{R}} W(R^*(\bar{R}), p^*(\bar{R})) \quad \text{s.t.} \quad \bar{R} \geq 0 \tag{2.16}$$

For $c < q(R_M)$, OPEC always charges an oil price of $p^*(\bar{R}) = c$, implying the climate coalition to choose the quota such as to equalize the marginal utility with the social marginal costs, i.e. the marginal environmental damage plus the oil price. The optimal quota is given by

$$\bar{R}^* = \max\{(1/\gamma)(a - c - \psi); 0\}. \tag{2.17}$$

If $a \leq c + \psi$, i.e. if the marginal utility of the first unit of oil does not exceed the social marginal costs, then the climate coalition optimally implements a quota of zero. For $a > c + \psi$, the optimal quota $\bar{R}^*$ is equivalent to the quantity that results from implementing the Pigouvian tax t_P and it turns out that also the permit price $q(\bar{R}^*) - c$ exactly equals t_P. Thus, both the allocation and the rent distribution are identical for both market-based instruments as long as c is not too large. However, for $c \geq q(R_M)$, the climate coalition may prefer to pursue another strategy, namely to implement a quota of R_M. To see this, consider Figure 2.3.

Figure 2.3: Optimal choice of the cap

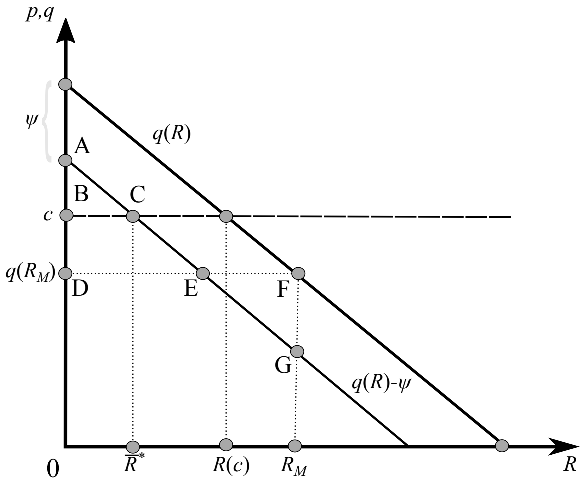


Figure 2.3 depicts the inverse demand function $q(R)$, the inverse demand function less the environmental damage $q(R) - \psi$, the marginal extraction costs $c > q(R_M)$ as well as the two potential strategies of the climate coalition $\bar{R}^*$ and R_M. The climate coalition chooses $\bar{R}^*$ such that the marginal utility net of the marginal environmental damage $q(R) - \psi$ equals the oil price c. In this case, the welfare is equal to the area of the triangle ABC. As c becomes larger, the area of

the triangle ABC and thus the welfare of this strategy declines. Then, the climate coalition may prefer to choose R_M, which leads to an oil price of $q(R_M)$ and yields a welfare of ADE minus EGF. Setting $\bar{R} \in (\bar{R}^*, R_M)$ cannot be welfare-optimal. First, for an increase of $\bar{R}$ beyond $\bar{R}^*$, the oil price c exceeds the marginal utility net of the marginal environmental damage. Second, in the interval $[R(c), R_M]$, the welfare function is convex due to the same reasons as pointed out in the previous section, leaving the corner solutions R_M and $R(c)$ as potential welfare maxima in that interval. However, $R(c)$ cannot be optimal because $\bar{R}^*$ yields a strictly higher welfare level than $R(c)$, so that the climate coalition's optimal quota is either $\bar{R}^*$ (for rather low c) or R_M (for high c). Proposition 2 reports the climate coalition's optimal quota strategy.

Proposition 2
Let $c_q \equiv a - \psi - (1/2)\sqrt{(a-4\psi)a}$. *Depending on the marginal extraction costs* c, *the climate coalition's optimal quota is given by*

$$\bar{R}^*(c) = \begin{cases} R_M = (1/2\gamma)a & \text{if} \quad c \geq c_q \text{ and } a - 4\psi \geq 0 \\ \bar{R}^* = \max\{(1/\gamma)(a - c - \psi); 0\} & \text{else.} \end{cases} \tag{2.18}$$

Proof. See Appendix. □

If $a - 4\psi < 0$, the climate coalition's welfare when choosing R_M would be negative and thus would never be optimal. For $a - 4\psi \geq 0$, the intuition behind Proposition 2 is that for c sufficiently high, the climate coalition would optimally set $\bar{R}^*$ so low (or even equal to zero) such that there is virtually no consumer surplus anymore. Setting the quota R_M instead implies a drop of the permit price from ψ to zero, but yields a higher consumer surplus, causing this alternative to be more favorable for large c.

In summary, the existence of the competitive fringe limits the market power of OPEC and alters OPEC's best response towards a given quota. For low extraction costs, this deters the climate coalition from choosing a corner solution that is welfare-inferior to the tax solution. Proposition 3 compares the carbon tax and cap-and-trade system for different intervals of c.

Proposition 3

Let $c_t \equiv (1/3)(3-\sqrt{3})(a-\psi)$, $c_q \equiv a-\psi-(1/2)\sqrt{(a-4\psi)a}$ *and assume* $a-4\psi \geq 0$. *Depending on the marginal extraction costs of the competitive fringe, the optimal tax* $t^*(c)$, *the permit price* $q(\bar{R}^*(c))-p^*(\bar{R}^*(c))$, *the net oil prices* $p^*(t^*(c))$ *and* $p^*(\bar{R}^*(c))$, *the oil quantity* $R(p^*(t^*(c))+t^*(c))$, *and the optimal quota* $\bar{R}^*(c)$ *as well as the comparisons between the climate coalition's welfare levels and OPEC's profits are given by the following table:*

Table 2.1: Comparison of instruments

	Variable	$c \leq c_t$	$c \in (c_t, c_q)$	$c \geq c_q$
Tax	Carbon tax	ψ	$\psi + (1/3)(a-\psi)$	$\psi + (1/3)(a-\psi)$
	Oil price	c	$(1/3)(a-\psi)$	$(1/3)(a-\psi)$
	Quantity	$(1/\gamma)(a-c-\psi)$	$(1/3\gamma)(a-\psi)$	$(1/3\gamma)(a-\psi)$
Quota	Permit price	ψ	ψ	0
	Oil price	c	c	$(1/2)a$
	Quantity	$(1/\gamma)(a-c-\psi)$	$(1/\gamma)(a-c-\psi)$	$1/(2\gamma)a$
Comparison	Welfare	$W_{Tax} = W_{Quota}$	$W_{Tax} > W_{Quota}$	$W_{Tax} > W_{Quota}$
	Profit	$\pi_{Tax} = \pi_{Quota}$	$\pi_{Tax} \lesseqgtr \pi_{Quota}$	$\pi_{Tax} < \pi_{Quota}$

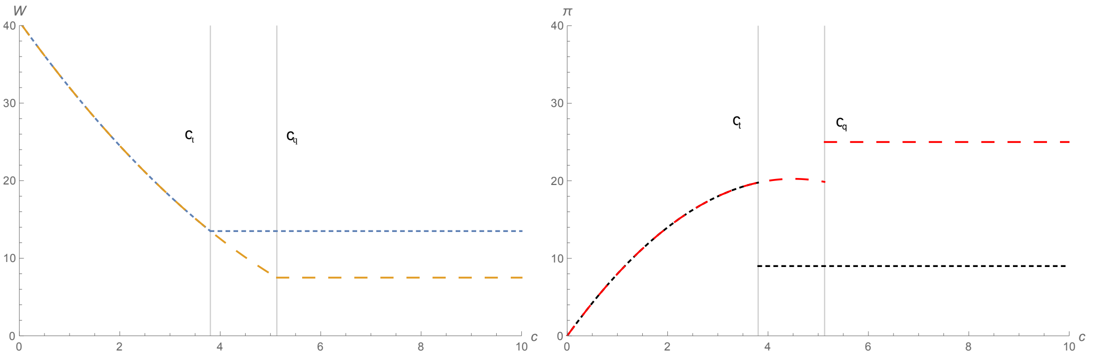
Proof. See Appendix. □

Proposition 3 shows that a carbon tax is welfare-superior to a cap-and-trade system, but that both instruments are equivalent for $c \leq c_t$. The reason is that the competitors with low marginal extraction costs restrict OPEC's price setting behavior, forcing OPEC to set its oil price equal to the fringe's costs, which finally prevents OPEC from exerting its market power. By anticipating this, the climate coalition sets the levels of its instrument as if there was perfect competition in the oil market, causing both instruments to be equivalent. Thus, in the presence of a competitive fringe with low marginal extraction costs, the result of Strand (2009) does not hold anymore. However, for $c > c_t$, OPEC can exert its market power and the climate coalition is strictly better off when using a price rather than a quantity instrument. Relative to a tax, a cap-and trade system allows OPEC to extract a larger share of the climate rent. However, this does not imply that OPEC's profits are generally higher under quantity regulation because the climate coalition may optimally set a very low quota. In this case, the climate coalition's welfare as well as OPEC's profit approach zero and both players are better off under the tax regulation. For $c \geq c_q$, OPEC strictly prefers quantity regulation, whereas the climate coalition is better off under tax regulation provided that $a - 4\psi \geq 0$. Remember that for $a - 4\psi < 0$, it will never be beneficial for the climate coalition to set a quota equal to the monopolistic quantity, so that the second column of Table 2.1 remains valid also beyond c_q.[8]

Numerical example

Figure 2.4 uses a numerical example with $a = 10$, $\psi = 1$ and $\gamma = 1$ to illustrate the climate coalition's welfare and OPEC's profits depending on c.

Figure 2.4: Comparison of tax and quantity regulation



(a) Welfare

(b) Profits

Legend: Dotted graph is tax regulation, dashed graph is quota regulation.

In the interval $c \leq c_t$, both regulations are equivalent. Since the costs for oil of the climate coalition respectively the oil revenue of OPEC are increasing in c, the consumer surplus and thus the welfare are decreasing, whereas profits are increasing in c. Beyond c_t the climate coalition alters its tax strategy towards $t^o = \psi + (1/3)(a - \psi)$ so that OPEC charges a price that only depends on the tax level, but not on c, implying both welfare and profit to remain constant. For $c > c_q$, the climate coalition optimally chooses a quota of R_M, which is why the welfare and the profit under quantity regulation do not change in this interval. Note that the climate coalition is strictly better off under a carbon tax for $c > c_t$, whereas OPEC's profit is lower when facing carbon taxation relative to a quota.

---

[8] For $c \geq a - \psi$, the climate coalition optimally implements a quota of zero. In this case, a marginal increase of $\bar{R}$ from zero would induce OPEC to charge a price of $q(0) = a$ as long as $c \geq a$, which implies the permit price to be zero. If $a - \psi \leq c < a$, then OPEC can charge c at most and the permit price would be $q(0) - c = a - c$ in this case.

2.4 Quantity regulation with base tax

In order to retain some of the carbon revenue, Schöb (2010) proposes to complement the cap-and-trade system by levying a base tax. This proposal is analyzed in the following. When the climate coalition implements a quota $\bar{R}$ with a base tax t_b, Figure 2.5 illustrates OPEC's reaction in the absence of the competitive fringe.

Figure 2.5: OPEC's reaction towards the dual instrument

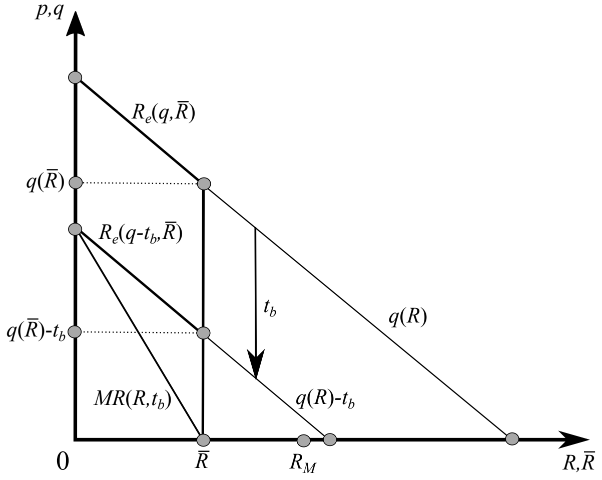


Figure 2.5 shows the quota $\bar{R}$, effective demand functions $R_e(q, \bar{R})$ and $R_e(q - t_b, \bar{R})$ as well as the marginal revenue $MR(R, t_b)$. Abstracting from the base tax, OPEC's best reaction towards any quota $\bar{R} \leq R_M$ is to marginally undercut that quota, thereby extracting the whole climate rent. Complementing the quota $\bar{R}$ with a base tax t_b forces OPEC to reduce its net oil price from $q(\bar{R})$ to $q(\bar{R}) - t_b$ and allows the climate coalition to appropriate a part of the climate rent equal to $t_b \cdot \bar{R}$.

Suppose that $\bar{R}$ was the optimal quota, then the climate coalition can do no better than setting t_b. Any base tax below t_b would yield the same oil consumption, but a lower carbon revenue. Setting the base tax above t_b leads OPEC to reduce its supply to some $R < \bar{R}$, which is welfare-inferior because $\bar{R}$ was assumed to be the optimal quota. Thus, for any given quota $\bar{R} \leq R_M$, there is exactly one optimal complementary base tax, which should be chosen such that the marginal revenue of OPEC equals zero at $\bar{R}$. Formally, the one-to-one relationship between quota and optimal base tax results from the profit maximization of OPEC, which is given by

$$\frac{\partial \pi(R, t_b)}{\partial R} = MR(R, t_b) = a - t_b - 2\gamma R \overset{!}{=} 0 \quad \Leftrightarrow \quad R^o(t_b) = (1/2\gamma)(a - t_b). \tag{2.19}$$

Putting it differently, in order to implement any desired quantity, the climate coalition only needs to set the base tax accordingly. This result also holds true in the presence of the competitive fringe. In this case, OPEC's profit maximizing quantity when facing a base tax only is given by[9]

$$R^*(t_b, c) = \begin{cases} (1/2\gamma)(a - t_b) & \text{if} \quad c \geq (1/2)(a - t_b) \\ (1/\gamma)(a - c - t_b) & \text{if} \quad c < (1/2)(a - t_b). \end{cases} \tag{2.20}$$

The climate coalition can induce OPEC to supply any desired quantity by choosing the base tax appropriately. More importantly, the climate coalition cannot improve its welfare by choosing a quota other than $R^*(t_b, c)$. Setting a quota $\bar{R} > R^*(t_b, c)$ makes this quota redundant because OPEC's actual supply is lower. On the other side, if a quota $\bar{R} < R^*(t_b, c)$ was optimal for the climate coalition, then the climate coalition could achieve a higher welfare level by increasing the base tax such that OPEC indeed supplies $\bar{R}$. By doing this, the climate coalition appropriates a larger share of OPEC's rent while consuming the same quantity $\bar{R}$. In summary, also in the presence of a competitive fringe, there is a one-to-one relationship between the base tax and OPEC's oil supply. To implement the welfare maximizing quantity, the climate coalition only needs to set the base tax appropriately and cannot improve its welfare by choosing a quota other than OPEC's profit maximizing oil supply. Proposition 4 reports the implication of this finding.

---

[9] This follows from equations (2.12) and (2.4).

Proposition 4
The quantity regulation with a complementary base tax is equivalent to the tax regulation.

Proof. Follows immediately from the one-to-one relationship between the base tax and OPEC's profit maximizing oil supply. ☐

Proposition 4 shows that by using a cap-and-trade system that is complemented by the optimal base tax, the climate coalition is neither worse off nor better off relative to the use of a carbon tax. The reason is that once the base tax is set optimally, the climate coalition cannot increase its welfare when setting a quota other than OPEC's profit maximizing oil supply.

2.5 Conclusion and discussion

This paper analyzes the impact of declining extraction costs of the competitive fringe on the choice of the climate policy instrument in a strategic game between a climate coalition and a dominant oil supplier such as OPEC. I show that, from the perspective of the climate coalition, a pure cap-and-trade system turns out to be weakly welfare-inferior relative to a carbon tax, while a cap-and-trade system that is accompanied by a base tax is equivalent to a carbon tax.

The marginal extraction costs of the competitive fringe constitute an upper bound for the price, OPEC can charge and thus impact the climate coalition's optimal tax strategy. High extraction costs allow OPEC to exert its market power and to charge the monopolistic price. Anticipating this, the climate coalition chooses a tax that both extracts some of OPEC's monopolistic rent and accounts for the damage from global warming. However, low marginal extraction costs prevent OPEC from exerting its market power, causing the climate coalition to optimally set the Pigouvian tax.

Relative to a carbon tax, a cap-and-trade system enables OPEC to extract a larger share of the climate rent by marginally undercutting the climate coalition's quota. Since the oil price cannot exceed the fringe's marginal extraction costs, lower costs limit the rent extraction of OPEC, leaving more revenue for the climate coalition. If the marginal extraction costs are sufficiently low, then the climate coalition will optimally choose the quota that is equivalent to the quantity that would have resulted from implementing the Pigouvian tax, implying both instruments to be equivalent.

The findings of this paper suggest that in the presence of a dominant oil supplier that faces competition from small oil extractors with higher extraction costs, a carbon tax should be preferred over a cap-and-trade system, confirming the implications of earlier papers such as Berg et al. (1997), Strand (2011), Wirl (2012) and Strand (2013). In fact, there are many other economic arguments, including lower administration costs or the absence of carbon price volatility, for why carbon taxes are superior to cap-and-trade. This superiority suggests that in the international climate negotiations in the coming years, the conference of the parties should rather aim at establishing a common carbon price than at negotiating country-specific emissions reduction targets. However, in the Paris Agreement, the conference of the parties committed themselves to fixed emissions reduction targets. Even though it remains to be seen which policy instrument each country will finally implement, it seems to be likely that cap-and-trade will turn out as the predominant climate policy instrument.

The political preference for cap-and-trade relative to carbon taxes originates primarily from two reasons. First, climate science suggests the existence of tipping points, i.e. dramatic, discontinuous, and irreversible changes of the climate system that occur after passing certain temperature or emissions concentration thresholds. Given the uncertainty about the marginal abatement costs, imposing adequate quotas guarantees to avoid passing these thresholds, while carbon taxes do not. Second, carbon taxes seem to lack political support at a national level. In some major emitting countries, such as the U.S., the political climate is characterized by a general resistance to any new taxes. In contrast, launching emissions trading schemes is likely to come along with a generous allocation of free emissions certificates for the regulated industries, which reduces the compliance costs. While firms bear both the abatement costs and the tax payments when facing a carbon tax, they incur only the abatement costs in the case of a cap-and-trade that allocates the allowances free of charge. This makes the private sector and the special interest groups less likely to oppose a cap-and-trade system relative to a carbon tax.

Provided that carbon taxes are politically not feasible, so that the conference of the parties needs to agree on quantities, the policy implication of this paper is that the quantity regulation should be complemented by levying a base tax. The base tax redistributes some rent from OPEC as tax revenues to the governments of the climate coalition, which potentially could pass the revenue on to the regulated firms. If the implementation of a base tax was politically not feasible, the climate coalition could accompany the cap-and-trade system by a floor price instead. A floor price is formally equivalent to a base tax and thus also guarantees the appropriation of some rent from OPEC. The regulated industries could be compensated by allocating a substantial share of allowances free of charge, making the ratification at the national level more likely.

