The Calculus of Climate Policy: Carbon Pricing and Technology Policies for Climate Change Mitigation

vorgelegt von
Diplom-Systemwissenschaftler
Matthias Kalkuhl
aus Heilbad Heiligenstadt

von der Fakultät VI – Planen Bauen Umwelt
der Technischen Universität Berlin
zur Erlangung des akademischen Grades
Doktor der Wirtschaftswissenschaften
Dr. rer. oec

genehmigte Dissertation

Promotionsausschuss:

Vorsitzender: Prof. Dr. Volkmar Hartje
Gutachter: Prof. Dr. Ottmar Edenhofer
Gutachter: Prof. Dr. Alfred Greiner

Tag der wissenschaftlichen Aussprache: 7. Mai 2012

Berlin 2012
D 83

Contents

Executive Summary

This thesis examines the role of carbon pricing and low-carbon technology policies for reducing CO_2 emissions from burning fossil fuels. Policies are evaluated according to their impact on welfare, emissions, fossil resource rents and energy prices. For the economic analysis, small analytical partial equilibrium models and, most importantly, the elaborate numerical intertemporal general equilibrium model PRIDE (Policy and Regulatory Instruments in a Decentralized Economy) are developed and studied. A major focus of these models lies on the intertemporal incentive effects of policies on fossil resource extraction and investments into new low-carbon technologies. An innovative strength of the PRIDE model is to calculate the welfare-maximizing potential of policies like carbon taxes and emissions trading schemes as well as subsidies, feed-in-tariffs or portfolio standards for renewable energy and carbon capture and sequestration (CCS).

The results indicate that a price on carbon emissions – established through a carbon tax or an emissions trading scheme – is the most important climate policy in the long run; reducing emissions permanently with subsidies on 'clean' technologies becomes very expensive. Technology policies, however, may have an important role in the short to medium run: First, technology policies addressing innovation market failures can increase welfare and reduce mitigation costs substantially even under a 'perfect' emissions trading scheme. Second, technology policies can serve as a temporary 'second-best' policy to reduce emissions when an 'optimal' carbon price cannot be established due to political economy reasons. Finally, technology policies may help to reduce the distributional conflict concerning fossil resource rents and the social conflict regarding increasing energy prices. The analytical and numerical results further highlight the relevance and the need of creating a global public institution that manages the use of the atmosphere and the associated 'climate rent' and fosters investments into low-carbon technologies.

Zusammenfassung

Diese Arbeit untersucht die Bedeutung von Kohlenstoffpreisen und Technologiepolitiken zur Reduzierung von CO_2-Emissionen, die bei der Verbrennung fossiler Energieträger anfallen. Die Politikinstrumente werden hierbei nach ihrer Wirkung auf Wohlfahrt, Emissionen, Energiepreise und Knappheitsrenten für fossile Rohstoffe ausgewertet. Für die ökonomische Analyse werden kleine analytische, partielle Gleichgewichtsmodelle und vor allem das numerische, intertemporale allgemeine Gleichgewichtsmodell PRIDE (Politik- und Regulierungsinstrumente in einer dezentralen Ökonomie) entwickelt und untersucht. Ein besonderer Schwerpunkt dieser Modelle liegt auf der intertemporalen Anreizwirkung von Politikinstrumenten bezüglich der Förderung fossiler Rohstoffe und der Investitionen in neue, kohlenstoffarme Technologien. Eine innovative Stärke des PRIDE-Modells liegt in der Berechnung des wohlfahrtsmaximierenden Potenzials von CO_2-Steuern und Emissionshandelssystemen sowie Subventionen, Einspeisetarifen oder *Portfolio Standards* für Erneuerbare Energien und Kohlenstoffabscheidung und -speicherung (CCS).