Future research could, firstly, incorporate more than one fuel, e.g. oil and natural gas or coal, as partly done by Berger et al. (1992) and Strand (2011). Their analyses indicate that the (uncorrelated) demand for the second fuel and thus for emissions allowances limits OPEC's rent extraction in a cap-and-trade system. Secondly, the model employed in the present paper is static, whereas the extraction of exhaustible resources is inherently a dynamic problem. Thus, a possible extension would analyze the research question of this paper within a two-period model in analogy to the framework of Eichner and Pethig (2011).

2.A Appendix

Proof of Proposition 1

First, I show that there are two equilibria for $c \in [(1/3)(a-\psi),(1/2)(a-\psi)]$ in which the climate coalition can either implement $t_P = \psi$ or $t^o = \psi + (1/3)(a-\psi)$. If the climate coalition sets t^o, then OPEC indeed chooses $p^*(t^o) = (1/2)(a-t^o) = (1/3)(a-\psi)$ as long as $c \geq (1/3)(a-\psi)$. If the climate coalition sets t_P, then OPEC cannot implement its profit maximizing price $p^*(t_P) = (1/2)(a-t_P) = (1/2)(a-\psi)$ for $c \leq (1/2)(a-\psi)$. Hence, if $c \in [(1/3)(a-\psi),(1/2)(a-\psi)]$, then the climate coalition can implement either t_P or t^o. The respective welfare levels are

$$W(R(p^*(t^o)+t^o), p^*(t^o)) = (1/6\gamma)(a-\psi)^2 \tag{B.1}$$

$$W(R(c+\psi), c) = (1/2\gamma)(a-c-\psi)^2 \tag{B.2}$$

It follows that $(1/2\gamma)(a-c-\psi)^2 \geq (1/6\gamma)(a-\psi)^2$ as long as $c \leq (1/3)(3-\sqrt{3})(a-\psi) \equiv c_t$ which proofs Proposition 1.

Proof of Proposition 2

Depending on c, the climate coalition either sets $\bar{R}^* = \max\{(1/\gamma)(a-c-\psi); 0\}$ or $R_M = (1/2\gamma)a$. The respective welfare levels are given by

$$W(R^*(\bar{R}^*), p^*(\bar{R}^*)) = \begin{cases} (1/2\gamma)(a-c-\psi)^2 & \text{if} \quad c \leq a-\psi \\ 0 & \text{if} \quad c > a-\psi \end{cases} \tag{B.3}$$

$$W(R^*(R_M), p^*(R_M)) = (1/8\gamma)(a-4\psi)a. \tag{B.4}$$

Note that $W(R^*(R_M), p^*(R_M))$ is positive for $a-4\psi \geq 0$ and thus welfare-superior to $\bar{R}^* = 0$. The quota R_M is welfare-superior to $\bar{R}^* > 0$ as long as $(1/8\gamma)(a-4\psi)a \geq (1/2\gamma)(a-c-\psi)^2$, which holds true for $c \geq a-\psi-(1/2)\sqrt{(a-4\psi)a} \equiv c_q$. This proofs Proposition 2.

Proof of Proposition 3

The first three lines of Table 2.1 follow from the proof of Proposition 1 and from equations (2.4) and (2.12). The lines four to six are proved by the proof of Proposition 2, equations (2.14) and (2.18) as well as the fact that the permit price is given by $q(\bar{R}^*(c)) - p^*(\bar{R}^*(c))$.

For the seventh line, the first two entries immediately follow from the proof of Proposition 1. Using (B.1) and (B.4) and noting that $(1/6\gamma)(a-\psi)^2 > (1/8\gamma)(a-4\psi)a$ proofs the last entry.

For the last line, we have

$$\pi(p = c, t = \psi) = (1/\gamma)(a - c - \psi)c \tag{B.5}$$

$$\pi(p = (1/3)(a - \psi), t = \psi + (1/3)(a - \psi)) = (1/9\gamma)(a - \psi)^2 \tag{B.6}$$

$$\pi(p = (1/2)a, t = 0) = (1/4\gamma)a^2 \tag{B.7}$$

The first entry of the last line is obvious. For the third entry, we have $(1/4\gamma)a^2 > (1/9\gamma)(a - \psi)^2$. For the second entry, note that $\pi(p = c, t = \psi)$ approaches zero when c approaches $a - \psi$, implying $\pi(p = (1/3)(a - \psi), t = \psi + (1/3)(a - \psi)) > \pi(p = c, t = \psi)$. However, the opposite holds true at, e.g. $c = c_t$, where $\pi(p = c, t = \psi)|_{c=c_t} - \pi(p = (1/3)(a - \psi), t = \psi + (1/3)(a - \psi))|_{c=c_t} = (1/9\gamma)(3\sqrt{3} - 1)(a - \psi)^2 > 0$, which proofs the ambiguous relation sign in the second entry of the last line.

Chapter 3

The green paradox and learning-by-doing in the renewable energy sector[1]

Daniel Nachtigall
Dirk Rübbelke

---

[1] published in *Resource and Energy Economics* as Nachtigall, D., D. Rübbelke (2016), 'The green paradox and learning-by-doing in the renewable energy sector' Vol. 43, p. 74-92. Link: https://doi.org/10.1016/j.reseneeco.2015.11.003

Chapter 4

Dynamic climate policy under firm relocation: The implications of phasing out free allowances

Daniel Nachtigall

4.1 Introduction

In a globalized world with mobile capital, unilateral climate policy by a group of countries may have adverse effects known as carbon leakage. As the pricing of carbon dioxide (CO_2) raises the production costs of firms in the cooperating countries, these firms lose competitiveness relative to their foreign competitors and may relocate to countries with laxer environmental regulations. The relocation involves severe welfare losses to the regulating countries and is associated with a loss of employment, which is why the design of climate policy should account for the relocation problem.

In practice, several instruments have been implemented to address the adverse effects of unilateral climate policy out of which the allocation of free emission allowances is the most prominent one. For instance, the European Union Emissions Trading System (EU ETS), the largest trading scheme for CO_2 emission allowances in the world, allocates a specified amount of allowances free of charge to firms that are deemed to be exposed to relocation. However, Martin et al. (2014) find that the current practice leads to windfall profits and substantial overcompensation for the regulated firms. That is why some stakeholders have called for a phasing out of free allowances at the latest stakeholder consultation of the EU.[1] This paper analyzes in a stylized dynamic model the consequences of free allowances to be phased out in the near term and derives the implications for the optimal inter-temporal carbon price structure.

At the 21st meeting of the Conference of the Parties in December 2015 in Paris, the representatives of 195 countries agreed on a worldwide treaty that aims to reduce CO_2 emissions substantially as suggested by the IPCC (2014). In particular, the Paris Agreement calls for 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (UNFCCC 2015: Art. 2a). In order to achieve this worldwide goal, each country individually has put forward its emissions reduction target known as nationally determined contribution (NDC). However, according to Jeffery et al. (2015), these pledges

---

[1] During the stakeholder consultation regarding the carbon leakage list organized by the EU in 2014, 61 % of civil stakeholders consider the allocation of free allowances as problematic. In particular, environmental NGOs such as Climate Action Network, Greenpeace and Worldwide Fund for Nature would like to replace free allowances by full auctioning in the next trading period.

vary substantially across countries. While only 5 out of 32 analyzed countries made pledges that are in line with the 2°C target, the pledges of 16 countries are rated as inadequate, meaning that global warming is likely to exceed 3-4°C if all governments had committed to similar efforts. When implementing the NDCs by national policies, it can be expected that the heterogeneity of efforts translates into different carbon prices across countries, implying the relocation problem to persist despite the Paris Agreement.

In the EU ETS, the major instrument to address relocation is the allocation of free allowances. Allocating allowances free of charge attenuates the negative impact of carbon pricing on firms' profits, reducing the incentive to relocate. In the third trading phase from 2013 to 2020, the EU ETS switched from allocating free allowances according to historical emissions (grandfathering) to output-based allocation (benchmarking according to best-available technology), where firms get a specified share of a sector-specific benchmark. The benchmark reflects the emissions of the 90% most efficient installation within each sub-sector that is necessary to produce one unit of the respective final good. While in 2013, firms got 80% of this benchmark, this share is going to drop to zero by 2027.[2]

The EU ETS addresses carbon leakage explicitly by the carbon leakage list which includes 'energy-intensive sectors or sub-sectors that have been determined to be exposed to significant risks of carbon leakage' (EU 2009: Directive 2009/29/EC, Article 10b, 1). Sectors qualify for this list if the EU ETS raises the production costs by at least 5% *and* if the trade intensity with third countries exceeds 10%.[3] In addition, sectors belong to the carbon leakage list when either the production costs increase by more than 30% due to the EU ETS or the trade intensity is above 30%.[4] The carbon leakage list is to be updated every five years starting in 2009.[5] In contrast to all other firms, firms in sectors belonging to the carbon leakage list receive 100% of the benchmark emissions free of charge until the end of the third phase in 2020.[6] There is an ongoing debate concerning the rules applying for these sectors beyond 2020. While representatives of the industry have expressed their wish to continue the allocation free of charge in a first

---

[2] EU (2009): Directive 2009/29/EC, Article 10a, 11.

[3] Ibid, Article 10a, 15.

[4] Ibid, Article 10a, 16.

[5] Ibid, Article 10a, 13.

[6] Ibid, Article 10a, 12.

stakeholder meeting, the majority of civil society respondents prefers phasing out or restricting the amount of free allowances.[7] This paper contrasts both scenarios and derives implications for the optimal carbon price path.

The research question has been partially addressed in the scientific literature by Mæstad (2001) and Schmidt and Heitzig (2014). Mæstad (2001) derives the optimal levels of a set of policy instruments, which includes import tariffs, emissions taxes and localization subsidies (formally equivalent to free allowances) when firms may relocate to a non-regulating country. Schmidt and Heitzig (2014) show in a dynamic setting that the temporary allocation of free allowances is sufficient to induce firms to produce in the regulating country permanently. While Mæstad (2001) uses a static setting, Schmidt and Heitzig (2014) focus on the analysis of the cost-minimal inter-temporal allocation of free allowances for a given carbon price. The present paper fills in the research gap by analyzing the implications for the optimal climate policy in a dynamic setting when free allowances may or may not be restricted in the future.

In a two-period model with two countries, one country unilaterally implements carbon prices in both periods to account for the damage from global warming. Carbon pricing induces domestic firms to invest in abatement capital at the beginning of the first period to reduce their actual emissions. However, in order to avoid carbon pricing, some firms may relocate to the other country before or after the first period at a fixed and firm specific relocation cost. The social planner addresses the relocation problem by a second policy instrument, namely by offering transfers, i.e. free allowances, to the firms contingent on the firm producing in the regulating country in the respective period. Depending on the carbon prices and transfers in the two periods, firms choose the profit maximizing location plan already at the beginning of the first period, meaning that firms choose to either relocate immediately, after the first period or never.

If transfers are unrestricted in both periods, then the social planner can implement the first best by setting carbon prices equal to the marginal environmental damage and averting relocation entirely through transfer payments. This is equivalent to the result of Mæstad (2001) in a static setting.

---

[7] In the first stakeholder consultation 'some 29% of civil society respondents expressed their preference for no more free allocation after 2020, while 25% believe the share of allowances dedicated to carbon leakage and competitiveness should be lower than in 2013-2020' (EC 2014, p.9).

When the regulator has committed to restrict the allocation of free allowances in the second period, the first best may not be feasible anymore. In the second best, the social planner can avert any immediate relocation by offering sufficiently high first period transfers. However, this entices some firms to play a ‘take the money and run’-strategy, collecting transfers in the first period, but relocating thereafter. In order to prevent delayed relocation, the social planner increases the first period carbon price above the marginal environmental damage. This induces firms to invest more in abatement capital, thereby creating a lock-in effect. A high abatement capital stock attenuates the negative impact of the carbon price in the future on firms' profits, making relocation less likely. Thus, by raising the first period carbon price above and lowering the second period price below the marginal environmental damage, the social planner increases the number of firms that permanently produce in the regulating country.

4.1.1 Related literature

The relocation problem forms one part of the literature on the strategic location decision of firms under asymmetric environmental regulation between countries known as the pollution haven effect (Copeland and Taylor 1994).[8] While Brunnermeier and Levinson (2004) report that most papers in the empirical literature find no evidence for the pollution haven effect, more recent papers, that use more advanced estimation techniques and data sets, find some - though small - evidence (Xing and Kolstad 2002, List et al. 2003, Kellenberg 2009, Dong et al. 2012 and Naughton 2014), concluding that unilateral environmental regulation shifts investment flows abroad. For the EU ETS, Martin et al. (2014) explicitly analyze the effect of allocating free allowances on relocation. Theoretically, efficient allocation of allowances requires the marginal relocation risk weighted by the damage of relocation to be equal across all firms. Using firm-level data that allows for eliciting the marginal relocation propensity of firms under the EU ETS, Martin et al. (2014) find that the current allocation of permits results in

---

[8] Taylor (2005) distinguishes between the pollution haven effect according to which tightening environmental standards leads to a shift of investments towards countries with laxer environmental regulation and the pollution haven hypothesis where abolishing trade barriers causes the shift of capital flows.

substantial overcompensation, which serves as the major argument to phase out the allocation of free allowances.

The theoretical literature on endogenous plant location can be broadly separated into three strands. While the first strand deals with the strategic interaction of governments when determining environmental regulation (Markusen et al. 1995, Rauscher 1995, Hoel 1997, Ulph and Valentini 2001 and Greaker 2003), the second strand analyzes the impact of environmental regulation on the location decision of the firm (Motta and Thisse 1994, Ulph and Valentini 1997). This paper is related to the third strand, that normatively derives the optimal level of a predetermined set of policy instruments (Markusen et al. 1993, Hoel 1996, Petrakis and Xepapadeas 2003, Pollrich and Schmidt 2014 and Ikefuji et al. 2016). The papers closest to the present one are Mæstad (2001) and Schmidt and Heitzig (2014).

In a static setting with two countries, Mæstad (2001) analyzes three policy instruments, namely an import tariff or export subsidy on the final good, an emissions tax and a localization subsidy. He shows that the welfare maximum requires the emissions tax to be equal to the marginal environmental damage, the import tariff to be set such that the marginal social costs of production are equalized across both countries and the localization subsidy to be positive. Without taking import tariffs into consideration, the present paper derives the same result in a dynamic setting when localization subsidies or transfers are unrestricted in the future. In an extension, Mæstad (2001) derives the optimal emissions tax in the absence of transfers and finds that this tax should be below the marginal environmental damage. This reflects the trade-off between the relocation of some firms and the distortion of the abatement decisions of the remaining firms, which is also found in this paper. In contrast to his static setting, the present paper uses a dynamic model which allows for deriving the optimal tax and transfer levels when transfer, i.e. free allowances, are not phased out immediately, but in the middle term.

Schmidt and Heitzig (2014) use a dynamic model with infinite time horizon and show that also temporary grandfathering schemes can avert the relocation of one firm permanently. While the carbon price triggers investments in abatement capital, free allowances prevent instantaneous relocation. For a fixed carbon price, the social planner averts the relocation of the firm for a sufficiently long time horizon by allocating free allowances. This increases the investment in abatement capital and creates a lock-in effect. Thus, the firm will also not relocate in the long run after the provision of free permits has ceased because a large abatement capital stock reduces the negative impact of carbon pricing on the firm's profit. While Schmidt and Heitzig (2014) focus on the cost minimal inter-temporal allocation of free allowances to avert the relocation of the firm for a given carbon price, the present paper normatively derives the optimal dynamic carbon prices and transfers when free allowances may or may not be phased out in the future. In addition, Schmidt and Heitzig (2014) analyze a one-firm setting. This does not allow for identifying the basic trade-off of the present paper, i.e. the trade-off between the relocation of some firms and the efficiency of the abatement decisions of the remaining firms.

The remainder of the paper is organized as follows. Section 4.2 describes the model and presents the objective functions of the firms and the social planner. Section 4.3 contrasts the case where free allowances are available in both periods to the case of phasing out free allowances in the second period and derives the optimal carbon prices for both cases. Section 4.4 extends the model by introducing a budget constraint for the government. Finally, Section 4.5 concludes and discusses the results.

4.2 The model

In a deterministic two-period model with two countries A and B, country A introduces a carbon price while country B does not. The model abstracts from discounting within and between the periods, setting the discount factor equal to one. All consumers permanently reside in country A and all firms are initially located in country A, but may relocate to country B. There is neither market entry nor market exit. In each period, each firm produces one unit of the final good whose price is normalized to 1.[9] The production of the good causes baseline emissions $\bar{\epsilon}$. Firms can reduce their actual emissions by short-term abatement as well as investments in abatement capital. Short-term abatement, e.g. the use of

---

[9] Implicitly, each firm is a monopolist, facing an inverse demand function that is a step function, where the price equals 1 up to the quantity of 1 and drops to 0 afterward. By assuming this, it can be abstracted from any loss of competitiveness due to carbon taxation, which allows for focusing on the interaction between relocation and carbon pricing.

less carbon-intensive, but costlier fossil fuels, reduces emissions by the amount q in the respective period and is associated with time-invariant abatement costs $\gamma(q)$ with $\gamma'(q) > 0$ and $\gamma''(q) > 0$.[10] Investments in abatement capital take place before period 1 and include the adoption of less carbon-intensive production technologies that reduce actual emissions by the amount k in *both* periods. Investment costs $\kappa(k)$ are assumed to be convex with $\kappa'(k) > 0$ and $\kappa''(k) > 0$. Moreover, the investment cannot be transferred to country B when a firm relocates after having invested.[11] Short-term abatement and investments in abatement capital are assumed to be independent of each other, i.e. they are additively separable. Finally, it is assumed that $\gamma'(0) = 0$ and $\kappa'(0) = 0$ to avoid corner solutions and that baseline emissions are sufficiently large such that actual emissions $\bar{\epsilon} - q - k$ are always positive.[12]

Firms may evade carbon pricing by relocating to country B, which causes relocation costs θ. The cost parameter θ reflects the investments necessary to install the production capacities in country B. Since those investments vary across different industries, firms are assumed to be heterogeneous with respect to θ with $\theta \sim UNI[\underline{\theta}, \overline{\theta}]$. While the parameter θ is private information of the firm, the regulator knows the distribution of θ.

Since θ is private information, the regulator makes use of uniform policy instruments. These instruments include carbon prices in the first and second period (p and P)[13] and transfers (or localization subsidies) g and G that are conditional on the firm operating in country A. Amundsen and Schöb (1999) show that there is a one to one relationship between carbon taxes and caps in a cap-and-trade system, provided that firms are not allowed to bank or borrow

---

[10] In the following, $f'(\cdot)$ and $f''(\cdot)$ denote the first and second derivative of the function $f(\cdot)$ with respect to its argument.

[11] This assumption is not crucial for the results, but makes the subsequent analysis more tractable. Implicitly, it is assumed that the new technology cannot be transferred to country B at zero costs, implying the relocating firm to have no incentive to install the more efficient technology in country B.

[12] If actual emissions were negative, firms would benefit from carbon pricing and thus would never relocate to country B. Alternatively, I could assume that $\lim_{q \to (1/2)\bar{\epsilon}} \gamma'(q) = \infty$ and $\lim_{k \to (1/2)\bar{\epsilon}} \kappa'(k) = \infty$ in order to guarantee actual emissions to be positive.

[13] In the following, lower case letters always refer to variables in the first and capital letters to variables in the second period.

emission allowances between the periods.[14] Since all firms are assumed to produce exactly one unit of the final good, uniform lump-sum transfers are equivalent to allocating free allowances based on the best available technology standard in a cap-and-trade system.[15] In the analysis of Section 4.3, transfers are assumed to be unlimited while the government must respect a budget constraint in Section 4.4. The regulator determines all policy variables at the beginning of the first period and is assumed to be able to fully commit to them.