Die Ergebnisse legen nahe, dass ein Preis für CO_2 (festgesetzt durch eine Steuer oder ein Emissionshandelssystem) das wichtigste Klimaschutzinstrument auf lange Sicht ist – Emissionen auf Dauer mit Subventionen auf ‘saubere’ Technologien reduzieren zu wollen, ist äußerst kostspielig. Technologiepolitik kann jedoch kurz- und mittelfristig eine bedeutende Rolle spielen: Erstens kann sie die Wohlfahrt erhöhen und die Kosten des Klimaschutzes senken, wenn sie auf gezieltes Marktversagen bei Innovationen gerichtet ist. Zweitens stellt sie eine pragmatische, zeitlich begrenzte Alternative zum CO_2-Preis dar, wenn dieser wegen politökonomischer Gründe überhaupt nicht oder nur in abgeschwächter Form eingeführt werden kann. Drittens können technologiepolitische Maßnahmen den Verteilungskonflikt um fossile Rohstoffrenten und soziale Konflikte um steigende Energiepreise entschärfen. Die analytischen wie auch die numerischen Modellergebnisse zeigen die Bedeutung und die Notwendigkeit einer zu schaffenden globalen, öffentlichen Institution auf, die die Knappheit der Atmosphäre und die damit verbundene Knappheitsrente (‘Klimarente’) verwaltet und Investitionen in emissionsarme Technologien fördert.

List of Figures

List of Tables

Abbrevations

BAU	Business-as-Usual
bbl	barrel
BGE	Balanced-Growth Equivalents
CBA	Cost-Benefit Analysis
CCS	Carbon Capture and Sequestration
CES	Constant Elasticity of Substitution
Ch.	Chapter
ETS	Emissions Trading Scheme
Eq.	Equation
Fig.	Figure
FIT	Feed-in-Tariff
FOC	First-Order-Conditions
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IAM	Integrated Assessment Model
ITR	Intertemporal Trading Rate
IPCC	Intergovernmental Panel on Climate Change
Lr.	Learning Rate
NLP	Non-linear Program
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PRIDE	Policy and Regulatory Instruments in a Decentralized Economy
R&D	Research and Development
Sec.	Section
Tab.	Table
tce	tons of coal equivalent
w/o	without

Chapter 1

Introduction

1.1 Motivation

1.1.1 The physical science basis

The Earth's temperature is the result of two basic energy flows (IPCC 2007c, pp. 94–95): (i) the amount of solar energy reaching the planet and (ii) the amount of thermal radiation emitted from the Earth back into the universe. The magnitude of the thermal radiation leaving the Earth depends on the albedo, i.e. to what extent solar radiation is directly reflected into the space, and on the concentration and composition of so-called greenhouse gases (GHG). These gases absorb radiation and, thus, keep thermal energy within the atmosphere. The components of the factors influencing the energy balance – i.e. the solar radiation, the albedo, and the GHGs – are also called 'radiative forcing agents' as the interplay of these agents determines the temperature. Thermodynamic laws say that if radiative forcing does not change, the earth's temperature converges to a stable steady state. However, if some of these factors change, temperature adjusts to a new equilibrium.

Scientists repeatedly record observations related to climate change: Since 1850 the global surface temperature has been increasing by 0.76 ± 0.19°C (IPCC 2007c, p. 36) and heat waves have increased in duration (ibid., p. 40). Precipitation in North and South America, Northern Europe and North and Central Asia increased while many regions in the Sahel and Mediterranean zone as well as Southern Africa and South Asia are drying (ibid., p. 41). Snow cover has decreased and glaciers, ice caps and arctic sea ice have shrunk, the latter by 2.7% per decade (ibid., pp. 43–44). Oceans became more acid (-0.1 pH since 1750); global sea level has been rising by 20 cm since 1870 and sea level increase is accelerating (ibid., pp. 48–49). The scientific community judges it very likely that anthropogenic GHGs are responsible for most of the observed pattern of warming (IPCC 2007c, p. 60).

Not only past temperatures increased, current concentration of GHGs commits mankind to experience further warming due to the inertia in the climate system: Even if atmospheric GHG concentration remained at the year 2000 level, warming would be 0.2°C for the next two decades (IPCC 2007c, p. 68) and 0.3–0.9°C until 2100 (IPCC 2007c, Tab. TS.6). Driven by economic growth and the increasing demand for energy, the global trend in CO_2 emissions is expected to grow further. For the 21st century, estimated temperature increases range between 1.1 and 6.4°C, depending on economic, technological and social development (IPCC 2007c, Tab. TS.6). The corresponding sea level rise until 2100 is 18–59 cm (ibid.), although new studies based on a semi-empirical approach suggest that sea level rise can exceed 100 cm considerably (Rahmstorf 2010).