The model consists of two stages. In the first stage, the regulator sets the levels of all current and future policy instruments, whereas in the second stage, the firms simultaneously determine their abatement and location decisions. The model is solved by backwards induction.

4.2.1 Decisions of the firms

Depending on the policy instruments and the relocation cost parameter θ, firms either relocate never (AA), relocate later (AB) or relocate immediately (BB).[16] The respective profits for both periods read

$$\begin{aligned}\pi_{AA}(p,g,P,G,k,q,Q) =& 1-p\cdot(\bar{\epsilon}-k-q)-\kappa(k)-\gamma(q)+g+\\ & 1-P\cdot(\bar{\epsilon}-k-Q)-\gamma(Q)+G \qquad (4.1)\\ \pi_{AB}(p,g,k,q,\theta) =& 1-p\cdot(\bar{\epsilon}-k-q)-\kappa(k)-\gamma(q)+g+1-\theta \qquad (4.2)\\ \pi_{BB}(\theta) =& 1-\theta+1 \qquad (4.3)\end{aligned}$$

where 1 denotes the revenue of the firm from selling the good in each period. While AA-firms face carbon prices in both periods, AB-firms do so only in period 1 and relocate thereafter. For a given location plan, firms maximize their profits

---

[14] If banking and borrowing was allowed, then carbon prices would equalize across the periods due to the arbitrage of firms, preventing the regulator from differentiating carbon prices across periods by setting the caps accordingly.

[15] In principle, the regulator may prevent firms from relocating by implementing an import tariff based on the carbon content of the final good. However, since this option requires to determine the carbon content of each final good, it seems to be hardly feasible to put into practice, which is why this model abstracts from the use of border carbon adjustment. In addition, there is an ongoing debate which questions the compatibility of border carbon adjustments with WTO law. See e.g. Fischer and Fox (2012).

[16] Relocation is assumed to be once and for all so that the location plan BA is excluded.

with respect to the short-term abatement, and the first-order conditions (FOC)s are given by

$$
\begin{aligned}
\frac{\partial \pi_{AA}(\cdot)}{\partial q} &= p - \gamma'(q) \overset{!}{=} 0 && (4.4)\\
\frac{\partial \pi_{AB}(\cdot)}{\partial q} &= p - \gamma'(q) \overset{!}{=} 0 && (4.5)\\
\frac{\partial \pi_{AA}(\cdot)}{\partial Q} &= P - \gamma'(Q) \overset{!}{=} 0. && (4.6)
\end{aligned}
$$

Firms choose their short-term abatement such that the marginal abatement costs equal the carbon price. The FOCs (4.4), (4.5) and (4.6) implicitly define the optimal short-term abatement quantities $q^*_{AA}(p) = q^*_{AB}(p) > 0$ as well as $Q^*_{AA}(P) > 0$ for strictly positive carbon taxes, where all quantities increase in their arguments.[17]Depending on the location plan, the FOCs for the investment in abatement capital read

$$
\begin{aligned}
\frac{\partial \pi_{AA}(\cdot)}{\partial k} &= p + P - \kappa'(k) \overset{!}{=} 0 && (4.7)\\
\frac{\partial \pi_{AB}(\cdot)}{\partial k} &= p - \kappa'(k) \overset{!}{=} 0. && (4.8)
\end{aligned}
$$

Equations (4.7) and (4.8) implicitly define the abatement capital stocks $k^*_{AB}(p) > 0$ and $k^*_{AA}(p + P) \geq k^*_{AB}(p)$ with strict inequality for $P > 0$. The capital stocks of both firm types are increasing in the carbon prices.[18] Even though an AB-firm plans to relocate after the first period, it invests some amount in abatement capital, thereby optimally responding to the first period carbon price. However, the investments of AA-firms are higher since they face the carbon price also in the second period. Note that for the investment decision of AA-firms, only the sum of the carbon prices over both periods is relevant, implying p and P to be perfect substitutes in triggering abatement capital investments.

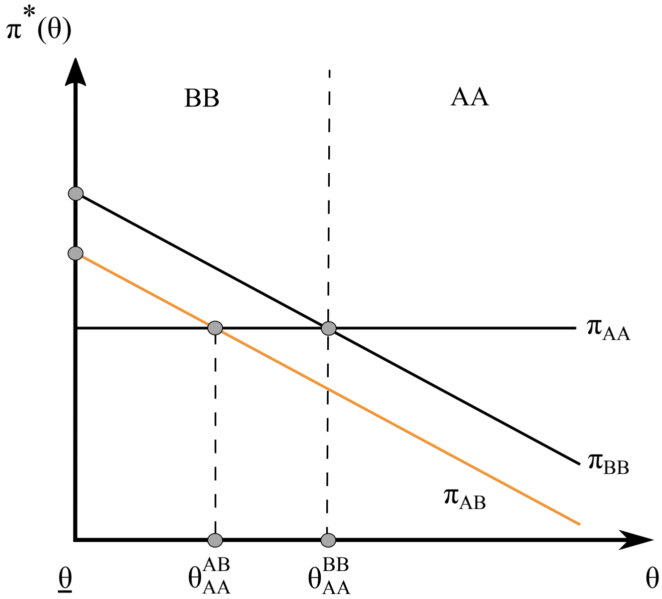
---

[17] Using the implicit functions theorem leads to ${q^*_{AA}}'(p) = {q^*_{AB}}'(p) = 1/\gamma''(q) > 0$ and ${Q^*_{AA}}'(P) = 1/\gamma''(Q) > 0$.

[18] Using the implicit functions theorem yields ${k^*_{AB}}'(p) = 1/\kappa''(k) > 0$ and ${k^*_{AA}}'(p + P) = 1/\kappa''(k) > 0$.

Plugging $q^*_{AB}(p)$, $q^*_{AA}(p)$, $Q^*_{AA}(P)$ as well as $k^*_{AB}(p)$ and $k^*_{AA}(p+P)$ into equations (4.1) and (4.2) yields $\pi^*_{AA}(p,g,P,G)$ and $\pi^*_{AB}(p,g,\theta)$, which only depend on the heterogeneity parameter θ and the policy instruments. From equations (4.1) and (4.3) it follows immediately that $\pi^*_{AA}(p=0,g=0,P=0,G=0) \geq \pi_{BB}(\theta)$, meaning that firms keep producing permanently in country A in the absence of any climate policy. Otherwise, they would already have relocated before. Figure 4.1 depicts the profits of the firms with different location plans depending on their relocation costs θ for $g=G=0$ and $p=P>0$.

Figure 4.1: Profits of firms without transfers

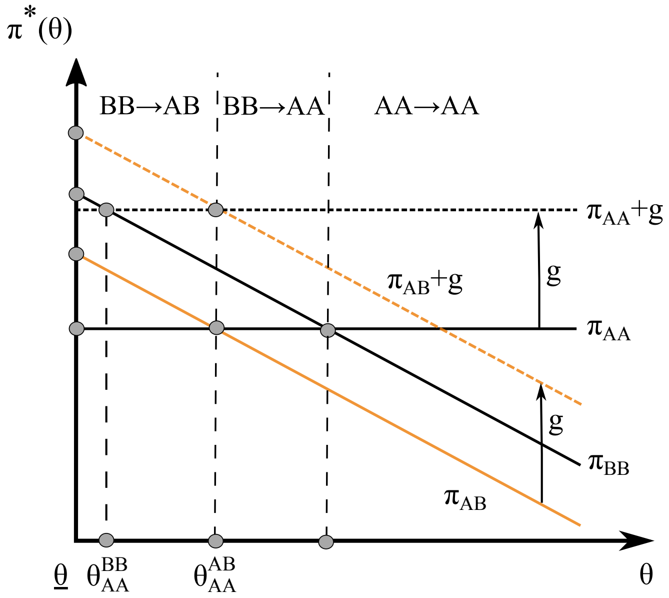


For positive carbon prices and low relocation costs ($\underline{\theta}$), the profit of BB-firms is the highest. However, this profit is declining in the relocation costs. Relative to BB-firms, the profit line of AB-firms is a parallel shift downwards because they incur the same relocation costs, but face carbon costs in the first period. The profit line of AA-firms is a horizontal line because they do not incur any relocation costs.

Firms choose the location plan which yields the highest profit. In Figure 4.1, all firms with $\theta \in [\underline{\theta};\theta^{BB}_{AA})$ relocate immediately while all firms with $\theta \geq \theta^{BB}_{AA}$ produce permanently in country A.

The profit lines of AA- and AB-firms depend on the policy instruments. The policy instruments of the second period only affect the profits of AA-firms, i.e. their profit line shifts upwards when G increases or P decreases, implying the number of AA-firms to rise. Increasing p reduces the profits of both AA- and AB-firms. Higher transfers g shift both profit lines upwards by the same amount. This situation is depicted in Figure 4.2.

Figure 4.2: Profits of firms with positive transfers



In Figure 4.2, increasing g induces some firms to switch from location plan BB to location plan AA so that all firms with $\theta \geq \theta_{AA}^{AB}$ prefer location plan AA. However, firms with $\theta \in [\underline{\theta}, \theta_{AA}^{AB}]$ relocate after the first period and are thus pursuing a 'take the money and run'-strategy. They benefit from transfers in the first period but relocate thereafter. Thus, first period transfers only induce firms to keep producing permanently in country A up to a certain point. Beyond this point, any further increase of g does not augment the number of AA-firms, but only replaces BB-firms by AB-firms. The indifference points θ_{AA}^{AB} and θ_{AA}^{BB} are given by

$$\begin{aligned}\theta_{AA}^{AB}(p,P,G) =& p\cdot(k_{AB}^*(p)-k_{AA}^*(p+P))-(\kappa(k_{AB}^*(p))-\kappa(k_{AA}^*(p+P)))\\ &+P\cdot(\bar{\epsilon}-Q_{AA}^*(P)-k_{AA}^*(p+P))+\gamma(Q_{AA}^*(P))+G \qquad (4.9)\\ \theta_{AA}^{BB}(p,g,P,G) =& p\cdot(\bar{\epsilon}-q_{AA}^*(p)-k_{AA}^*(p+P))+\gamma(q_{AA}^*(p))+\kappa(k_{AA}^*(p+P))+g\\ &+P\cdot(\bar{\epsilon}-Q_{AA}^*(P)-k_{AA}^*(p+P))+\gamma(Q_{AA}^*(P))+G. \qquad (4.10)\end{aligned}$$

Note that $\theta_{AA}^{AB}(p,P,G)$ does not depend on g because the first period transfer affects the profits of AA- and AB-firms by the same amount. Table 4.1 summarizes the properties of the indifference points by reporting the signs of the partial derivatives with respect to the policy instruments.

Table 4.1: Properties of indifference points

Indifference point	Condition	$\partial\theta(\cdot)/\partial p$	$\partial\theta(\cdot)/\partial g$	$\partial\theta(\cdot)/\partial P$	$\partial\theta(\cdot)/\partial G$
$\theta_{AA}^{AB}(p,P,G)$	$\pi_{AA}=\pi_{AB}$	-	0	+	-
$\theta_{AA}^{BB}(p,g,P,G)$	$\pi_{AA}=\pi_{BB}$	+	-	+	-

Note that, for instance, $\partial\theta_{AA}^{AB}(\cdot)/\partial p = k_{AB}^*(\cdot)-k_{AA}^*(\cdot)<0$ implies the number of AA-firms to be increasing in p.

4.2.2 Social welfare

Welfare is based on the national concept of country A and is the sum of consumer surplus, producer surplus, environmental damage and the government budget. Since the price and quantity of the final good is constant, the consumer surplus is also constant and can be normalized to zero. The producer surplus is given by the profits of the firms, which are assumed to be entirely owned by citizens living in country A. Hence, carbon taxes cannot be used as an instrument to expropriate foreign firm owners.[19] Moreover, the model abstracts from any welfare losses that may arise due to the loss of jobs when firms relocate. Relaxing the ownership assumption or introducing welfare costs due to unemployment would

---

[19] When firms are (partially) owned by foreigners, Hoel (1997) shows that carbon taxes imply a transfer from the foreign firm owners to the government or local residents. Hence, in the presence of foreign firm ownership, we would expect carbon taxes to be higher than in this model.

only strengthen the results of this paper. Emissions are assumed to be a global public bad and a stock pollutant with constant marginal environmental damage ψ.[20] For simplicity, it is assumed that the damage occurs only in the long term, meaning in the second period, which adequately reflects the basic characteristics of global warming. Relaxing this assumption or assuming increasing instead of constant marginal environmental damages would not alter the qualitative results of this paper, but would complicate the analysis unnecessarily. Finally, the government budget consists of tax revenues minus transfers made to the firms, where both are assumed to be welfare-neutral.

The welfare contribution of firms depends on their location plan. For the three firm types, the contributions are given by

$$\begin{aligned} W_{AA}(p,P) =& 2-\kappa(k^*_{AA}(p+P))-\gamma(q^*_{AA}(p))-\gamma(Q^*_{AA}(P)) \\ &-\psi\cdot(2\bar{\epsilon}-2k^*_{AA}(p+P)-q^*_{AA}(p)-Q^*_{AA}(P)) \end{aligned} \tag{4.11}$$

$$W_{AB}(p,\theta) =2-\kappa(k^*_{AB}(p))-\gamma(q^*_{AB}(p))-\theta-\psi\cdot(2\bar{\epsilon}-k^*_{AB}(p)-q^*_{AA}(p)) \tag{4.12}$$

$$W_{BB}(\theta) =2-\theta-2\psi\bar{\epsilon}. \tag{4.13}$$

where tax payments and transfers have canceled out. Hence, the welfare contribution consists of the firms' revenue, the abatement costs, the relocation costs and the environmental damage. As long as the marginal abatement costs are below the marginal environmental damage, i.e. as long as $p \leq \psi$ and $P \leq \psi$, there is a clear welfare ranking of firms, that is $W_{AA}(p,P) > W_{AB}(p,\theta) > W_{BB}(\theta)$.[21] However, for a sufficiently large p (or P), this welfare ranking may alter because too high carbon prices distort the abatement decision, leading to inefficiently high abatement levels. Relative to both other types, AA-firms are more valuable in welfare terms because they put more effort in internalizing the environmental damage and do not incur relocation costs. While both AB- and BB-firms bear

---

[20] The parameter ψ can also be interpreted as political shadow price that the citizens of the home country accept for a marginal increase of emissions.

[21] If AB firms were to transfer their abatement capital to country B, then the welfare contribution of one AB firm would alter to $W_{AB}(p,\theta) = 2-\kappa(k^*_{AB}(p))-\gamma(q^*_{AB}(p))-\theta-\psi\cdot(2\bar{\epsilon}-2k^*_{AB}(p)-q^*_{AA}(p))$, meaning that there would be less environmental damage because the transferred abatement capital also lowers emissions in the second period when the firm is operating in country B. However, this would not change any of the qualitative results since the welfare ranking would be the same.

relocation costs, AB-firms internalize some of the environmental damage at least in the first period, implying their welfare contribution to be higher than that of BB-firms as long as they do not abate too much.

For the aggregated welfare, it must be distinguished between three cases. In the first case, there is no relocation, meaning that there are only AA-firms, in the second case, there are only AA- and BB-firms as depicted in Figure 4.1, and in the third case, there are only AA- and AB-firms as depicted in Figure 4.2. Aggregating the welfare components over the whole range of values for θ yields the following functions

$$W_{AA}^{AA}(p,P) = \int_{\underline{\theta}}^{\overline{\theta}} W_{AA}(p,P)\,d\theta = (\overline{\theta}-\underline{\theta})\cdot W_{AA}(p,P) \tag{4.14}$$

$$W_{AA}^{AB}(p,g,P,G,\theta) = \int_{\underline{\theta}}^{\theta_{AA}^{AB}(p,P,G)} W_{AB}(p,\theta)\,d\theta + \int_{\theta_{AA}^{AB}(p,P,G)}^{\overline{\theta}} W_{AA}(p,P)\,d\theta \tag{4.15}$$

$$W_{AA}^{BB}(p,g,P,G,\theta) = \int_{\underline{\theta}}^{\theta_{AA}^{BB}(p,g,P,G)} W_{BB}(\theta)\,d\theta + \int_{\theta_{AA}^{BB}(p,g,P,G)}^{\overline{\theta}} W_{AA}(p,P)\,d\theta \tag{4.16}$$

The overall welfare function that characterizes all relocation scenarios finally reads

$$W(\cdot) = \begin{cases} W_{AA}^{AA} & \text{if} \quad \pi_{AA}(p,P,g,G) \geq \pi_{AB}(p,g,\underline{\theta}) \quad \text{and} \quad \pi_{AA}(p,P,g,G) \geq \pi_{BB}(\underline{\theta}) \\ W_{AA}^{AB} & \text{if} \quad \pi_{AA}(p,P,g,G) < \pi_{AB}(p,g,\underline{\theta}) \quad \text{and} \quad \pi_{AB}(p,g,\underline{\theta}) \geq \pi_{BB}(\underline{\theta}) \\ W_{AA}^{BB} & \text{if} \quad \pi_{AA}(p,P,g,G) < \pi_{BB}(\underline{\theta}) \quad \text{and} \quad \pi_{AB}(p,g,\underline{\theta}) \leq \pi_{BB}(\underline{\theta}) \end{cases} \tag{4.17}$$

where the arguments of the functions have been partially omitted.

4.3 Policy analysis

This section analyzes the impact of restricting transfers, i.e. free allowances, in the second period, as was proposed by several NGOs during the stakeholder consultations of the European Commission, and derives optimality conditions for first and second period carbon prices. As a reference case, the analysis starts with the case where transfers are unrestricted in both periods.

4.3.1 Transfers are unrestricted in both periods

Since the welfare contribution of AA-firms is higher than that of AB-firms, it is a dominant strategy for the social planner to offer transfer payments in the second period only. By doing this, the regulator exclusively enhances the profits of AA-firms, not running the risk to attract firms playing a 'take the money and run'-strategy. Given that transfer payments are welfare-neutral and its availability is unlimited, the social planner uses them in order to raise the profits of AA-firms and to prevent all relocation for any carbon prices. Thus, by setting the second period transfer sufficiently high, the two conditions in the first line of the welfare function (4.17) are always fulfilled, implying the maximization problem to reduce to

$$\max_{p,P} W_{AA}^{AA}(p,P). \tag{4.18}$$

The FOCs when maximizing this welfare function with respect to the carbon prices, are given by[22]

$$\begin{aligned}
\frac{\partial W_{AA}^{AA}(\cdot)}{\partial p} =& (\overline{\theta}-\underline{\theta}) \cdot \big({q_{AA}^{*}}'(\cdot) \cdot \big(\psi - \gamma'(q_{AA}^{*}(\cdot))\big) + {k_{AA}^{*}}'(\cdot) \cdot \big(2\psi - \kappa'(k_{AA}^{*}(\cdot))\big)\big) \\
=& (\overline{\theta}-\underline{\theta}) \cdot \big({q_{AA}^{*}}'(\cdot) \cdot (\psi - p) + {k_{AA}^{*}}'(\cdot) \cdot \big(2\psi - p - P\big)\big) \overset{!}{=} 0 \qquad (4.19) \\
\frac{\partial W_{AA}^{AA}(\cdot)}{\partial P} =& (\overline{\theta}-\underline{\theta}) \cdot \big({Q_{AA}^{*}}'(\cdot) \cdot \big(\psi - \gamma'(Q_{AA}^{*}(\cdot))\big) + {k_{AA}^{*}}'(\cdot) \cdot \big(2\psi - \kappa'(k_{AA}^{*}(\cdot))\big)\big) \\
=& (\overline{\theta}-\underline{\theta}) \cdot \big({Q_{AA}^{*}}'(\cdot) \cdot (\psi - P) + {k_{AA}^{*}}'(\cdot) \cdot \big(2\psi - p - P\big)\big) \overset{!}{=} 0 \qquad (4.20)
\end{aligned}$$

where the profit maximization conditions of AA-firms from equations (4.4), (4.6) and (4.7) have been used. Both FOCs immediately lead to Proposition 1.