Despite the scientific consensus about the basic mechanisms of anthropogenic global warming, there are uncertainties about the exact temperature increase due to greenhouse gas emissions. These uncertainties originate basically from feed-back mechanisms that are difficult to quantify and the problems to predict the dynamics of clouding (IPCC 2007c, pp. 87–88).[1].

1.1.2 The economics of climate change

The costs of continued global warming

Do we have to be concerned about global warming and its impact on human well-being? Existing climate damage assessments portray a heterogeneous picture: A moderate warming could improve well-being and productivity in some regions in the northern latitudes but poses already pressure on many agricultural systems in arid zones. For example, crop production is expected to increase for a warming of 1–3°C in higher latitudes and decreasing beyond this threshold while it is projected to decrease already for 1–2°C in lower latitudes (IPCC 2007a, p. 11). As developing countries' economies depend highly on agriculture, agricultural losses have therefore a sizable impact on gross domestic product (GDP) and welfare (Stern 2007, p. 95). Increasing temperatures have beneficial health effects in temperate zones, i.e. due to fewer deaths from exposure to the cold (Stern 2007, p. 74). In contrast, many developing countries will suffer from heat waves and (infectious) diseases (IPCC 2007a, p. 12). Sea level rise affects small island and densely-populated areas especially the mega-deltas in Africa and Asia (ibid., p. 12). The impacts on agriculture, water supply and coastal zones could induce 200 million people to relocate or migrate to other

[1] These uncertainties are often covered by the climate sensitivity parameter, which describes the equilibrium temperature increase if GHG concentrations are doubled. IPCC (2007c, p. 65) gives as a likely range of 2–4.5°C with 3°C as best guess. While it judges values below 1.5°C as very unlikely, numbers "substantially higher than 4.5°C cannot be excluded" (ibid., p.65).

countries (Stern 2007, p. 56) – which could lead to severe conflicts and geopolitical risks. Ecosystems are highly sensitive to temperature change above 1.5°C and the IPCC (2007a, p. 11) expects "predominantly negative consequences for biodiversity, and ecosystem goods and services e.g., water and food supply". Already a 2°C of warming exposes 15–40% of land species to the risk of extinction (Stern 2007, p. 80).

Although this mere enumeration of impacts draws an impressive picture on what we can expect from higher temperatures, it can neither tell us for what temperatures negative impacts 'out-weigh' positive impacts of warming nor how the net impact compares to the economic capability of societies to compensate for these impacts. Hence, a one-dimensional quantification of impacts may be useful, in particular, when comparing the size of the damages with the costs of avoiding global warming.

Several attempts have been made to quantify the damages of global warming (see IPCC 2007a, Ch. 20.6 for an overview). The outcomes of these studies vary considerably due to different assumptions about normative (or ethical) preferences, economic and physical uncertainties, and valuation of non-market damages (which are assumed to be higher than market damages, see IPCC (2007a, p. 823)). The Stern (2007, p. 143) Review concluded that a business-as-usual warming could reduce per capita consumption by 5–20% for now and forever. While the lower bound reflects the pure market impacts of global warming, the higher number also considers non-market impacts, a higher response of the climate system to GHG emissions, and an explicit equity weighting that captures social inequality aversion. As other studies report lower numbers for climate damages, the IPCC (2007a, p. 17) summarizes:

> "It is very likely that all regions will experience either declines in net benefits or increases in net costs for increases in temperature greater than about 2–3°C. [...] [W]hile developing countries are expected to experience larger percentage losses, global mean losses could be 1–5% GDP for 4°C of warming."