---

[22] One can show that the second order conditions for a maximum, i.e. a negative definite Hessian, are satisfied provided that the third derivatives of the abatement cost functions $\gamma(q)$ and $\kappa(k)$ are sufficiently small. This holds true for a wide range of frequently applied cost functions, in particular for quadratic ones where the third derivatives are zero. In the following, I assume that this condition is fulfilled, so that we have a global maximum.

Proposition 1

If transfer payments are unrestricted in both periods, then the regulator can implement the first best by setting the carbon prices in both periods equal to the marginal environmental damage and using the second period transfer to prevent all relocation.

Proof. Given that ${q^*_{AA}}'(\cdot) > 0$, ${Q^*_{AA}}'(\cdot) > 0$ and ${k^*_{AA}}'(\cdot) > 0$, it is easy to verify that the FOCs (4.19) and (4.20) are fulfilled for the optimal carbon prices $p = P = \psi$. Suppose that $p < \psi$, then we must have $2\psi - p - P < 0$ in order to satisfy FOC (4.19). This requires that $P > \psi$, which together with $2\psi - p - P < 0$ cannot satisfy the FOC (4.20). The same holds true for $p > \psi$, so that we can conclude that $p = P = \psi$ is the only combination satisfying both FOCs. □

This is the first best result.[23] The Pigouvian carbon prices internalize the negative environmental externality (Pigou 1920), potentially causing some relocation. The relocation problem can be perfectly addressed by the transfers in the second period, which are chosen such that there is no relocation. Since there are two perfect instruments to address the two negative welfare effects, namely the environmental damage and the relocation of firms, the Tinbergen (1952) rule is fulfilled. The same result was obtained by Mæstad (2001) in a static model. However, in contrast to Mæstad, this paper can analyze the effect when transfers are restricted in the second period which will be done in the following.

4.3.2 Transfers are restricted in the second period

Transfers in the second period may be restricted due to political pressure of lobby groups calling for a reduction of free allowances. In the following, I assume that $\overline{G}$ is the highest possible second period transfer. As before, it is a dominant strategy for the social planner to make use of this transfer as much as possible because AA-firms are more valuable for the regulator than AB-firms. The first period transfer g is unrestricted, implying that the regulator could avert any immediate relocation by offering a sufficiently high g. However, as was shown by Figure 4.2, increasing g only attracts firms playing a 'take the money and run'-strategy beyond a certain transfer level. Hence, g is an imperfect instrument to address the relocation problem adequately, which may require the social planner to move the carbon prices away from

---

[23] Note that this is only the first best from a national welfare perspective. Since the environmental damage of the foreign country is not taken into account, the global first best may require higher carbon prices.

the first best in order to increase the number of AA-firms and thus the welfare. The regulator can implement the first best as long as the profits of AA-firms at first best prices exceed the profit of the AB-firm with the lowest relocation cost, i.e. as long as $\pi_{AA}(p = \psi, g, P = \psi, \bar{G}) \geq \pi_{AB}(p = \psi, g, \underline{\theta})$. This is the case if $\underline{\theta}$ is sufficiently large. If $\underline{\theta}$ is not large enough, some firms will relocate later at first best prices. In this case, the maximization of the welfare from equation (4.17) reduces to

$$\max \left\{ \begin{array}{llll} \max\limits_{p,P,g} W_{AA}^{AB}(p, P, g, \bar{G}, \theta) & \text{s.t.} & \pi_{AB}(p, g, \theta) & \geq \pi_{BB}(\theta) \\ & & \pi_{AB}(p, g, \underline{\theta}) & \geq \pi_{AA}(p, g, P, \bar{G}) \\ \max\limits_{p,P,g} W_{AA}^{BB}(p, P, g, \bar{G}, \theta) & \text{s.t.} & \pi_{AB}(p, g, \theta) & \leq \pi_{BB}(\theta) \\ & & \pi_{BB}(\underline{\theta}) & \geq \pi_{AA}(p, g, P, \bar{G}) \end{array} \right\} \tag{4.21}$$

where the regulator takes the maximum of the result from the optimization problem of either $W_{AA}^{AB}(p, P, g, \bar{G}, \theta)$ or $W_{AA}^{BB}(p, P, g, \bar{G}, \theta)$. The Lagrangian for the first optimization problem in (4.21) is given by

$$\mathcal{L} = W_{AA}^{AB} - \lambda\big(\pi_{BB} - \pi_{AB}\big) - \mu\big(\pi_{AA} - \pi_{AB}\big) \tag{4.22}$$

where the arguments of the functions have been skipped. In the Appendix, I show that the first derivatives of the Lagrangian with respect to p and P when taking into account the first derivative with respect to g can be simplified to

$$\frac{\partial \mathcal{L}}{\partial p} = \underbrace{\big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p}}_{>0} + \underbrace{\big(\theta_{AA}^{AB} - \underline{\theta}\big)}_{>0}\frac{\partial W_{AB}}{\partial p} + \underbrace{\big(\bar{\theta} - \theta_{AA}^{AB}\big)}_{>0}\frac{\partial W_{AA}}{\partial p} \stackrel{!}{=} 0 \tag{4.23}$$

$$\frac{\partial \mathcal{L}}{\partial P} = \underbrace{\big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial P}}_{<0} + \underbrace{\big(\bar{\theta} - \theta_{AA}^{AB}\big)}_{>0}\frac{\partial W_{AA}}{\partial P} \stackrel{!}{=} 0. \tag{4.24}$$

Assuming $\mu = 0$ for a moment, it follows from equation (4.23) that increasing p has essentially two effects on the welfare. First, as indicated by the first term, it augments the number of AA-firms and lowers the number of AB-firms by the same amount because θ_{AA}^{AB} decreases in p. An increase in p reduces the profits of AB-firms more than those of AA-firms. Since the abatement capital investments of AA-firms are relatively higher, their actual emissions are lower, which is why their profits do not decrease as much as those of AB-firms. Second, an increase of p alters the abatement decisions and therefore the welfare contribution of both AB- and AA-firms as shown by the second and third term in equation (4.23). From (4.24), increasing P impacts welfare through the same channels, namely it decreases the number of AA-firms (first term) and alters their abatement decisions (second term) and welfare contributions. Hence, when choosing the carbon prices, the regulator trades off the number of AA-firms with the abatement decisions of the firms operating in country A.

In the Appendix, I prove that FOCs (4.23) and (4.24) can only be satisfied as long as p is above and P is below ψ. Raising p above ψ and lowering P below ψ increases the number of AA-firms and thus the welfare. However, moving the carbon prices away from the first best distorts the abatement decision of firms. Thus, in an interior solution the regulator exactly trades off the welfare gain by increasing the number of AA-firms with the welfare loss that stems from inefficient abatement decisions of AB- and AA-firms.

This qualitative result does not alter for $\mu > 0$ which holds true if the constraint $\pi_{AB}(p, g, \underline{\theta}) \geq \pi_{AA}(p, g, P, \bar{G})$ is binding. In this case, the regulator increases p and decreases P only until there is no relocation anymore, meaning that all firms permanently operate in country A.

Remember that AB-firms are more valuable than BB-firms in welfare terms for $p \leq \psi$. However, for a sufficiently large p, this welfare relation may reverse because $p > \psi$ leads to a distortion of AB-firms' abatement decision to the extent that AB-firms abate inefficiently many emissions. If this distortion is large enough, the welfare contribution of BB-firms is larger than that of AB-firms and the regulator chooses the solution of the second maximization problem of (4.21). I show in the Appendix that the FOCs of this problem are almost equivalent to the FOCs (4.23) and (4.24), implying the regulator to set $p > \psi > P$ as before in order to increase the number of AA-firms.[24] In contrast to the first solution, the regulator chooses the first period transfer such that the profit of BB-firms is marginally higher than that of AB-firms, so that there are only AA- and BB-firms. Proposition 2 summarizes the insights.

---

[24] In fact, the major difference is that the first term of both FOCs read $W_{BB} - W_{AA} + \mu$ instead of $W_{AB} - W_{AA} + \mu$.

Proposition 2
If transfer payments in the second period are restricted and it holds that $\underline{\theta} \geq \psi \cdot (k^*_{AB}(\psi) - k^*_{AA}(2\psi)) - \kappa(k^*_{AB}(\psi)) + \kappa(k^*_{AA}(2\psi)) + \psi \cdot (\bar{\epsilon} - k^*_{AA}(2\psi) - Q^*_{AA}(\psi)) + \gamma(Q^*_{AA}(\psi)) + \bar{G}$*, then the regulator implements the first best by setting carbon prices equal to the marginal environmental damage and preventing all relocation through transfers. If transfer payments in the second period are restricted and the above inequality does not hold true, then the regulator sets the first period carbon price above the marginal environmental damage, the second period carbon price below the marginal environmental damage and chooses the first period transfer depending on whether AB- or BB-firms have a higher welfare contribution.*

Proof. See Appendix. □

Proposition 2 displays the second best solution. Since transfers in the second period are restricted, the regulator must rely on first period transfers to address the relocation problem. However, the first period transfer is an imperfect instrument to induce firms to produce permanently in the regulating country because it only increases the number of AA-firms up to a certain point, but attracts firms playing a 'take the money and run'-strategy beyond that point. Thus, the only option for the regulator to increase the number of AA-firms is to choose a price path according to Proposition 2.

Proposition 2 also displays the lock-in effect. Raising the first period carbon price above the marginal environmental damage triggers higher investments in abatement capital. This reduces the negative impact of the second period carbon price on firms' profits, inducing some firms to produce permanently in country A. The lock-in effect was also illustrated by Schmidt and Heitzig (2014) in a time-continuous model with one firm. In their paper, the regulator offers transfers for a sufficiently long time horizon, thereby increasing the investment in abatement capital of the regulated firm and rendering relocation less attractive after transfer payments have ceased.[25] While in Schmidt and Heitzig (2014) the regulator prolongs the time horizon in which the firm receives transfers to create the lock-in effect, the lock-in effect in the present two period model requires raising p above ψ and, at the same time, adjusting g accordingly. Moreover, Schmidt and Heitzig (2014) analyze only one firm that finally produces permanently in country A, whereas this paper considers a continuum of firms. This

---

[25] A similar result is found in a setting with asymmetric information by Pollrich and Schmidt (2014), where the regulator offers contracts consisting of emission limits and transfers to a single firm. When the regulator cannot commit to transfers in the second period, she may optimally tighten the emission limit in the first period to trigger investments in abatement capital, inducing the firm to produce permanently in country A.

allows for deriving the optimal carbon prices from the trade-off between the relocation of some firms and distorting the abatement decision of the remaining firms.

Due to the distortion of the abatement decision, the regulator cannot spread the carbon prices infinitely. Note that the distortion for AA-firms primarily originates from the decision of the short-term abatement that depends on the carbon price in the corresponding period. Since the optimal investment in abatement capital depends on the sum of carbon prices $p + P$ as shown in equation (4.7), this decision may not be distorted for $p > \psi > P$. Hence, if there was no short-term abatement in the model, Lemma 1 summarizes the model implications.

Lemma 1

If transfer payments in the second period are restricted and if there is no short-term abatement option, then the regulator implements the first best by setting $p = 2\psi$, $P = 0$ and g such that there is no relocation.

Lemma 1 also holds true for other combinations of $p > \psi$ and $P < \psi$ as long as $p+P = 2\psi$ and as long as there is no delayed relocation, meaning that $\pi_{AA}(p, g, P, \bar{G}) \geq \pi_{AB}(p, g, \underline{\theta})$. In the absence of short-term abatement, any deviation of the carbon prices from ψ does not negatively affect the welfare contribution of AA-firms, enabling the regulator to spread carbon prices until there is no relocation anymore. As long as $p+P = 2\psi$, AA-firms choose the welfare optimal abatement capital investment so that there is no distortion with respect to the abatement decision. Since the investment decision in abatement capital is not distorted and there is no relocation, the regulator can implement the first best despite the fact that the second period transfer is restricted.

So far, the analysis has assumed first period transfers to be unlimited. However, offering high transfers to all firms may imply substantial transfers from the government to the firms which may lead to a budget deficit of the government. One could argue that alleviating the adverse effects of unilateral climate policy should at least be self-financing. This issue will be addressed in the following Section.

4.4 Self-financing climate policy

This Section extends the analysis by introducing a budget constraint in the regulator's maximization problem, which reflects the fact that transfers to the firms should be self-financing to the extent that they should be entirely financed by the revenues from carbon taxation. In terms of free allowances, the interpretation of the budget constraint becomes even clearer. In this case, the regulator can at most give 100% free allowances to the firms. If she was to compensate the firms more heavily by offering additional allowances, the regulator would need to take them from another sector, which may not be fully compensated. However, in the present model such sector does not exist, implying 100% to be the highest possible compensation rate.

In the following, it is assumed that the budget constraint must hold at least intertemporally. Thus, in principle, it is possible that firms receive the free allowances for *both* periods already in the first or only in the second period.[26] The tax revenue from either selling emissions permits or taxing carbon reads

$$T_{AA}(p,P) = p \cdot (\bar{\epsilon} - q^*_{AA}(p) - k^*_{AA}(p+P)) + P \cdot (\bar{\epsilon} - Q^*_{AA}(P) - k^*_{AA}(p+P)) \quad (4.25)$$

$$T_{AB}(p) = p \cdot (\bar{\epsilon} - q^*_{AB}(p) - k^*_{AB}(p)) \quad (4.26)$$

for one and each AA- or AB-firm. The analysis starts with the case in which second period transfers are unrestricted except for the budget constraint in order to contrast this case with the restricted scenario.

4.4.1 Transfers are unrestricted in both periods

When transfers are unrestricted in the second period, it is the dominant strategy for the regulator to use exclusively second period transfers since this only benefits AA-firms while not attracting AB-firms. The social planner collects the entire tax revenue from both periods and allocates uniform transfers to all firms that are still operating in the second period in country A subject to the budget constraint. Since there are no AB-firms, the maximization problem reduces to

$$\max \left\{ \begin{array}{llll} \max\limits_{p,P,G} W^{AA}_{AA}(p, g=0, P, G) & \text{s.t.} & \pi_{AA}(p, g=0, P, G) & \geq \pi_{BB}(\underline{\theta}) \\ & & G \cdot (\bar{\theta} - \underline{\theta}) & \leq T_{AA}(p,P) \cdot (\bar{\theta} - \underline{\theta}) \\ \max\limits_{p,P,G} W^{BB}_{AA}(p, g=0, P, G) & \text{s.t.} & \pi_{AA}(p, g=0, P, G) & \leq \pi_{BB}(\underline{\theta}) \\ & & G \cdot (\bar{\theta} - \theta^{BB}_{AA}) & \leq T_{AA}(p,P) \cdot (\bar{\theta} - \theta^{BB}_{AA}) \end{array} \right\} \quad (4.27)$$

---

[26] Given that banking and borrowing is not allowed, allocating free allowances of the second period already in the first one means that firms can sell their second period permits in the second period regardless of whether or not they are still operating in country A. Receiving free allowances for the first period only in the second one can be thought of as getting a rebate for carbon expenses in the first period conditional on still operating in country A in the second period.

where the second line of each maximization problem represents the budget constraint with $G \cdot (\bar{\theta} - \underline{\theta})$ and $G \cdot (\bar{\theta} - \theta_{AA}^{AB})$ being the total transfer expenditures of the government. Note that since the carbon tax payments and transfers do not differ across AA-firms, each firm gets its entire tax refunded by the transfer if the budget constraint is binding.[27] Even though firms anticipate this refunding, it is still individually rational for each firm to abate emissions until the marginal abatement costs equal the carbon prices.

If the budget constraint is not binding at first best carbon prices, then the regulator can implement the first best by setting $p = P = \psi$. This is the case when $\pi_{AA}(p = \psi, g = 0, P = \psi, G = T_{AA}(p, P)) \geq \pi_{BB}(\underline{\theta})$, i.e. when $\underline{\theta} \geq \kappa(k_{AA}^*(2\psi)) + \gamma(q_{AA}^*(\psi)) + \gamma(Q_{AA}^*(\psi))$. However, if the budget constraint at first best prices is binding, then the transfers are not high enough so that some firms will relocate. In this case, the regulator solves the second maximization problem in (4.27). As shown in the Appendix, the FOCs of the corresponding Lagrangian can be simplified to

$$\frac{\partial \mathcal{L}}{\partial p} = \underbrace{\left(W_{BB} - W_{AA} + \mu\right) \cdot \left(\frac{\partial \theta_{AA}^{BB}}{\partial p} - \frac{\partial T_{AA}}{\partial p}\right)}_{<0} + \underbrace{\left(\bar{\theta} - \theta_{AA}^{BB}\right)}_{>0} \frac{\partial W_{AA}}{\partial p} \overset{!}{=} 0 \tag{4.28}$$

$$\frac{\partial \mathcal{L}}{\partial P} = \underbrace{\left(W_{BB} - W_{AA} + \mu\right) \cdot \left(\frac{\partial \theta_{AA}^{BB}}{\partial P} - \frac{\partial T_{AA}}{\partial P}\right)}_{<0} + \underbrace{\left(\bar{\theta} - \theta_{AA}^{BB}\right)}_{>0} \frac{\partial W_{AA}}{\partial P} \overset{!}{=} 0 \tag{4.29}$$

where μ is the Lagrangian multiplier for the constraint $\pi_{AA}(\cdot) \leq \pi_{BB}(\underline{\theta})$. The first term of each FOC represents the welfare loss caused by more relocation in response to a higher carbon price. Relative to the FOCs (4.23) and (4.24) from Section 4.3, the effect of increasing carbon prices on AA-firms' profits and thus on θ_{AA}^{BB} is attenuated by the effect on the tax revenue $\frac{\partial T_{AA}}{\partial p}$ and $\frac{\partial T_{AA}}{\partial P}$. Since the tax payments of each firm are entirely refunded, but firms increase their abatement effort with rising carbon prices, we have $\frac{\partial \theta_{AA}^{BB}}{\partial i} - \frac{\partial T_{AA}}{\partial i} > 0$ for $i = p$, P, implying the number of AA-firms to decrease.[28] The second term of FOCs (4.28) and (4.29) denotes the change of the welfare contribution of all firms permanently operating in country A caused by a marginal increase of the carbon price. From both FOCs, Proposition 3 follows immediately.

---

[27] If the budget constraint is not binding, then the social planner may choose to refund less than the tax payment.

[28] Formally, we have $\frac{\partial \theta_{AA}^{BB}}{\partial p} - \frac{\partial T_{AA}}{\partial p} = -\frac{\partial \pi_{AA}}{\partial p} - \frac{\partial T_{AA}}{\partial p} = \gamma'(q_{AA}^*(p)) \cdot {q_{AA}^*}'(p) + \kappa'(k_{AA}^*(p+P)) \cdot {k_{AA}^*}'(p+P) > 0$.

Proposition 3
If the government budget needs to be balanced and if transfer payments are unrestricted in both periods, then the regulator can implement the first best as long as $\underline{\theta} \geq \kappa(k^*_{AA}(2\psi)) + \gamma(q^*_{AA}(\psi)) + \gamma(Q^*_{AA}(\psi))$*. Otherwise the regulator chooses the optimal carbon prices to be equal in both periods and to be below the marginal environmental damage.*

Proof. See Appendix. □

If the budget balance is binding, the regulator faces a trade-off between the relocation of some firms and distorting the abatement decisions of firms permanently operating in country A. As a solution, the regulator is willing to distort the abatement decision in order to prevent the relocation of some firms and therefore chooses carbon prices to be below the marginal environmental damage. A similar result was also reported by Mæstad (2001) in a static model.[29] However, Mæstad (2001) could not analyze the following case.

4.4.2 Transfers are restricted in the second period

This Section deals with the case where transfers are not only restricted by the budget constraint of the government, but second period transfers are also restricted due to political reasons. For simplicity, the regulator is assumed to use exclusively first period transfers, meaning that $G = 0$. The use of first period transfers may attract firms playing a 'take the money and run'-strategy. Analogously to the analysis in Section 4.3, we focus on the more interesting case where the first best is not feasible. In this case, the reduced maximization problem reads

$$\max \left\{ \begin{array}{llll} \max\limits_{p,P,g} W^{AB}_{AA}(p,P,g,G=0) & \text{s.t.} & \pi_{AB}(p,g,\theta) & \geq \pi_{BB}(\theta) \\ & & \pi_{AB}(p,g,\underline{\theta}) & \geq \pi_{AA}(p,g,P,G=0) \\ & & g \cdot (\bar{\theta} - \underline{\theta}) & \leq T(p,P) \\ \max\limits_{p,P,g} W^{BB}_{AA}(p,P,g,G=0) & \text{s.t.} & \pi_{AB}(p,g,\theta) & \leq \pi_{BB}(\theta) \\ & & \pi_{BB}(\underline{\theta}) & \geq \pi_{AA}(p,g,P,G=0) \\ & & g \cdot (\bar{\theta} - \theta^{BB}_{AA}) & \leq T_{AA}(p,P) \cdot (\bar{\theta} - \theta^{BB}_{AA}) \end{array} \right\} \tag{4.30}$$

---

[29] In contrast to this paper, Mæstad (2001) does not assume that the transfers must be self-financing, but analyzes a case where transfers are not available for the regulator.

where in the first optimization problem $T(p,P) \equiv (\theta_{AA}^{AB}(\cdot) - \underline{\theta}) \cdot T_{AB}(p) + (\bar{\theta} - \theta_{AA}^{AB}(\cdot)) \cdot T_{AA}(p,P)$ is the aggregate tax revenue when there are both AB- and AA-firms. Note that in this case, the tax and transfer system implicitly redistributes profits from AA- to AB-firms because it allocates the tax revenues generated from AA-firms in the second period uniformly to all firms that operate in country A in the first period. As shown in the Appendix, the first derivative of the Lagrangian for the first optimization problem of (4.30) with respect to p and P can be simplified to

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial p} =& \big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} + \big(\theta_{AA}^{AB} - \underline{\theta}\big)\frac{\partial W_{AB}}{\partial p} + \big(\bar{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial p} + \\ & \nu\left(\frac{\partial T}{\partial p} + \frac{\partial \pi_{AB}}{\partial p}(\bar{\theta} - \underline{\theta})\right) && \overset{!}{=} 0 \quad (4.31)\\ \frac{\partial \mathcal{L}}{\partial P} =& \big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial P} + \big(\bar{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial P} + \nu\frac{\partial T}{\partial P} && \overset{!}{=} 0 \quad (4.32)\end{aligned}$$

where ν is the Lagrangian multiplier for the budget constraint. The FOCs differ from the FOCs in equation (4.23) and (4.24) only with respect to the last term that contains ν. Thus, if the budget constraint is not binding, then we have $\nu = 0$ and the regulator optimally chooses the second best prices with $p > \psi > P$ as in Proposition 2. However, if the budget constraint is binding, the regulator needs to adjust the carbon prices. The direction of this adjustment depends on the impact of a price increase on the aggregate tax revenue. Exemplified on the second period carbon price, this impact is given by

$$\begin{aligned}\frac{\partial T}{\partial P} =& \underbrace{(\bar{\theta} - \theta_{AA}^{AB})(\bar{\epsilon} - Q_{AA}^{*} - k_{AA}^{*})}_{>0} \\ & \underbrace{-(\bar{\theta} - \theta_{AA}^{AB})((p+P)k_{AA}^{*'} + PQ_{AA}^{*'})}_{<0} \underbrace{+\frac{\partial \theta_{AA}^{AB}}{\partial P}(T_{AA} - T_{AB})}_{<0}. \qquad (4.33)\end{aligned}$$

A marginal increase of P has three effects on the tax revenue which are illustrated by the three terms in equation (4.33). First, it increases the tax revenue of all AA-firms by their actual emissions. Second, it increases the short-term and long-term abatement which reduces the tax revenues of all AA-firms. Third, it lowers the number of AA-firms and increases the number of AB-firms, implying the aggregate tax revenue to shrink. Due to these opposing effects, the overall effect is indeterminate.

If an increase of P augments the aggregate tax revenue, then it follows from equation (4.32) that the government will raise P above the second best because this raises the revenue, which enables the government to increase transfers to avert immediate relocation.[30] However, if the opposite holds true, then the regulator chooses a third best P which is below the second best.

Concerning the first period price, the last term of equation (4.31) indicates that there are two different effects for a change in p. First, as before, a higher p either increases or decreases the aggregate tax revenue.[31] Second, increasing p also reduces the profits of AB-firms, meaning that higher transfers are required to avert immediate relocation. This effect alone would result in a reduction of p relative to the second best price. However, the overall effect is also indeterminate because the second effect could be exceeded by a potential increase of tax revenues from raising p provided that this increase is sufficiently large.

For both prices it holds that departing from the second best prices increases the welfare loss even further because it leads to more relocation and to higher distortions of the abatement decisions. If this welfare loss is very substantial, then the social planner may pursue a different strategy which does not aim at attracting AB-firms. In this case, the first derivatives of the Lagrangian for the second optimization problem in (4.30) with respect to p and P can be simplified to

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial p} &= \underbrace{\left(W_{BB} - W_{AA} + \mu\right)\left(\frac{\partial \theta^{BB}_{AA}}{\partial p} - \frac{\partial T_{AA}}{\partial p}\right)}_{<0} + \underbrace{\left(\bar{\theta} - \theta^{BB}_{AA}\right)}_{>0}\frac{\partial W_{AA}}{\partial p} \\ &\quad - \lambda\left(\frac{\partial \pi^{AB}_{AA}}{\partial p} + \frac{\partial T_{AA}}{\partial p}\right) \overset{!}{=} 0\end{aligned} \tag{4.34}$$

$$\frac{\partial \mathcal{L}}{\partial P} = \underbrace{\left(W_{BB} - W_{AA} + \mu\right)\left(\frac{\partial \theta^{BB}_{AA}}{\partial P} - \frac{\partial T_{AA}}{\partial P}\right)}_{<0} + \underbrace{\left(\bar{\theta} - \theta^{BB}_{AA}\right)}_{>0}\frac{\partial W_{AA}}{\partial P} - \lambda\frac{\partial T_{AA}}{\partial P} \overset{!}{=} 0 \tag{4.35}$$

where λ is the multiplier for the constraint $\pi_{BB}(\cdot) \geq \pi_{AB}(\cdot)$. If the budget constraint is not binding, then it can be shown that the results correspond to those reported in Proposition 2.[32] However, in the more interesting case when the budget constraint is binding, the social planner may pursue two different strategies, depending on whether

---

[30] Note that it is also possible that the social planner raises the second period price above the marginal environmental damage in order to raise more tax revenue.

[31] Note that $\frac{\partial T}{\partial p}$ slightly differs from equation (4.33) because an increase of p also impacts the tax revenues of AB firms. However, the basic trade-offs are equivalent to those reported above.

[32] To see this, note that $\frac{\partial \mathcal{L}}{\partial g} = W_{AA} - W_{BB} - \lambda - \mu + \nu$. If the budget constraint is not binding, we have $\nu = 0$. Solving equation $\frac{\partial \mathcal{L}}{\partial g} = 0$ for λ and plugging in into equations (4.34) and (4.35) leads to equations (A.13) and (A.14), implying that we obtain the same results as in Proposition 2.

or not the constraint $\pi_{BB}(\cdot) \geq \pi_{AB}(\cdot)$ is binding.

First, if this constraint is binding, then $\lambda > 0$ and we have a similar case as was explained before Proposition 2. In short, since the first period carbon price distorts the abatement decisions of AB-firms so much that $W_{BB} > W_{AB}$, the regulator uses transfers only up to the point where the profits of AB-firms are marginally below those of BB-firms. Since the budget constraint is binding, transfers are endogenous and depend on the carbon prices in both periods. Thus, the regulator chooses the third best carbon prices such that there are no AB-firms. It is hard to make any qualitative statement regarding the level of third best prices in this case because of the different impacts on firms' profits and tax revenues. However, equation (4.35) indicates that the third best P is below ψ as long as an increase in P raises the aggregate tax revenues.

The second strategy refers to the case where the tax revenues and thus the transfers are not large enough to attract AB-firms such that the constraint $\pi_{BB} \geq \pi_{AB}$ is not binding. In this case, we have $\lambda = 0$ and the FOCs (4.34) and (4.35) reduce to the FOCs (4.28) and (4.29) from Section 4.4.1. Thus, the social planner trades off the relocation of some firms and the efficiency of the abatement decisions and chooses $p = P < \psi$ as reported in Proposition 3.

Summing up, the social planner has three pricing strategies where one includes AB- and AA-firms while the other two focus on BB- and AA-firms. The properties of these strategies are summarized in Proposition 4.

Proposition 4

If the government's budget needs to be balanced, if transfer payments are restricted to zero in the second period and if the first best and second best are not feasible, then the regulator chooses the welfare maximizing strategy out of the strategies in Table 4.2 and implements the third best prices accordingly:

Table 4.2: Third best strategies

Strategy	Firms	Price p	Price P	
			Tax revenue increases in P	
			no	yes
Strategy 1	AA and AB	$p \lesseqgtr \psi$	$P \lesseqgtr \psi$	$P < \psi$
Strategy 2	AA and BB	$p \lesseqgtr \psi$	$P \lesseqgtr \psi$	$P < \psi$
Strategy 3	AA and BB	$p < \psi$	$p = P < \psi$	

Proof. See Appendix. □

Out of the three strategies from Proposition 4, the regulator chooses the one that yields the highest welfare level. Since a qualitative statement regarding the welfare ranking of the strategies is not possible, the following numerical example sheds some light on the choice of the social planner.

Numerical example

The abatement cost functions are assumed to be quadratic and given by $\gamma(q) = (1/2)c_q q^2$ and $\kappa(k) = (1/2)c_k k^2$. For quadratic functions, it can be shown that the welfare contribution of AB-firms always exceeds that of BB-firms in the range of plausible carbon prices.[33] Hence, it is never optimal for the regulator to pursue strategy 2 from Proposition 4, which is why the focus is on the remaining strategies.

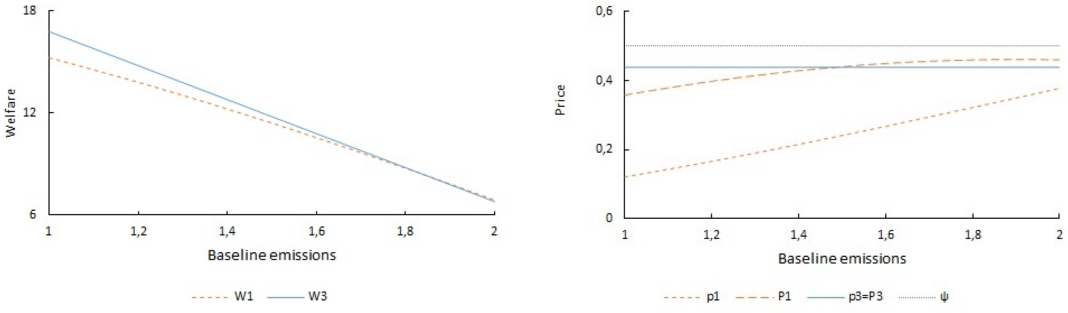
Remember that strategy 1 involves a deviation from second best prices because transfers are not sufficiently high to attract AB-firms. If the profit difference between AB-firms and BB-firms for second best prices and the respective transfers is small, the carbon prices need to be adjusted only slightly, implying the associated welfare loss to be rather moderate. However, if the profit difference is large, the regulator needs to distort the prices substantially, which leads to a sizable welfare loss, in particular due to the loss of AA-firms. In this case, the welfare under strategy 3, that contains exclusively AA-firms and BB-firms, may be higher.

When choosing between strategy 1 or strategy 3, the regulator faces a trade-off between distorting the carbon prices, but attracting AB-firms and having only BB-firms, but potentially lower carbon price distortions. The choice between both strategies depends, in particular, on the level of the transfer and thus on the tax revenues. As was shown above, strategy 1 entails a redistribution of profits from AA-firms to AB-firms, so that one would expect the regulator to prefer strategy 1 over strategy 3 for high tax revenues, whereas the reverse holds true for low tax revenues. Tax revenues are increasing in baseline emissions $\bar{\epsilon}$. Assuming $c_q = c_k = 1$, $\underline{\theta} = 0$, $\bar{\theta} = 10$ and $\psi = 0.5$, Figure 4.3 depicts the welfare levels and the carbon prices for strategy 1 and 3 for $\bar{\epsilon}$ ranging from 1 to 2.

---

[33] The reason is that the welfare contribution of AB-firms $W_{AB}(p, \theta)$ exceeds $W_{BB}(\theta)$ as long as $0 < p < 2\psi$. Since carbon prices $p + P > 2\psi$ distort the investment decision of AA-firms, it is never optimal to choose $p + P > 2\psi$. Thus, it follows that p is always smaller than 2ψ and therefore $W_{AB}(p, \theta) > W_{BB}(\theta)$.

Figure 4.3: Comparison of tax and quantity regulation


(a) Welfare (b) Prices

In the left panel of Figure 4.3, it can be seen that the welfare levels of both strategies are decreasing in the baseline emissions $\bar{\epsilon}$ because higher emissions cause more damage from global warming. As was expected, for low values of $\bar{\epsilon}$, the welfare from strategy 3 outweighs that of strategy 1 whereas this relationship reverses for sufficiently large $\bar{\epsilon}$. The reason for this can be inferred from the right panel of Figure 4.3, which shows the carbon prices of both strategies. While the carbon prices of strategy 3 remain constant[34], those of strategy 1 start from a rather low level for small values of $\bar{\epsilon}$ and increase with higher values of $\bar{\epsilon}$. If $\bar{\epsilon}$ is low, so are the tax revenues and the transfers to the firms. Thus, to attract AB-firms, it is necessary to reduce p substantially relative to the second best prices. A small p implies low investments in abatement capital which is why the regulator also wants to set P rather low in order to prevent the relocation of too many AA-firms. Higher values of $\bar{\epsilon}$ increase the tax revenues and transfers to the firms, allowing the regulator to raise both carbon prices towards the second best. For sufficiently large $\bar{\epsilon}$, the regulator finally prefers strategy 1 over strategy 3.

4.5 Conclusion

This paper studied the consequences of a restriction of free allowances in the near term as was demanded by many members of the civil society during the stakeholder consultations of the European Commission regarding the future of the carbon leakage list within the EU ETS. Allocating free allowances has not only distributive consequences, but also allocative implications to the extent that it alters the profits of firms and thus their location decision.

---

[34] Constant carbon prices imply the abatement effort of firms to remain constant as well, causing the welfare level of strategy 3 to decline linearly in $\bar{\epsilon}$.

Using a stylized two-period two-country framework with mobile firms, this paper shows that when transfers or free allowances are unrestricted in both periods, the social planner can perfectly address the relocation problem and implements the first best by setting carbon prices equal to the marginal environmental damage and preventing any relocation by sufficiently high transfer payments. However, if transfers in the second period are restricted, the first best may not be achieved because first period transfers are an imperfect instrument for inducing firms to produce permanently in the regulating country. For a sufficiently high first period transfer, some firms will play a 'take the money and run'-strategy and relocate in the second period. The social planner addresses this problem by raising the first period carbon price above the marginal environmental damage, which creates a lock-in effect. It triggers higher investments in abatement capital, which benefits firms permanently producing in the regulated country disproportionately more than those that planned to relocate later. In the second best, the planner faces a trade-off between locking some firms in and distorting the abatement decisions of firms, resulting in strictly lower welfare levels relative to the first best.

Section 4.4 requires the government's budget to be balanced. If the budget constraint is binding and transfers in the second period are not restricted, then the regulator optimally sets both carbon prices to be equal and below the marginal environmental damage, trading-off the distortion of firms' abatement decision and the relocation pressure. If transfers in the second period are restricted, the regulator may choose essentially between two strategies. Either she chooses the carbon prices to be equal and below the marginal environmental damage as in the unrestricted scenario or she attempts to attract AB-firms and sets the carbon prices accordingly.

When transfers are not restricted in the second period, this paper derives the same results as Mæstad (2001). However, since Mæstad (2001) uses a static model, he cannot analyze the implications of phasing out free allowances in the middle term for the carbon price path and thus cannot obtain the lock-in effect. The lock-in effect was shown by Schmidt and Heitzig (2014) in a time-continuous model with one firm. While in Schmidt and Heitzig (2014), the regulator locks the firm in by offering transfers for a sufficiently long time horizon which increases the investments in abatement capital and induces the firm to produce permanently in the regulating country, the lock-in effect in this paper results from raising the carbon price in the first period. Since in Schmidt and Heitzig (2014) there is only one firm, they cannot derive the trade-off between the relocation of some firms and the distortion of the abatement decision of the remaining firms, which characterizes the second and third best results of this paper.

The policy implications of this paper are twofold. First, it argues for maintaining a high share of free emission allowances for energy-intensive firms that are subject to relocation and therefore opposes the position of the stakeholders calling for a phasing out in the near term. By restricting the share of free allowances in the future, the regulator loses one powerful instrument that perfectly addresses the relocation problem caused by carbon pricing. Hence, free allowances should be maintained as long as there are substantial carbon price differences between the countries despite a potential overcompensation of firms. In order to reduce the overallocation, this paper suggests to narrow the allocation of free allowances to the most mobile firms, i.e. the firms with the lowest relocation costs. The European Union partially follows this strategy in recent years to the extent that in the third trading period of the EU ETS, local electricity producers do not get any free allowances and that there are special provisions for firms with high relocation risk in form of the carbon leakage list. Currently, the European Commission seems to pursue a refinement of that list and has proposed a differentiated allocation scheme that takes the sector-specific relocation risk into account. The second implication refers to the choice of carbon prices (or the emissions cap) provided that free allowances are to be phased out in the near future. In this case, the EU ETS should strive for a high carbon price in the near term in order to trigger investments in abatement capital and to create the lock-in effect. Thus, recently implemented measures aiming at raising the carbon price such as backloading or proposed measures such as the introduction of a floor price go in the right direction.