For most non-economists, it is often not convincing to express the value of a functioning global environment in one single monetary number. There is too much hidden aggregation and value judgment nobody can follow. Even in the economic community there are controversial debates about explicit or implicit normative judgments cost-benefit analysis relies on: Which discount rate is appropriate for discounting future damages? Which intra- and intergenerational inequality aversion to choose to consider the heterogeneity of costs and benefits? Which aggregation of individuals to decide on to simplify heterogeneity?[2] How

[2]This is of great importance when inequality aversion plays a role: Considering heterogeneous regions which consist again of one 'representative' agent accounts for the regional heterogeneity of climate damages, but not

to measure the role of natural capital, ecosystem services, stable geo-political environment etc. for human well-being – and for the well-being of humans that do not exist yet? How to deal with deep uncertainties and risks?

The last question also rises some methodical problems within standard approaches of cost-benefit analysis. The ‘Dismal Theorem’ of Weitzman (2009) states that the expected utility does not converge to a finite number if uncertainties are characterized by so-called fat-tailed distributions. Intuitively spoken, extreme unlikely events with extremely high damages cannot by quantified (i.e. measured in one single monetary number) in a meaningful way. With existing estimates of the climate sensitivity, it is impossible to decide whether the climate sensitivity follows a normal or Pareto distribution. In the latter case a concentration stabilization at 800 ppm CO_2-eq. implies an equilibrium temperature increase by more than 10°C with a probability of roughly 5% (Weitzman 2011). Due to the possibility of such extreme events, Weitzman (2011) concludes that “fat tails favor more aggressive policies to lower GHGs than the ‘standard’ BCA [benefit-cost analysis]”.

Finally, quantifying the damages of global warming is criticized as relying primarily on a Utilitarian (or consequentialist) approach: Although it is possible to capture different perceptions about (intra- and intergenerational) inequality in societies, it does not consider the violation of fundamental rights of people. A minimal formulation of these rights as ‘negative’ rights[3] is the base of the Libertarian conviction. The corresponding approach for environmental issues is also denoted with ‘free market environmentalism’ (see Adler 2009; Shahar 2009; Dawson 2011, for some proponents). While this position rejects governments’ legitimacy to impose carbon taxes or upper caps on emissions, it focuses on the Coasian way to refine and precise property rights that are violated by global warming such as land ownership due to increasing sea levels. Victims can ally to enforce compensation from the polluters (e.g. with respect to the firms’ or countries’ share in global emissions).[4] A broader approach on fundamental rights may also integrate positive rights as, for example, formulated by the capabilities approach of Sen (1985). These rights have been concretized, among others, in the Universal Declaration of Human Rights or the UN Millennium De-

for the intra-regional heterogeneity (Anthoff et al. 2009). The lower the aggregation level is, the higher are heterogeneous damages under an inequality averse welfare function.

[3]Negative rights refer to the right of an individual and define what others are not allowed to to with him. Examples are the prohibition of violating physical integrity or property. In contrast, positive rights define what others (or the society) have to do for an individual, such as helping in an emergency situation or affording a basic education and health system.

[4]The approach poses obviously many challenges: How to establish (global) courts that judge causality and size of damages? How to enforce compensation from persons or firms that do not exist anymore but contributed to global warming? How to ‘update’ the judgments if emissions and temperatures continue to increase? How high are the transaction costs and the bargaining power of the affected parties? See also Posner (2007) for a critical appraisal of litigation against human right violations in the context of global warming.

velopment Goals. As global warming increases the risk of droughts, diseases and social conflicts, it may impede the development of individuals and nations, and the reduction of poverty.

From a rights-based perspective, it is difficult to measure how costly such violations of rights are in monetary terms. One possibility is to quantify the amount necessary to compensate the violations (based upon the victims' 'willingness to accept'). If the willingness-to-accept is measured correctly, a mere summing up of these costs (as done by Utilitarian approaches without inequality aversion) gives the costs of these violations. However, such an approach is only valid if the compensation is not only used as theoretical benchmark calculation but actually *realized* in practice. As such realization is not only questionable (Who will *enforce* the compensation? Can governments credibly commit to compensation?) it may also come at high transaction costs (How to determine the concrete amount for an individual person? How to avoid rent-seeking and resource course problems due to large financial flows?). It remains open how to value the violation of fundamental rights that are not compensated.