For future research, this paper could be extended towards several directions. First, it may take into account the loss of jobs that is associated with the relocation of firms and which is the major argument in the political debate. Accounting for this would only strengthen the result of this paper, implying unrestricted transfers to become even more important. Second, the model could account for foreign firm ownership of domestic firms. While taxes imply a redistribution from foreign owners to the government or local residents, transfers or free allowances work in the other direction, meaning that there are further trade-offs that need to be considered for the optimal tax and transfer scheme. Third, this model restricted the regulator to use uniform taxes and transfers because firm-specific relocation costs were private information. However, the regulator could also make use of more sophisticated tax and transfer schemes as suggested by the mechanism design literature. The paper of Pollrich and Schmidt (2014) goes in this direction. Using a different setting, they also conclude that the regulator should require a high first period carbon price or a tough emission reduction target in order to prevent the relocation of the firm permanently.

4.A Appendix

Proof of Proposition 2

The Kuhn-Tucker conditions for the Lagrangian from equation (4.22) read

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial p} =& \big(W_{AB} - W_{AA}\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} + \big(\theta_{AA}^{AB} - \underline{\theta}\big)\frac{\partial W_{AB}}{\partial p} + \big(\overline{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial p} \\
& + \lambda \frac{\partial \pi_{AB}}{\partial p} - \mu\left(\frac{\partial \pi_{AA}}{\partial p} - \frac{\partial \pi_{AB}}{\partial p}\right) && \overset{!}{=} 0 \qquad \text{(A.1)} \\
\frac{\partial \mathcal{L}}{\partial P} =& \big(W_{AB} - W_{AA}\big)\frac{\partial \theta_{AA}^{AB}}{\partial P} + \big(\overline{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial P} - \mu \frac{\partial \pi_{AA}}{\partial P} && \overset{!}{=} 0 \qquad \text{(A.2)} \\
\frac{\partial \mathcal{L}}{\partial g} =& \lambda \frac{\partial \pi_{AB}}{\partial g} - \mu \underbrace{\left(\frac{\partial \pi_{AA}}{\partial g} - \frac{\partial \pi_{AB}}{\partial g}\right)}_{=0} && \overset{!}{=} 0 \qquad \text{(A.3)} \\
& \lambda(\pi_{BB} - \pi_{AB}) + \mu(\pi_{AA} - \pi_{AB}) && = 0 \qquad \text{(A.4)} \\
& \lambda, \mu && \geq 0 \qquad \text{(A.5)}
\end{aligned}$$

Since $\frac{\partial \pi_{AB}}{\partial g} = 1 > 0$, FOC (A.3) can only be satisfied for $\lambda = 0$. Using $\frac{\partial \theta_{AA}^{AB}}{\partial p} = \frac{\partial \pi_{AB}}{\partial p} - \frac{\partial \pi_{AA}}{\partial p}$ and $\frac{\partial \theta_{AA}^{AB}}{\partial P} = -\frac{\partial \pi_{AA}}{\partial P}$ immediately leads to equations (4.23) and (4.24) which are the starting points for the proof of Proposition 2.

First, note that at $p = P = \psi$, we have $\frac{\partial W_{AB}}{\partial p}\big|_{p=P=\psi} = \frac{\partial W_{AA}}{\partial p}\big|_{p=P=\psi} = \frac{\partial W_{AA}}{\partial P}\big|_{p=P=\psi} = 0$. Since $\frac{\partial \theta_{AA}^{AB}}{\partial P} > 0$, $\frac{\partial \theta_{AA}^{AB}}{\partial p} < 0$ and $(W_{AB} - W_{AA} - \mu) < 0$, it follows that $\frac{\partial \mathcal{L}}{\partial p}\big|_{p=P=\psi} = \big(W_{AB} - W_{AA} - \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} > 0$ and $\frac{\partial \mathcal{L}}{\partial P}\big|_{p=P=\psi} = \big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial P} < 0$. Hence, a marginal increase (decrease) of p (P) raises the welfare at $p = P = \psi$.

Second, given that $\frac{\partial \theta_{AA}^{AB}}{\partial p} < 0$ and assuming for a moment that $\big(W_{AB} - W_{AA} + \mu\big) < 0$, we must have $\frac{\partial W_{AA}}{\partial P} = {Q_{AA}^{*}}'(\psi - P) + {k_{AA}^{*}}'(2\psi - p - P) > 0$ to satisfy equation (4.24). For $p \geq \psi$, this requires P to be smaller than ψ. As $\big(W_{AB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} > 0$, we must have $p > \psi$ for $P \leq \psi$ to satisfy FOC (4.23). This leads to $p > \psi > P$. Moreover, we can exclude the case $P > \psi > p$ because $P > \psi$ requires $2\psi - p - P > 0$ to satisfy equation (4.24), whereas $p < \psi$ requires $2\psi - p - P < 0$ to satisfy FOC (4.23), leading to a contradiction. Thus, we must have $p > \psi > P$ to satisfy both FOCs.

Third, to show that $\big(W_{AB} - W_{AA} + \mu\big) < 0$, note that for $\mu > 0$ we must have $\pi_{AA}(p, g, P, \bar{G}) = \pi_{AB}(p, g, \underline{\theta})$. If $\big(W_{AB} - W_{AA} + \mu\big) > 0$, then we would have $p < \psi < P$ for the same reasons as above. But then $\pi_{AA}(p < \psi, g, P > \psi, \bar{G}) = \pi_{AB}(p < \psi, g, \underline{\theta})$ implies that $\pi_{AA}(\psi, g, \psi, \bar{G}) > \pi_{AB}(\psi, g, \underline{\theta})$, meaning that the first best was feasible. Hence, we must have $\big(W_{AB} - W_{AA} + \mu\big) < 0$.

The Lagrangian for the second maximization problem of (4.21) is given by

$$\mathcal{L} = W_{AA}^{BB} - \lambda\big(\pi_{AB} - \pi_{BB}\big) - \mu\big(\pi_{AA} - \pi_{BB}\big) \tag{A.6}$$

and the Kuhn-Tucker conditions read

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial p} &= \big(W_{BB} - W_{AA}\big)\frac{\partial \theta_{AA}^{BB}}{\partial p} + \big(\overline{\theta} - \theta_{AA}^{BB}\big)\frac{\partial W_{AA}}{\partial p} - \lambda\frac{\partial \pi_{AB}}{\partial p} - \mu\frac{\partial \pi_{AA}}{\partial p} && \overset{!}{=} 0 \qquad \text{(A.7)}\\
\frac{\partial \mathcal{L}}{\partial P} &= \big(W_{BB} - W_{AA}\big)\frac{\partial \theta_{AA}^{BB}}{\partial P} + \big(\overline{\theta} - \theta_{AA}^{BB}\big)\frac{\partial W_{AA}}{\partial P} - \mu\frac{\partial \pi_{AA}}{\partial P} && \overset{!}{=} 0 \qquad \text{(A.8)}\\
\frac{\partial \mathcal{L}}{\partial g} &= \big(W_{BB} - W_{AA}\big)\frac{\partial \theta_{AA}^{BB}}{\partial g} - \lambda\frac{\partial \pi_{AB}}{\partial g} - \mu\frac{\partial \pi_{AA}}{\partial g} && \overset{!}{=} 0 \qquad \text{(A.9)}\\
&\lambda(\pi_{AB} - \pi_{BB}) + \mu(\pi_{AA} - \pi_{BB}) && \overset{!}{=} 0 \qquad \text{(A.10)}\\
&\lambda, \mu && \geq 0 \qquad \text{(A.11)}
\end{aligned}$$

Since $\frac{\partial \pi_{AA}}{\partial g} = \frac{\partial \pi_{AB}}{\partial g} = 1$ and $\frac{\partial \theta_{AA}^{BB}}{\partial g} = -\frac{\partial \pi_{AA}}{\partial g} = -1$, it follows from equation (A.9) that

$$\lambda = W_{AA} - W_{BB} - \mu > 0. \tag{A.12}$$

In order to satisfy equation (A.10), we must have $\pi_{AB} = \pi_{BB}$, meaning that the regulator chooses g such that firms are indifferent between relocating later or immediately. Note that $\pi_{AB} = \pi_{BB}$ implies $\theta_{AA}^{BB} = \theta_{AA}^{AB}$. Plugging in equation (A.12) into equation (A.7) and using the facts that $\frac{\partial \theta_{AA}^{BB}}{\partial p} = -\frac{\partial \pi_{AA}}{\partial p}$ and $\frac{\partial \theta_{AA}^{AB}}{\partial p} = \frac{\partial \pi_{AB}}{\partial p} - \frac{\partial \pi_{AA}}{\partial p}$ immediately leads to

$$\frac{\partial \mathcal{L}}{\partial p} = \big(W_{BB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial p} + \big(\overline{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial p} \overset{!}{=} 0. \tag{A.13}$$

Using $\frac{\partial \theta_{AA}^{BB}}{\partial P} = -\frac{\partial \pi_{AA}}{\partial P} = \frac{\partial \theta_{AA}^{AB}}{\partial P}$ for equation (A.8) yields

$$\frac{\partial \mathcal{L}}{\partial P} = \big(W_{BB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{AB}}{\partial P} + \big(\overline{\theta} - \theta_{AA}^{AB}\big)\frac{\partial W_{AA}}{\partial P} \overset{!}{=} 0. \tag{A.14}$$

Equations (A.13) and (A.14) are almost equivalent to the FOCs (4.23) and (4.24). Hence, for the same reasons as above, we must have $p > \psi > P$.

Proof of Proposition 3

The Lagrangian of the second maximization problem of (4.27) is given by

$$\mathcal{L} = W_{AA}^{BB} - \mu(\pi_{AA} - \pi_{BB}) - \nu(G - T_{AA}) \tag{A.15}$$

where the term $(\bar{\theta} - \theta_{AA}^{BB})$ in the budget constraint has canceled out. The Kuhn-Tucker conditions read

$$\frac{\partial \mathcal{L}}{\partial p} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial p} + (\bar{\theta} - \theta_{AA}^{BB})\frac{\partial W_{AA}}{\partial p} - \mu\frac{\partial \pi_{AA}}{\partial p} + \nu\frac{\partial T_{AA}}{\partial p} \overset{!}{=} 0 \tag{A.16}$$

$$\frac{\partial \mathcal{L}}{\partial P} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial P} + (\bar{\theta} - \theta_{AA}^{BB})\frac{\partial W_{AA}}{\partial P} - \mu\frac{\partial \pi_{AA}}{\partial P} + \nu\frac{\partial T_{AA}}{\partial P} \overset{!}{=} 0 \tag{A.17}$$

$$\frac{\partial \mathcal{L}}{\partial G} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial G} - \mu\frac{\partial \pi_{AA}}{\partial G} - \nu \overset{!}{=} 0 \tag{A.18}$$

$$\mu(\pi_{AA} - \pi_{BB}) + \nu(G - T_{AA}) \overset{!}{=} 0 \tag{A.19}$$

$$\mu, \nu \geq 0 \tag{A.20}$$

Taking into account that $\frac{\partial \theta_{AA}^{BB}}{\partial G} = -1$ and $\frac{\partial \pi_{AA}}{\partial G} = 1$, it follows from equation (A.18) that $\nu = W_{AA} - W_{BB} - \mu$. Substituting ν in equations (A.16) as well as (A.17) and bearing in mind that $\frac{\partial \theta_{AA}^{BB}}{\partial i} = -\frac{\partial \pi_{AA}}{\partial i}$ for $i = p,\ P,\ G$ leads to equations (4.28) and (4.29) from the text. Moreover, note that

$$\frac{\partial \theta_{AA}^{BB}}{\partial p} - \frac{\partial T_{AA}}{\partial p} = p(q_{AA}^{*'} + k_{AA}^{*'}) + P(Q_{AA}^{*'} + k_{AA}^{*'}) > 0. \tag{A.21}$$

For the first part of Proposition 3, note that if the regulator sets the highest possible transfer $G = T_{AA}(p, P)$, then the profit of an AA firm reads $\pi_{AA}^{*}(p, P, g = 0, G = T_{AA}(p, P)) = 2 - \kappa(k_{AA}^{*}(p + P)) - \gamma(q_{AA}^{*}(p)) - \gamma(Q_{AA}^{*}(P))$. Thus, there is no relocation for first-best prices as long as $\underline{\theta} \geq \kappa(k_{AA}^{*}(2\psi)) + \gamma(q_{AA}^{*}(\psi)) + \gamma(Q_{AA}^{*}(\psi))$ and the regulator can implement the first-best.

For the second part, if $\underline{\theta} < \kappa(k_{AA}^{*}(2\psi)) + \gamma(q_{AA}^{*}(\psi)) + \gamma(Q_{AA}^{*}(\psi))$, the regulator optimally reduces the carbon prices. At $p = P = \psi$, we have $\frac{\partial W_{AA}}{\partial p}\big|_{p=P=\psi} = \frac{\partial W_{AA}}{\partial P}\big|_{p=P=\psi} = 0$, meaning that $\frac{\partial \mathcal{L}}{\partial p}\big|_{p=P=\psi} = \frac{\partial \mathcal{L}}{\partial P}\big|_{p=P=\psi} = \big(W_{BB} - W_{AA} + \mu\big)\frac{\partial \theta_{AA}^{BB}}{\partial i} < 0$ for $i = p,\ P$. Since $\frac{\partial \theta_{AA}^{BB}}{\partial p} > 0$ as well as $\frac{\partial \theta_{AA}^{BB}}{\partial P} > 0$ and $W_{BB} - W_{AA} + \mu < 0$, we must have $\frac{\partial W_{AA}}{\partial p} > 0$ and $\frac{\partial W_{AA}}{\partial P} > 0$ to satisfy the FOCs (4.28) and (4.29). This requires $p + P < 2\psi$. Since the FOCs (4.28) and (4.29) are symmetric, there is a unique welfare maximum with $p = P < \psi$.

Proof of Proposition 4

The Lagrangian for the first optimization problem in (4.30) reads

$$\mathcal{L} = W_{AA}^{AB} - \lambda(\pi_{BB} - \pi_{AB}) - \mu(\pi_{AA} - \pi_{AB}) - \nu(g(\bar{\theta} - \underline{\theta}) - T) \tag{A.22}$$

and the Kuhn-Tucker conditions are given by

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial p} =& (W_{AB} - W_{AA})\frac{\partial \theta_{AA}^{AB}}{\partial p} + (\theta_{AA}^{AB} - \underline{\theta})\frac{\partial W_{AB}}{\partial p} + (\bar{\theta} - \theta_{AA}^{AB})\frac{\partial W_{AA}}{\partial p} + \\
& \lambda\frac{\partial \pi_{AB}}{\partial p} - \mu\left(\frac{\partial \pi_{AA}}{\partial p} - \frac{\partial \pi_{AB}}{\partial p}\right) + \nu\frac{\partial T}{\partial p} && \overset{!}{=} 0 \qquad \text{(A.23)} \\
\frac{\partial \mathcal{L}}{\partial P} =& (W_{AB} - W_{AA})\frac{\partial \theta_{AA}^{AB}}{\partial P} + (\bar{\theta} - \theta_{AA}^{AB})\frac{\partial W_{AA}}{\partial P} - \mu\frac{\partial \pi_{AA}}{\partial P} + \nu\frac{\partial T}{\partial P} && \overset{!}{=} 0 \qquad \text{(A.24)} \\
\frac{\partial \mathcal{L}}{\partial g} =& \lambda\frac{\partial \pi_{AB}}{\partial g} - \mu\left(\frac{\partial \pi_{AA}}{\partial g} - \frac{\partial \pi_{AB}}{\partial g}\right) - \nu(\bar{\theta} - \underline{\theta}) && \overset{!}{=} 0 \qquad \text{(A.25)} \\
& \lambda(\pi_{BB} - \pi_{AB}) + \mu(\pi_{AA} - \pi_{AB}) + \nu(g(\bar{\theta} - \underline{\theta}) - T) && \overset{!}{=} 0 \qquad \text{(A.26)} \\
& \lambda, \mu, \nu && \geq 0 \qquad \text{(A.27)}
\end{aligned}$$

Taking into account that $\frac{\partial \pi_{AB}}{\partial g} = 1$ and that $\frac{\partial \pi_{AA}}{\partial g} - \frac{\partial \pi_{AB}}{\partial g} = 0$, equation (A.25) can be reduced to $\lambda = \nu(\bar{\theta} - \underline{\theta})$. Plugging this in into equation (A.23) and performing the same transformations as in the proof of Proposition 2 leads to equation (4.31) from the text. For the first line in Table 4.2 from Proposition 4 note that the sign of the last term of equation (4.31) is indeterminate. Hence, the third best p can be either above or below ψ. For the last entry in the first line, the last term of equation (4.32) is certainly negative, implying the term $\frac{\partial W_{AA}}{\partial P}$ to be positive which holds only true for $P < \psi$ for the same reasons as pointed out in the proof of Proposition 2. However, if $\frac{\partial T(p,P)}{\partial P} > 0$, then P can be below or above ψ.

The Lagrangian for the second optimization problem in (4.30) reads

$$\mathcal{L} = W_{AA}^{BB} - \lambda(\pi_{AB} - \pi_{BB}) - \mu(\pi_{AA} - \pi_{BB}) - \nu(g - T_{AA}) \tag{A.28}$$

and the Kuhn-Tucker conditions are given by

$$\frac{\partial \mathcal{L}}{\partial p} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial p} + (\overline{\theta} - \theta_{AA}^{BB})\frac{\partial W_{AA}}{\partial p} - \lambda\frac{\partial \pi_{AB}}{\partial p} - \mu\frac{\partial \pi_{AA}}{\partial p} + \nu\frac{\partial T_{AA}}{\partial p} \overset{!}{=} 0 \tag{A.29}$$

$$\frac{\partial \mathcal{L}}{\partial P} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial P} + (\overline{\theta} - \theta_{AA}^{BB})\frac{\partial W_{AA}}{\partial P} - \mu\frac{\partial \pi_{AA}}{\partial P} + \nu\frac{\partial T_{AA}}{\partial P} \overset{!}{=} 0 \tag{A.30}$$

$$\frac{\partial \mathcal{L}}{\partial g} = (W_{BB} - W_{AA})\frac{\partial \theta_{AA}^{BB}}{\partial g} - \lambda\frac{\partial \pi_{AB}}{\partial g} - \mu\frac{\partial \pi_{AB}}{\partial g} + \nu \overset{!}{=} 0 \tag{A.31}$$

$$\lambda(\pi_{BB} - \pi_{AB}) + \mu(\pi_{AA} - \pi_{BB}) + \nu(g - T_{AA}) \overset{!}{=} 0 \tag{A.32}$$

$$\lambda, \mu, \nu \geq 0 \tag{A.33}$$

Taking into account that $\frac{\partial \theta_{AA}^{BB}}{\partial g} = -1$ and $\frac{\partial \pi_{AB}}{\partial g} = 1$, equation (A.31) reduces to $\nu = W_{AA} - W_{BB} - \lambda - \mu$. Plugging this into equations (A.29) and (A.30) leads to equations (4.34) and (4.35) from the text. If $\lambda > 0$, then p can be above or below ψ because the sign of the last term in equation (4.34) is indeterminate which proofs the first entry in the second line of Table 2. If $\frac{\partial T_{AA}}{\partial P} > 0$, then the last term of equation (4.35) is negative and P must be below ψ. If the opposite holds true, then P can be above or below ψ which proofs the other entries of the second line. For the last line, if $\lambda = 0$, then the FOCs (4.34) and (4.35) are equivalent to (4.28) and (4.29) and we have $p = P < \psi$ for the same reasons as outlined in the proof of Proposition 3.

Bibliography

Aldy, J. E., A. J. Krupnick, R. G. Newell, I. W. H. Parry, and W. a. Pizer (2010). Designing climate mitigation policy. *Journal of Economic Literature 48*(4), 903–934.

Amundsen, E. S. and R. Schöb (1999). Environmental taxes on exhaustible resources. *European Journal of Political Economy 15*(2), 311–329.

Archer, D., M. Eby, V. Brovkin, A. Ridgwell, L. Cao, U. Mikolajewicz, K. Caldeira, K. Matsumoto, G. Munhoven, A. Montenegro, and K. Tokos (2009). Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences 37*(1), 117–134.

Argote, L. and D. Epple (1990). Learning curves in manufacturing. *Science 247*(4945), 920–924.

Arrow, K., M. Cropper, C. Gollier, B. Groom, G. Heal, R. Newell, W. Nordhaus, R. Pindyck, W. Pizer, P. Portney, T. Sterner, R. S. J. Tol, and M. Weitzman (2013). Determining benefits and costs for future generations. *Science 341*(6144), 349–350.

Arrow, K. J. (1962). The economic implications of learning by doing. *The Review of Economic Studies 29*(3), 155–173.

Arrow, K. J. (2007). Global climate change: A challenge to policy. *The Economists' Voice 4*(3), 1–5.

Babiker, M. H. (2005). Climate change policy, market structure, and carbon leakage. *Journal of International Economics 65*(2), 421–445.

Bahel, E., W. Marrouch, and G. Gaudet (2013). The economics of oil, biofuel and food commodities. *Resource and Energy Economics 35*(4), 599–617.

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers 46*, 878–894.

Bauer, N., I. Mouratiadou, G. Luderer, L. Baumstark, R. Brecha, O. Edenhofer, and E. Kriegler (2013). Global fossil energy markets and climate change mitigation – an analysis with REMIND. *Climatic Change 136*(1), 69–82.

Baumol, W. J. and W. E. Oates (1988). *The Theory of Environmental Policy.* Cambridge: Cambridge University Press.

Berg, E., S. Kverndokk, and K. E. Rosendahl (1997). Market power, international CO_2 taxation and oil wealth. *The Energy Journal 18*(4), 33–71.

Berger, K., F. Øyvind, R. Golombek, and M. Hoel (1992). The oil market and international agreements on CO_2 emissions. *Resources and Energy 14*(4), 315–336.

Bergstrom, B. T. C. (1982). On capturing oil rents with a national excise tax. *The American Economic Review 72*(1), 194–201.

Brunnermeier, S. B. and A. Levinson (2004). Examining the evidence on environmental regulations and industry location. *The Journal of Environment & Development 13*(1), 6–41.

Carraro, C. and D. Siniscalco (1993). Strategies for the international protection of the environment. *Journal of Public Economics 52*(3), 309–328.

Chakravorty, U., A. Leach, and M. Moreaux (2011). Would Hotelling kill the electric car? *Journal of Environmental Economics and Management 61*(3), 281–296.

Chakravorty, U., A. Leach, and M. Moreaux (2012). Cycles in nonrenewable resource prices with pollution and learning-by-doing. *Journal of Economic Dynamics and Control 36*(10), 1448–1461.

Chakravorty, U., J. Roumasset, and K. Tse (1997). Endogenous substitution among energy resources and global warming. *Journal of Political Economy 105*(6), 1201–1234.

Copeland, B. R. and M. S. Taylor (1994). North-south trade and the environment. *The Quarterly Journal of Economics 109*(3), 755–787.

Dales, J. (1968). *Pollution, Property and Prices.* Toronto: University of Toronto Press.

Dasgupta, P. and G. M. Heal (1979). *Economic Theory and Exhaustible Resources.* London: Cambridge University Press.

Demailly, D. and P. Quirion (2006). CO_2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: Grandfathering versus output-based allocation. *Climate Policy 6*(1), 93–113.

Dong, B., J. Gong, and X. Zhao (2012). FDI and environmental regulation: Pollution haven or a race to the top? *Journal of Regulatory Economics 41*(2), 216–237.

Duke, R. and D. M. Kammen (1999). The economics of energy market transformation programs. *The Energy Journal 20*(4), 15–64.

Edenhofer, O., C. Flachsland, M. Jakob, and K. Lessman (2014). The atmosphere as a global commons - Challenges for international cooperation and governance. In L. Bernard and W. Semmler (Eds.), *The Oxford Handbook of the Macroeconomics of Global Warming*, Chapter 12, pp. 261–297. Oxford: Oxford University Press.

Edenhofer, O. and M. Kalkuhl (2011). When do increasing carbon taxes accelerate global warming? A note on the green paradox. *Energy Policy 39*(4), 2208–2212.

Eichner, T. and R. Pethig (2011). Carbon leakage, the green paradox, and perfect future markets. *International Economic Review 52*(3), 767–805.

Eisenack, K., O. Edenhofer, and M. Kalkuhl (2012). Resource rents: The effects of energy taxes and quantity instruments for climate protection. *Energy Policy 48*, 159–166.

Ekholm, N. (1901). On the variations of the climate of the geological and historical past and their causes. *Quarterly Journal of the Royal Meteorological Society 27*(117), 1–62.

EU (2009). European Parliament and the Council of the European Union: Directive 2009/29/EC of 23 April 2009.

European Commission (2014). Stakeholder consultation analysis: Emission Trading System (ETS) post-2020 carbon leakage provisions. *http://ec.europa.eu/clima/consultations/docs/0023/stakeholder-consultation-carbon-leakage-en.pdf*.

Felder, S. and T. F. Rutherford (1993). Unilateral CO_2 reductions and carbon leakage: The consequences of international trade in oil and basic materials. *Journal of Environmental Economics and Management 25*(2), 162–176.

Finus, M. (2008). Game theoretic research on the design of international environmental agreements: Insights, critical remarks, and future challenges. *International Review of Environmental and Resource Economics 2*(1), 29–67.

Fischer, C. and A. K. Fox (2012). Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of Environmental Economics and Management 64*(2), 199–216.

Fischer, C. and R. D. Morgenstern (2006). Carbon abatement costs: Why the wide range of estimates? *The Energy Journal 27*(2), 73–86.

Fischer, C. and R. G. Newell (2007). *Environmental and technology policies for climate mitigation.* RFF Discussion Paper Nr. 04-05.

Fischer, C. and R. G. Newell (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management 55*(2), 142–162.

Fischer, C. and L. Preonas (2010). Combining policies for renewable energy: Is the whole less than the sum of its parts? *International Review of Environmental and Resource Economics 4*(1), 51–92.

Foster, A. D. and M. R. Rosenzweig (1995). Learning by doing and learning from others: Human capital and technical change in agriculture. *Journal of Political Economy 103*(6), 1176–1209.

Franks, M., O. Edenhofer, and K. Lessmann (2015). Why finance ministers favor carbon taxes, even if they do not take climate change into account. *Environmental and Resource Economics*, 1–28.

Gerlagh, R. (2011). Too much oil. *CESifo Economic Studies 57*(1), 79–102.

Goulder, L. H. (1995). Environmental taxation and the double dividend: A reader's guide. *International tax and public finance 2*(2), 157–183.

Goulder, L. H. and A. R. Schein (2013). Carbon taxes versus cap and trade: A critical review. *Climate Change Economics 4*(3), 1–28.

Grafton, R., T. Kompas, and N. van Long (2012). Substitution between biofuels and fossil fuels: Is there a green paradox? *Journal of Environmental Economics and Management 64*(3), 328–341.

Greaker, M. (2003). Strategic environmental policy when the governments are threatened by relocation. *Resource and Energy Economics 25*(2), 141–154.

Gruber, H. (1998). Learning by doing and spillovers: Further evidence for the semiconductor industry. *Review of Industrial Organization 13*(6), 697–711.

Hardin, G. (1968). The tragedy of the commons. *Science 162*(3859), 1243–1248.

Heal, G. (1976). The relationship between price and extraction cost for a resource with a backstop technology. *The Bell Journal of Economics 7*(2), 371–378.

Hepburn, C. (2006). Regulation by prices, quantities, or both: A review of instrument choice. *Oxford Review of Economic Policy 22*(2), 226–247.

Hoel, M. (1996). Should a carbon tax be differentiated across sectors? *Journal of Public Economics 59*(1), 17–32.

Hoel, M. (1997). Environmental policy with endogenous plant locations. *Scandinavian Journal of Economics 99*(2), 241–259.

Hoel, M. (2011). The supply side of CO_2 with country heterogeneity. *The Scandinavian Journal of Economics 113*(4), 846–865.

Hoel, M. and S. Jensen (2012). Cutting costs of catching carbon—Intertemporal effects under imperfect climate policy. *Resource and Energy Economics 34*(4), 680–695.

Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy 39*(2), 137–175.

Ikefuji, M., J. Itaya, and M. Okamura (2016). Optimal emission tax with endogenous location choice of duopolistic firms. *Environmental and Resource Economics 65*(2), 463–485.

International Energy Agency (2008). *Issues behind competitiveness and carbon leakage - Focus on heavy industry.* IEA Information Paper.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

Irwin, D. A. and P. J. Klenow (1994). Learning-by-doing spillovers in the semiconductor industry. *Journal of Political Economy 102*(6), 1200–1227.

IWGSCC (2013). Technical update of the social cost of carbon for regulatory impact of the interagency working group on the social cost of carbon. Washington, D.C.: U.S. Government.

Jeffery, L., C. Fyson, R. Alexander, J. Gütschow, M. Rocha, J. Cantzler, M. Schaeffer, and B. Hare (2015). 2.7°C is not enough - We can get lower. Technical report, Climate Action Tracker, Berlin.

Kalkuhl, M., O. Edenhofer, and K. Lessmann (2012). Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics 34*(1), 1–23.

Kalkuhl, M., O. Edenhofer, and K. Lessmann (2013). Renewable energy subsidies: Second-best policy or fatal aberration for mitigation? *Resource and Energy Economics 35*(3), 217–234.

Karp, L. and D. M. Newbery (1991). Optimal tariffs on exhaustible resources. *Journal of International Economics 30*(3-4), 285–299.

Karp, L., S. Siddiqui, and J. Strand (2015). Dynamic climate policy with both strategic and non-strategic agents: Taxes versus quantities. *Environmental and Resource Economics 65*(1), 135–158.

Kellenberg, D. K. (2009). An empirical investigation of the pollution haven effect with strategic environment and trade policy. *Journal of International Economics 78*(2), 242–255.

Keohane, N. O. (2009). Cap and trade, rehabilitated: Using tradable permits to control US greenhouse gases. *Review of Environmental Economics and Policy 3*(1), 42–62.

Keutiben, O. (2014). On capturing foreign oil rents. *Resource and Energy Economics 36*(2), 542–555.

Knoema (2014). Cost of oil production by country. *https://knoema.com/vyronoe/cost-of-oil-production-by-country.*

Kuik, O., L. Brander, and R. S. J. Tol (2009). Marginal abatement costs of greenhouse gas emissions: A meta-analysis. *Energy Policy 37*(4), 1395–1403.

Kverndokk, S. and K. E. Rosendahl (2007). Climate policies and learning by doing: Impacts and timing of technology subsidies. *Resource and Energy Economics 29*(1), 58–82.

Lehmann, P. (2013). Supplementing an emissions tax by a feed-in tariff for renewable electricity to address learning spillovers. *Energy Policy 61*(1), 635–641.

Liski, M. and O. Tahvonen (2004). Can carbon tax eat OPEC's rents? *Journal of Environmental Economics and Management 47*(1), 1–12.

List, J. A., D. L. Millimet, P. G. Fredriksson, and W. W. McHone (2003). Effects of environmental regulations on manufacturing plant births: Evidence from a propensity score matching estimator. *Review of Economics and Statistics 85*(4), 944–952.

Long, N. V. and H.-W. Sinn (1985). Surprise price shifts, tax changes and the supply behavior of resource extracting firms. *Australian Economic Papers 24*(45), 278–289.

Mæstad, O. (2001). Efficient climate policy with internationally mobile firms. *Environmental and Resource Economics 19*(3), 267–284.

Mankiw, N. G. (2009). Smart taxes: An open invitation to join the Pigou Club. *Eastern Economic Journal 35*(1), 14–23.

Markusen, J. R. (1975). International externalities and optimal tax structures. *Journal of International Economics 5*(1), 15–29.

Markusen, J. R., E. R. Morey, and N. Olewiler (1995). Competition in regional environmental policies when plant locations are endogenous. *Journal of Public Economics 56*(1), 55–77.

Markusen, J. R., E. R. Morey, and N. D. Olewiler (1993). Environmental policy when market structure and plant locations are endogenous. *Journal of Environmental Economics and Management 24*(1), 69–86.

Martin, R., M. Muûls, L. B. de Preux, and U. J. Wagner (2014). Industry compensation under relocation risk: A firm-level analysis of the EU Emissions Trading Scheme. *The American Economic Review 104*(8), 2482–2508.

McDonald, A. and L. Schrattenholzer (2001). Learning rates for energy technologies. *Energy Policy 29*(4), 255–261.

McKinsey (2009). Pathways to a low carbon society: Version 2 of the global greenhouse gas abatement cost curve. *http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/pathways-to-a-low-carbon-economy*.

Metcalf, G. E. and D. Weisbach (2009). The design of a carbon tax. *Harvard Environmental Law Review 33*(2), 499–556.

Montgomery, W. (1972). Markets in licenses and efficient pollution control programs. *Journal of Economic Theory 5*(3), 395–418.

Motta, M. and J. F. Thisse (1994). Does environmental dumping lead to delocation? *European Economic Review 38*(3-4), 563–576.

Murray, B. C., R. G. Newell, and W. A. Pizer (2009). Balancing cost and emissions certainty: An allowance reserve for cap-and-trade. *Review of Environmental Economics and Policy 3*(1), 84–103.

Nachtigall, D. (2016). *Climate policy under firm relocation: The implications of phasing out free allowances.* Discussion paper series / Free University of Berlin Nr. 2016/25.

Nachtigall, D. and D. Rübbelke (2016). The green paradox and learning-by-doing in the renewable energy sector. *Resource and Energy Economics 43*, 74–92.

Naughton, H. T. (2014). To shut down or to shift: Multinationals and environmental regulation. *Ecological Economics 102*(C), 113–117.

Nordhaus, W. D. (2006). After Kyoto: Alternative mechanisms to control global warming. *The American Economic Review 96*(2), 31–34.

Nordhaus, W. D. (2007). A review of the Stern review on the economics of climate change. *Journal of Economic Literature 45*(3), 686–702.

Nordhaus, W. D. (2013). *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World.* New Haven and London: Yale University Press.

OPEC (2016). Annual statistical bulletin. *http://www.opec.org/opec-web/en/publications/202.htm*.

Oreskes, N. (2004). The scientific consensus on climate change. *Science 306*(5702), 1686–1686.

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change 20*(4), 550–557.

Paltsev, S. V. (2001). The Kyoto protocol: Regional and sectoral contributions to the carbon leakage. *The Energy Journal 22*(4), 53–79.

Petrakis, E. and A. Xepapadeas (2003). Location decisions of a polluting firm and the time consistency of environmental policy. *Resource and Energy Economics 25*(2), 197–214.

Pigou, A. C. (1920). *The Economics of Welfare.* London: Macmillan and Co.

Pittel, K. and D. T. G. Rübbelke (2008). Climate policy and ancillary benefits: A survey and integration into the modelling of international negotiations on climate change. *Ecological Economics 68*(1), 210–220.

Pizer, W., M. Adler, J. Aldy, D. Anthoff, M. Cropper, K. Gillingham, M. Greenstone, B. Murray, R. Newell, R. Richels, A. Rowell, S. Waldhoff, and J. Wiener (2014). Using and improving the social cost of carbon. *Science 346*(6214), 1189–1190.

Pollrich, M. and R. C. Schmidt (2014). *Unobservable investments, limited commitment, and the curse of firm relocation.* BDPEMS Working Paper Series Nr. 2014-04.

Rauscher, M. (1995). Environmental regulation and the location of polluting industries. *International Tax and Public Finance 2*(2), 229–244.

Reichenbach, J. and T. Requate (2012). Subsidies for renewable energies in the presence of learning effects and market power. *Resource and Energy Economics 34*(2), 236–254.

Ritter, H. and M. Schopf (2014). Unilateral climate policy: Harmful or even disastrous? *Environmental and Resource Economics 58*(1), 155–178.

Rogner, H.-H. (1997). An assessment of world hydrocarbon resources. *Annual review of energy and the environment 22*(1), 217–262.

Rubio, S. J. and L. Escriche (2001). Strategic pigouvian taxation, stock externalities and polluting non-renewable resources. *Journal of Public Economics 79*(2), 297–313.

Rystad Energy (2016). North american shale report. *https://www.rystadenergy.com/NewsEvents/PressReleases/shale-well-breakeven*.

Schellnhuber, H. J. (2006). *Avoiding Dangerous Climate Change*. Cambridge: Cambridge University Press.

Schellnhuber, H. J., S. Rahmstorf, and R. Winkelmann (2016). Why the right climate target was agreed in Paris. *Nature Climate Change 6*(7), 649–653.

Schmidt, R. C. and J. Heitzig (2014). Carbon leakage: Grandfathering as an incentive device to avert firm relocation. *Journal of Environmental Economics and Management 67*(2), 209–223.

Schöb, R. (2010). Climate policy: Reaping an additional employment dividend. *Public Finance and Management 10*(2), 251–283.

Shobe, W. and D. Burtraw (2012). Rethinking environmental federalism in a warming world. *Climate Change Economics 3*(4), 1–33.

Sinclair, P. (1992). High does nothing and rising is worse: Carbon taxes. *The Manchester School 60*(1), 41–52.

Sinn, H.-W. (2008a). *Das grüne Paradoxon*. Berlin: Econ Verlag.

Sinn, H.-W. (2008b). Public policies against global warming: A supply side approach. *International Tax and Public Finance 15*(4), 360–394.

Sinn, H.-W. (2012). *The Green Paradox: A Supply-Side Approach to Global Warming*. Cambridge, Mass: MIT Press.

Smulders, S., Y. Tsur, and A. Zemel (2012). Announcing climate policy: Can a green paradox arise without scarcity? *Journal of Environmental Economics and Management 64*(3), 364–376.

Stavins, R. N. (2008). Addressing climate change with a comprehensive US cap-and-trade system. *Oxford Review of Economic Policy 24*(2), 298–321.

Stern, N. (2007). *The Economics of Climate Change: The Stern review*. Cambridge, UK: Cambridge University Press.

Strand, J. (2007). Technology treaties and fossil-fuels extraction. *The Energy Journal 28*(4), 129–141.

Strand, J. (2009). *Who Gains and Who Loses by Fossil-Fuel Taxes and Caps: Importers Versus Exporters.* Unpublished, Washington D.C.: World Bank.

Strand, J. (2011). Taxes and caps as climate policy instruments with domestic and imported fuels. In G. Metcalf (Ed.), *U.S. Energy Tax Policy*, Chapter 7, pp. 233–268. Cambridge, Mass: Cambridge University Press.

Strand, J. (2013). Strategic climate policy with offsets and incomplete abatement: Carbon taxes versus cap-and-trade. *Journal of Environmental Economics and Management 66*(2), 202–218.