The considerations above show that there is no simple and satisfying answer to the question how 'bad' or 'good' global warming is. We have gained some rough perceptions about economic, ecological and social impacts but the uncertainties that remain in the Earth system, the manifestation of damages and the choice of the normative approach are tremendous.

The costs of mitigating global warming

After having assessed the impacts of continued global warming, the costs of avoiding global warming (at least to a certain extent) are now discussed. The IPCC (2007c, p. 25) concluded that "[i]ncreases in atmospheric CO_2 since pre-industrial times are responsible for a radiative forcing of $+1.66 \pm 0.17\ W/m^2$; a contribution which dominates all other radiative forcing agents considered in this report". Other greenhouse gases like methane or halocarbons have a higher warming potential, i.e. they induce a higher radiative forcing than CO_2 at the same concentration. Their concentration in the atmosphere, however, is so low that their overall contribution to global warming turns out to be moderate. The sources CO_2 mainly arises from are deforestation including natural biomass use for firing, natural decomposition of biomass, peat fires, cement production, and natural gas flaring. The biggest share of CO_2 emissions, however, comes from using fossil fuels to generate energy: In 2004, more than 55% of the effective global warming potential resulted from CO_2 from fossil fuel use (Fig. 1.1). Since 2004, emissions from fossil fuels continue to increase despite an exceptional drop in 2009 following the financial crises (Friedlingstein et al. 2010).

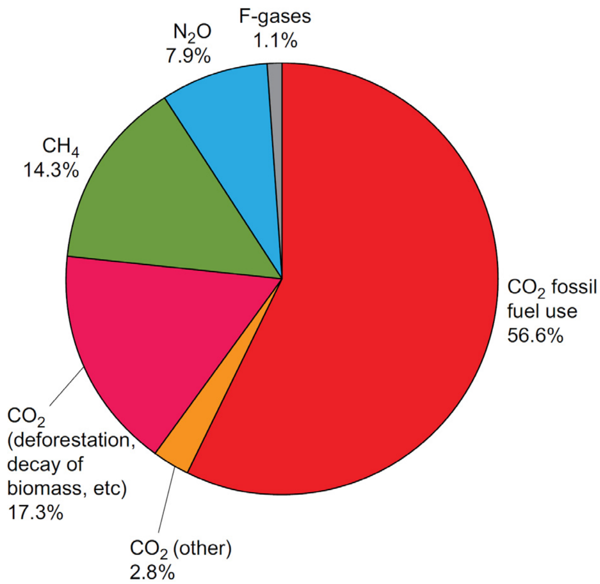


Figure 1.1: Greenhouse gas emissions in 2004 from different sources converted into their 100-year global warming potential (figure taken from IPCC 2007b, p. 28).

Due to the dominant role of fossil fuels and CO_2, mitigating global warming primarily requires to reduce carbon emissions from fossil fuels. Assessing the options and costs for reducing carbon emissions basically relies on information about available energy technologies and their costs, as well as the development of energy demand. It is also necessary to understand the role of infrastructure (often a public capital stock with difficult monetary quantification) and consumers' (and societies') inter-temporal preferences regarding investment decisions. IPCC (2007b, pp. 204–206) presents the calculations of different integrated assessment models (IAMs) for several stabilization targets. Only few models are capable to calculate ambitious stabilization scenarios in the range of 450–535 ppm CO_2-eq. which imply temperature increases by approximately 2–2.8°C. For these low-stabilization scenarios, (current-value) GDP losses vary between -1 and 6%. More recent model comparison projects complement these numbers: Fig. 1.2 shows the mitigation costs for low-stabilization scenarios from two model intercomparison projects (Edenhofer et al. 2010; Luderer et al. 2011). They suggest that ambitious temperature targets are possible at costs lower than 4%, often even lower than 2%. These figures usually assume a comprehensive availability of low-carbon technologies as well as some kind of optimization behavior or the absence of other market failures. In case of limited availability of technologies due to social or environmental constraints (e.g. for nuclear power or biomass use) these costs further increase (Edenhofer et al. 2010; Luderer et al. 2011). Additional market or policy failures in

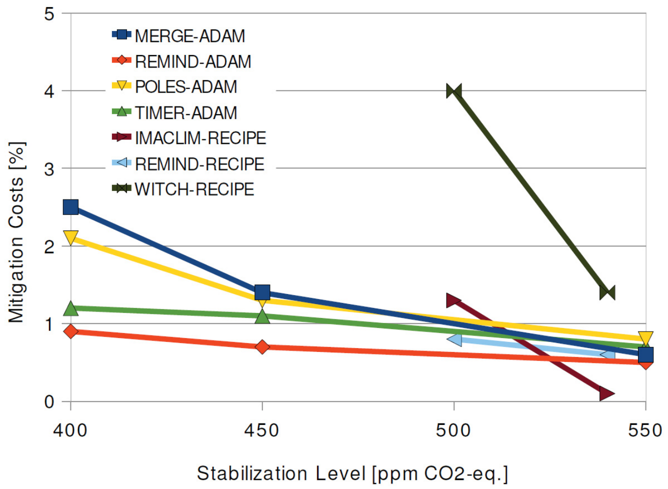


Figure 1.2: Mitigation costs for low stabilization scenarios. Model results from the ADAM project (Edenhofer et al. 2010) report discounted GDP losses, model results from the RECIPE project (Luderer et al. 2011) report discounted consumption losses. Mitigation costs from the model E3MG in Edenhofer et al. (2010) were excluded as they were negative.

the economy (i.e. innovation spillover, regulatory uncertainty, delayed action) will equally raise costs.

Similarly to the estimation of damages, quantifying mitigation costs also relies on implicit or explicit normative judgments. They cover the distributional issues regarding the costs for current and future generations as well as the burden sharing between countries and households with different incomes. Additionally, there is the concern that ambitious mitigation will impede development and increase poverty, i.e. due to rising energy prices or food prices (if cultivation of energy crops is extended). Access to (cheap) energy potentially causes increasing returns to scale and plays a crucial role in the development process (Toman and Jemelkova 2003). Although developing countries are mostly affected by climate change damages, they reject claims for binding mitigation targets (e.g. Reuters 2009). Thus, not only climate change but also its mitigation could violate fundamental human rights, in particular with respect to human development. As typical cost estimates simply sum up monetary costs for reducing emissions, the social costs of mitigation might be substantially higher, especially when no appropriate transfer regimes for compensation can be established.[5]

[5]The difficulties of such transfers lie with their high administration and transaction costs. When carried out on an individual level (that is necessary for a Pareto improvement of the poor) informational requirements are tremendous.

Optimal temperature targets

The huge uncertainties in the estimation of temperature increase, damages and their normative valuation render it difficult to derive an optimal level of global warming. Nevertheless, IAMs aim to quantify damages and costs to give a more precise estimation of the optimal temperature which minimizes costs and damages. One of the most prominent IAMs, the DICE model, calculates 2.6°C warming in 2100 and 3.5°C warming in 2200 as the optimum (Nordhaus 2008, p. 106). In the regionalized model variant RICE, Nordhaus (2010) calculates an optimal increase of 2.7°C for 2100–2300 compared to the base year 1900.

Article 2 of the UNFCCC (1992) demands avoiding "dangerous anthropogenic interference with the climate system" but leaves open how the attribute 'dangerous' relates to concrete temperature levels.[6] In contrast to IAMs, scientists, environmentalists, policy makers, and recently even the international community in the Copenhagen Accord called for limiting global warming to two degree Celsius above pre-industrial levels.[7] This two-degree target seems to be consistent with a cost-benefit analysis where damages are high or mitigation costs low.[8] There are precautionary arguments against standard cost-benefit analysis because uncertainties are tremendous and mankind should simply avoid *terra incognita* if costs are not prohibitive (Weitzman 2010). Another source of precaution arises from the existence of tipping points in the Earth system: Once certain thresholds are crossed, the state of a system is irreversibly altered for centuries or millennia. Lenton et al. (2008) suggest that these tipping points are between 0.5°C and 2°C for the Arctic summer-sea ice and the Greenland ice shield and 3°C or higher for other systems.