Tahvonen, O. (1997). Fossil fuels, stock externalities, and backstop technology. *The Canadian Journal of Economics 30*(4a), 855–874.

Tahvonen, O. and S. Salo (2001). Economic growth and transitions between renewable and nonrenewable energy resources. *European Economic Review 45*(8), 1379–1398.

Taylor, M. S. (2005). Unbundling the pollution haven hypothesis. *Advances in Economic Analysis & Policy 3*(2), 1–28.

Tinbergen, J. (1952). *On the Theory of Economic Policy.* Amsterdam: North-Holland Publishing Company.

Tol, R. S. J. (2011). The social cost of carbon. *Annual Review of Resourse Economics 3*(1), 419–443.

Ulph, A. and D. Ulph (1994). The optimal time path of a carbon tax. *Oxford Economic Papers 46*, 857–868.

Ulph, A. and L. Valentini (1997). Plant location and strategic environmental policy with inter-sectoral linkages. *Resource and Energy Economics 19*(4), 363–383.

Ulph, A. and L. Valentini (2001). Is environmental dumping greater when plants are footloose? *The Scandinavian Journal of Economics 103*(4), 673–688.

UNFCCC (1992). *United Nations Framework Convention on Climate Change.* New York: United Nations.

UNFCCC (1997). *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. Kyoto: United Nations.

UNFCCC (2015). *Adoption of the Paris Agreement*. Paris: United Nations.

van der Meijden, G., F. van der Ploeg, and C. Withagen (2015). International capital markets, oil producers and the green paradox. *European Economic Review 76*, 275–297.

van der Ploeg, F. and C. Withagen (2012). Is there really a green paradox? *Journal of Environmental Economics and Management 64*(3), 342–363.

Weitzman, M. L. (1974). Prices vs. quantities. *The Review of Economic Studies 41*(4), 477–491.

Weitzman, M. L. (2007). A review of the Stern review on the economics of climate change. *Journal of Economic Literature 45*(3), 703–724.

Wirl, F. (1995). The exploitation of fossil fuels under the threat of global warming and carbon taxes: A dynamic game approach. *Environmental and Resource Economics 5*(4), 333–352.

Wirl, F. (2012). Global warming: Prices versus quantities from a strategic point of view. *Journal of Environmental Economics and Management 64*(2), 217–229.

Wirl, F. and E. Dockner (1995). Leviathan governments and carbon taxes: Costs and potential benefits. *European Economic Review 39*(6), 1215–1236.

Withagen, C. (1994). Pollution and exhaustibility of fossil fuels. *Resource and Energy Economics 16*(3), 235–242.

Wright, T. P. (1936). Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences 3*(4), 122–128.

Xing, Y. and C. D. Kolstad (2002). Do lax environmental regulations attract foreign investment? *Environmental and Resource Economics 21*(1), 1–22.

Zhang, Z. and A. Baranzini (2004). What do we know about carbon taxes? An inquiry into their impacts on competitiveness and distribution of income. *Energy policy 32*(4), 507–518.

English Summary

'Climate change is the biggest market failure the world has ever seen' according to economist Sir Nicolas Stern (Stern 2006, p. viii). In fact, the expected temperature increase within the 21^{st} century is unprecedented over millions of years of earth history, leading to substantial impacts such as a rising sea level and a change of precipitation patterns. This poses a major threat on the food security of human beings and may force inhabitants on the ocean shores to abandon their settlements. It is undisputed among the scientific community that climate change is anthropogenic, caused by the increasing concentration of greenhouse gases (GHG) in the atmosphere. The exhaust of greenhouse gas emissions is a by-product of economic activity and constitutes a negative externality that is responsible for a market failure in a decentralized market economy. In order to induce the economic agents to internalize the negative externality, climate policy aiming at mitigating GHG emissions should implement cost-efficient market-based instruments such as carbon taxes or tradable emission quotas. However, these instruments may come along with unintended side effects, which should be taken into account when designing effective climate policy. This thesis explores three areas where unintended side effects arise and discusses the implications for the design of climate policy. These areas include the rent capturing by cartelized oil suppliers, the intertemporal extraction decision of fossil fuel owners, and the relocation of firms in case of existing carbon price differences between countries.

The Paris Agreement calls for 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels' (UNFCCC 2015: Art. 2a). As a first step of coordinated action against global warming, this agreement can be thought of as the formation of a global climate coalition. Since more than two thirds of all GHG emissions stem from the combustion of fossil fuels, any coordinated climate policy affects both the demand for fossil fuels and the extraction decision of the owners of fossil fuels such as coal, gas and oil. The oil market is characterized by market power due to the dominant role of the Organization of Petroleum Exporting Countries (OPEC). Previous papers found that in the presence of market power, the equivalence between carbon taxes and tradable emissions permits does not hold anymore (Berger et al. 1992). However, OPEC's dominance is challenged by the emergence of the shale oil industry, whose extraction costs have been decreasing considerably in recent years. Chapter 2 analyzes the impact of declining extraction costs of shale oil producers on the choice of the policy instrument of a climate coalition in the presence of OPEC. Relative to OPEC, shale oil producers, i.e. the competitive fringe, still face higher extraction costs, which represent an upper bound for the oil price OPEC can charge.

Declining extraction costs limit OPEC's price setting behavior and thus impact the optimal climate policy of the climate coalition.

Chapter 2 finds that from the perspective of the climate coalition, a pure cap-and-trade system turns out to be weakly welfare-inferior relative to a carbon tax. For high extraction costs, OPEC's reaction towards a fixed quota is to marginally undercut that quota, which drives the permit price to zero and leaves no revenue for the climate coalition. If extraction costs are decreasing, then OPEC continues undercutting the quota, but can capture only a part of the climate rent because the oil price is limited by the fringe's costs. Relative to a quota, a carbon tax always generates positive revenue for the government and thus is generally welfare-superior. However, low extraction costs prevent OPEC from charging the monopolistic price and from exerting its market power, leading the climate coalition to implement the Pigouvian tax in the first place. It turns out that both market-based instruments are equivalent in this case. If the quota is complemented by a base tax, then this dual instrument is equivalent to a carbon tax regardless of the fringe's extraction costs.

The reaction of fossil fuel owners is also relevant in the absence of market power because fossil fuels are exhaustible resources, meaning that any tax on the carbon content affects the inter-temporal extraction decision of resource owners (Sinclair 1992). If resource owners anticipate the implementation of carbon taxes in the future, then they will optimally evade this taxation by shifting some extraction towards the present. This increases the carbon dioxide emissions in the present and accelerates global warming, which is why this phenomenon is referred to as green paradox (Sinn 2008b). Chapter 3 analyzes the optimal extraction decision of resource owners within a two-period model and asks whether the green paradox also arises in the presence of a clean energy source, that is a perfect substitute and exhibits learning-by-doing.

The main finding of Chapter 3 is that there is a reversal of the green paradox under certain conditions. If the marginal extraction cost curve of the fossil fuel suppliers is sufficiently flat, resource owners respond to a future carbon tax with lowering their total extraction and only slightly increase the current extraction. Moreover, taxation leads to higher energy prices, which induces firms in the renewable energy sector to increase their output not only in the future, but also in the present due to the anticipated benefits from learning-by-doing. This leads to a crowding out of energy from the combustion of fossil fuels and may outweigh the initial increase in current emissions, leading to fewer emissions in the present and to a reversal of the green paradox.

When some countries put a price on carbon while others do not, this may lead emission intensive firms to relocate their production capacities abroad. The European Union Emissions Trading System (EU ETS) accounts for the relocation problem by allocating additional free allowances to firms belonging to the carbon leakage list. However, this allocation was found to lead to substantial overcompensation (Martin et al. 2014), which is why some stakeholders recently have called for a phasing out of free allowances in the near term. Chapter 4 analyzes the consequences of phasing out free allowances in a two-period two-country model and derives the optimal carbon price path for the case of a phasing-out. The carbon price induces firms to invest in abatement capital, but may also lead to the relocation of some firms. The social planner addresses the relocation problem by offering firms transfers, i.e. free allowances, conditional on maintaining the production in the regulating country.

Chapter 4 finds that if transfers are unrestricted in both periods, then the social planner can implement the first best by setting the carbon prices equal to the marginal environmental damage and using transfers to prevent any relocation. However, if transfers in the future period are restricted, some firms may play a 'take the money and run'-strategy, collecting the transfers of the first period, but relocating thereafter. In this case, it is optimal to implement a declining carbon price path with the first period price exceeding the marginal environmental damage. A high carbon price triggers investments in abatement capital and thus creates a lock-in effect. With a larger abatement capital stock, firms are less affected by carbon prices in the future and therefore less prone to relocate in the second period when transfers are restricted.

Deutsche Zusammenfassung

Sir Nicolas Stern bezeichnet Klimawandel als das „größte Marktversagen, das die Welt je gesehen hat“ (Stern 2006, p. viii). Tatsächlich ist der erwartete Temperaturanstieg für das 21. Jahrhundert beispiellos für die letzten Millionen Jahre der Erdgeschichte. Mit der Erderwärmung gehen beträchtliche Auswirkungen, wie ein Ansteigen des Meeresspiegels oder die Veränderung bestehender Niederschlagsmuster, einher. Dies führt unter anderem zu einer Bedrohung der Nahrungsmittelsicherheit bzw. zu einer potentiellen Zwangsmigration von Menschen in den Küstengebieten. Klimawissenschaftler sind sich darüber einig, dass der Klimawandel anthropogen ist und durch eine zunehmende Konzentration von Treibhausgasen in der Atmosphäre verursacht wird. Der Ausstoß von Treibhausgasen ist ein Nebenprodukt wirtschaftlicher Tätigkeiten und stellt im ökonomischen Sinne eine negative Externalität dar, die zu einem Marktversagen in einer dezentralen Marktwirtschaft führt. Damit die Marktteilnehmer die negative Externalität internalisieren, sollte Klimapolitik kosteneffiziente marktbezogene Politikinstrumente wie CO_2 Steuern oder handelbare Verschmutzungsrechte verwenden. Allerdings verursachen diese Instrumente unter Umständen unbeabsichtigte Nebeneffekte, welche bei der Ausgestaltung von Klimapolitik mit berücksichtigt werden sollten. Die vorliegende Dissertation beleuchtet drei Bereiche, in denen es zu unbeabsichtigten Nebeneffekten kommen kann, und diskutiert die Implikationen für die Ausgestaltung von Klimapolitik. Die drei Bereiche umfassen die Anbieterreaktion von monopolisierten Besitzern fossiler Brennstoffe, die zeitliche Verlagerung der Extraktion fossiler Brennstoffe sowie die potentielle Abwanderung von Firmen in Ländern mit weniger restriktiven Klimapolitiken.

Das Übereinkommen von Paris sieht die Begrenzung der globalen Erwärmung auf deutlich unter 2°C gegenüber vorindustriellen Werten vor. Als erster Schritt in Richtung einer koordinierten Zusammenarbeit gegen die globale Erwärmung kann das Übereinkommen auch als die Gründung einer globalen Klimakoalition verstanden werden. Da mehr als zwei Drittel aller Treibhausgasemissionen durch die Verbrennung fossiler Brennstoffe entstehen, wirkt sich jegliche koordinierte Klimapolitik unvermeidlich auf die Nachfrage und das Angebot fossiler Brennstoffe, wie Kohle, Gas und Öl, aus. Der Ölmarkt ist durch eine marktbeherrschende Stellung der Organisation erdölexportierender Länder (OPEC) gekennzeichnet. Es wurde gezeigt, dass bei Marktmacht auf der Anbieterseite die Äquivalenz zwischen CO_2 Steuer und handelbaren Verschmutzungsrechten nicht mehr gegeben ist (Berger et al. 1992). Die marktbeherrschende Stellung der OPEC wird allerdings zunehmend durch Unternehmen der Schieferölindustrie gefährdet, deren Kosten in den letzten Jahren substantiell gesunken sind. Kapitel 2 analysiert die Auswirkungen von immer geringer werdenden Förderkosten der Schieferölproduzenten auf die Instrumentenwahl einer Klimakoalition, wenn die OPEC nach wie vor eine marktbeherrschende Stellung auf dem Ölmarkt inne hat. Im Vergleich zur OPEC haben die Produzenten von Schieferöl höhere Förderkosten, welche eine Preisobergrenze für die OPEC darstellen. Sinkende Förderkosten führen zu einer Begrenzung von OPEC's Marktmacht und haben dadurch auch einen Einfluss auf die optimale Politik der Klimakoalition.

In Kapitel 2 wird gezeigt, dass die Klimakoalition mit einer CO_2 Steuer im Vergleich zu handelbaren Verschmutzungsrechten eine höhere Wohlfahrt erzielt. OPEC's beste Reaktion hinsichtlich einer festgelegten Emissionsobergrenze ist die Förderung einer marginal geringeren Ölmenge, was zu einem Absinken des Zertifikatspreises auf null führt und somit keine Staatseinnahmen für die Klimakoalition generiert. Wenn die Förderkosten in der Schieferölindustrie sinken, dann behält OPEC seine Mengenstrategie bei, kann sich allerdings nur einen Teil der Klimarente aneignen, weil der Ölpreis durch die Kosten der Wettbewerber nach oben begrenzt ist. Im Gegensatz zum Emissionshandel, generiert eine CO_2 Steuer immer Staatseinnahmen und ist deswegen im Allgemeinen wohlfahrtsdominant. Wenn die Förderkosten jedoch hinreichend klein sind, dann kann die OPEC nicht den Monopolpreis durchsetzen und verliert ihre Marktmacht. Die Klimakoalition wird dann die CO_2 Steuer in Höhe der Pigousteuer festsetzen und es zeigt sich, dass beide klimapolitischen Instrumente in diesem Fall zum gleichen Ergebnis führen.

Die Anbieterreaktionen der Besitzer fossiler Brennstoffe sind auch ohne Marktmacht von Bedeutung, da fossile Brennstoffe erschöpfbare Ressourcen sind und damit jegliche Steuer auf den CO_2 Gehalt dieser Ressourcen die inter-temporale Förderentscheidung der Besitzer beeinflußt (Sinclair 1992). Wenn Ressourcenbesitzer die Einführung einer CO_2 Steuer in der Zukunft erwarten, dann ist es für sie optimal, die Steuerlast zu minimieren, indem sie einen Teil ihrer Ressourcen bereits in der Gegenwart fördern. Das führt zu einer Steigerung der gegenwärtigen CO_2 Emissionen und beschleunigt die globale Erwärmung, weswegen dieses Phänomen auch als grünes Paradoxon bezeichnet wird (Sinn 2008a). Kapitel 3 analysiert die optimale inter-temporale Förderentscheidung von Ressourcenbesitzern in einem zwei-Perioden Modell und untersucht, ob das grüne Paradoxon auch auftritt, wenn es gleichzeitig ein perfektes Substitut in Form von Energie aus regenerativen Quellen gibt, dessen Kostenstruktur durch 'Learning-by-doing' gekennzeichnet ist.

Das Hauptresultat von Kapitel 3 ist, dass es unter bestimmten Bedingungen zu einer Umkehrung des grünen Paradoxons kommt. Wenn die Grenzkostenkurve der

Erdölförderung hinreichend flach ist, dann führt die Einführung einer CO_2 Steuer in der Zukunft dazu, dass Ressourcenbesitzer einerseits einen Teil ihrer Förderung in die Gegenwart verlagern, aber andererseits auch ihre Gesamtförderung beträchtlich reduzieren. Gleichzeitig führt die CO_2 Steuer zu höheren Energiepreisen, wodurch die Produzenten erneuerbarer Energien ihre Produktionsmenge in der Zukunft und - durch die antizipierten Kostenersparnisse vom 'Learning-by-doing' - auch in der Gegenwart erhöhen. Letzteres verdrängt das Angebot von Energie aus fossilen Brennstoffen und kann den ursprünglichen Anstieg der gegenwärtigen Emissionen überkompensieren. Dadurch werden weniger CO_2 Emissionen in der Gegenwart emittiert, was eine Umkehrung des grünen Paradoxons bedeutet.

Wenn einige Länder CO_2 Emissionen höher besteuern als andere, dann kann dies zu Firmenabwanderungen energieintensiver Firmen in Länder mit geringeren Steuersätzen führen. Der europäische Emissionshandel trägt der potentiellen Firmenabwanderung Rechnung und verteilt zusätzliche Freizertifikate für Firmen innerhalb der Carbon-Leakage-Liste. Allerdings kommt die Analyse von Martin et al. (2014) zu dem Schluss, dass diese Freizuteilung zu einer erheblichen Überkompensation führt, weswegen einige Akteure ein Auslaufen der Freizertifikate innerhalb der nächsten Jahren fordern. Kapitel 4 analysiert die Konsequenzen dieser Forderung in einem zwei-Perioden zwei-Länder Modell und leitet den optimalen CO_2 Steuerpfad für den Fall her, in dem Firmen zukünftig keine Freizertifikate mehr bekommen. Ein positiver CO_2 Preis veranlasst die Firmen, Investitionen in Vermeidungskapitel vorzunehmen, aber kann auch dazu führen, dass einige Firmen abwandern. Um Abwanderung zu verhindern, zahlt der soziale Planer Transfers in Form von Freizertifikaten an die Firmen unter der Bedingung, dass diese ihre Produktionsstätten im Inland beibehalten.

Wenn Transfers in beiden Perioden unbeschränkt verfügbar sind, dann zeigt Kapitel 4, dass der soziale Planer die First-Best-Lösung implementieren kann, indem er die CO_2 Preise in Höhe des Grenzumweltschadens festsetzt und mit den Transfers jegliche Abwanderung verhindert. Wenn die Transfers allerdings in der Zukunft beschränkt sind, dann könnten einige Firmen die Strategie verfolgen, bei der sie die Transfers in der ersten Periode kassieren, aber danach abwandern. In diesem Fall ist es optimal, einen fallenden CO_2 Preispfad zu implementieren, wobei der CO_2 Preis der ersten Periode den Grenzumweltschaden übersteigt. Ein hoher CO_2 Preis erhöht die Investitionen in Vermeidungskapital und erzeugt dadurch einen Lock-in Effekt. Mit einem größeren Bestand an Vermeidungskapital sind die Gewinne der Firmen weniger vom CO_2 Preis der zweiten Periode betroffen, wodurch das Abwanderungsrisiko in der zweiten Periode sinkt.

Vorveröffentlichungen

Anmerkungen des Autors
Die folgende Liste enthält alle Vorveröffentlichungen. Darunter sind auch Versionen der Kapitel, die zum Teil stark überarbeitet wurden, bevor sie Eingang in die vorliegende Dissertation fanden.

Kapitel 2: Prices versus Quantities: The Impact of Fracking on the Choice of Climate Policy Instruments in the Presence of OPEC

- BDPEMS Working Paper, Nr. 2017-01
- School of Business and Economics Discussion Paper, Freie Universität Berlin, Nr. 2017/6

Kapitel 3: The green paradox and learning-by-doing in the renewable energy sector (mit Dirk Rübbelke)

- Resource and Energy Economics, 43, S. 74-92
- BC3 Working Paper, Nr. 2013-09
- BDPEMS Working Paper, Nr. 2014-02
- CESifo Working Paper, Nr. 4880
- School of Business and Economics Discussion Paper, Freie Universität Berlin, Nr. 2014/31

Kapitel 4: Dynamic climate policy under firm relocation: The implications of phasing out free allowances

- BDPEMS Working Paper, Nr. 2016-07
- School of Business and Economics Discussion Paper, Freie Universität Berlin, Nr. 2016/25