So far, the ongoing debate has been inconclusive to what extent cost-benefit-analysis or Weitzman's Dismal Theorem can be applied to the climate problem (Horowitz and Lange 2008; Millner 2011). Due to the deep underlying uncertainties regarding climate sensitivity, damages and normative valuations, the WBGU (2009) proposed a constraint on cumulative emissions – a so-called *carbon budget* – as a pragmatic alternative for climate policy analysis. When set appropriately, such a budget can with a certain probability limit temperature increase to moderate levels and, hence, reduce many of the risks of global warming.

[6] See Oppenheimer and Petsonk (2005) for an interpretation.

[7] The history of the two-degree target is illustrated in Randalls (2010).

[8] Sterner and Persson (2008) use a modified DICE model with imperfect substitutability between (economic) consumption goods and environmental amenities. They find that even for a pure social time preference rate of 3 percent CO_2 concentrations peak at 450 ppm and temperature increase only slightly overshoots two degrees. In case of lower discounting, the optimal CO_2 concentration reaches even 400 ppm in 2100.

1.1.3 Policy instruments for mitigation

Although there prevails (scientific) controversy about the optimal level of temperature increase and, thus, the optimal extent of mitigation, there is a consensus that emissions should be reduced (rather than increased). Two major issues render the practical realization of emission reductions on a global scale. The first is a global coordination problem. The provision of a stable climate is challenging because of its pure public good nature that evokes high free-rider incentives for single states in combination with the lack of an international enforcement authority.[9] The second issue is concerned with the operation of different policy instruments in a decentralized economy to reduce emissions.

Questions related to international cooperation are usually discussed within game-theoretic models that explore the scope of cooperation if countries maximize their own pay-off. Here, only two basic ideas are presented how to deal with this issue. One approach is to use coalition models where countries of a climate coalition maximize joint welfare. Such a coalition can be extended and stabilized by using the market power of the coalition, i.e. by implementing tariffs against free-riders (Barrett 1997; Stiglitz 2007; Lessmann et al. 2009) or by establishing technology transfers for coalition members (Lessmann and Edenhofer 2011). Another approach relies on the theory of repeated games, where iterated responses to other players' behavior are able to transform a suboptimal Nash equilibrium into a Pareto-optimal Nash equilibrium. For the case of global warming, Heitzig et al. (2011) establish a mechanism that uses specific allocation rules in a repeated emissions trading game to punish free-riders.

Despite the difficulties to overcome free-rider incentives in public good problems, many economic analysis focuses on the performance of different policies given a regulatory authority that is able to implement and enforce them. This strand of research use the theory of externalities as starting point and elaborates to what extent different policy instruments can 'internalize' them. The classic definition of an externality corresponds to an 'indirect' effect of an economic activity that affects other individuals or firms positively or negatively. The effect is 'indirect' as there is no explicit price or market transaction assigned to which would signal the real (social) costs of this activity. Hence, an externality simply describes a situation where markets for specific activities are missing – either because transaction costs are high, information asymmetries persist or (private) property rights cannot be assigned in a meaningful way. The latter is the case for climate change, as the atmosphere or the good

[9] A public good is defined by the two properties non-rivalry and non-excludability. A stable climate is a non-rival good because – once provided – its 'use' does not diminish (i.e. marginal costs are zero). It is non-excludable because nobody can be prevented from benefiting from a stable climate. The latter property causes free-rider incentives: For each agent (individuum or country) it is better to let the others contribute to the public good provision while oneself enjoys the benefits.

'stable climate' is non-excludable and cannot be separately allocated to different agents. The basic approach to solve this form of market failure is to internalize the social costs by putting a price on GHG emissions.

There has been a controversial debate between economists whether the social costs are better internalized via a direct tax or indirectly via a cap-and-trade system where prices are established on a certificate market. Under idealized conditions, both instruments are equivalent and can achieve an efficient allocation of pollution. Under uncertainty, however, the classical Weitzman (1974) paper shows under which conditions one instrument outperforms the other: If the marginal damage curve is steeper (flatter) than the marginal cost curve, quantity regulation leads to higher (lower) expected welfare than price regulation. Newell and Pizer (2003) transfer the static Weitzman framework to the dynamic stock-pollutant problem of global warming. As damages become a function of the cumulative amount of emissions, marginal damages of (flow) emissions are initially low and grow over time (when atmospheric concentration increases). Hence, after an initial phase of using taxes, the regulator should shift to quantity instruments in the long run.[10] Sinn (2008b) motivates a different perspective on the price vs. quantity debate by focusing on the supply-side dynamics: Mal-designed carbon taxes can accelerate rather than reduce or postpone emissions ('green paradox'). Resource owners fear the threat of increasing carbon taxes in the future and therefore extract emissions as long as carbon taxes are low. The underlying mechanism is based on the huge amount of carbon that exists in the ground and that mitigation policies devalue these resources (see Fig. 1.3). In contrast to the complex response of fossil resource extraction to carbon taxes, a global cap-and-trade system controls emissions directly and rules out the occurrence of a green paradox. Besides pure economic arguments, there are political economy arguments in favor of price or quantity instruments. Nordhaus (2007) prefers carbon taxes due to a series of reasons: First, it is difficult to set a clear baseline for quantity policies which increases the possibility of hot air where large transfers between countries arise. Secondly, due to inelastic supply of permits under an emissions trading scheme (ETS) and the inelastic short-term demand for energy, permit prices will be highly volatile with disruptive effects on the economy and investment. Thirdly, experience with the US SO_2 and EU CO_2 emissions trading scheme suggests that permits are grandfathered to a large extent (rather than used to cut existing taxes) which increases deadweight losses of the existing tax system[11]. Finally, an ETS is an explicit rent-creating policy inducing rent-seeking behavior or 'resource curses'-like effects due to massive financial flows in

[10] The timing of this shift depends on the discount rate, the decay of CO_2 in the atmosphere, the damage function and the correlation of cost shocks. For a critical discussion of these parameters see Edenhofer et al. (2011, pp. 172–178).

[11] See also Parry and Williams III (2010) on this issue.

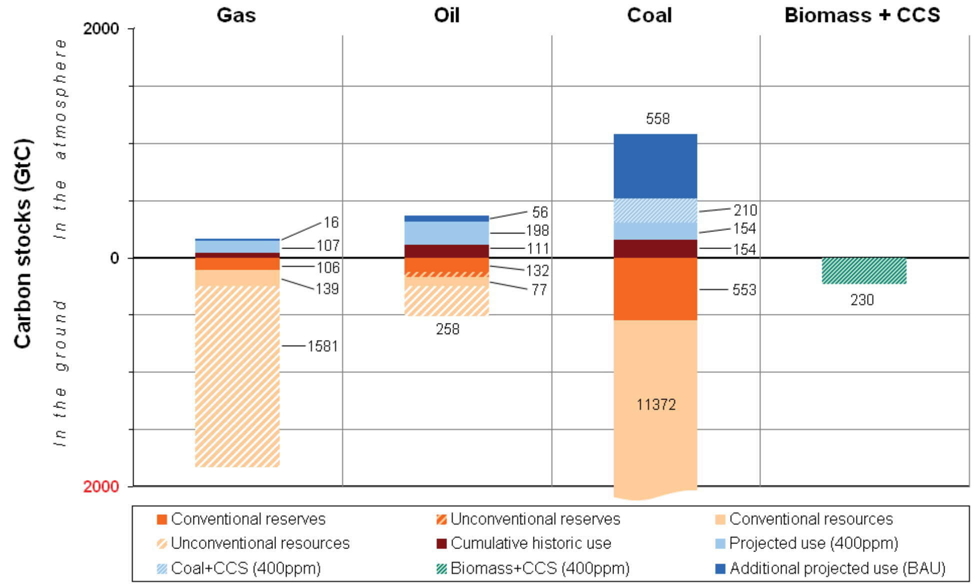


Figure 1.3: Cumulative historic carbon consumption (1750-2004), estimated carbon stocks in the ground, and estimated future consumption (2005-2100) for a business-as-usual scenario and an ambitious 400ppm CO_2-eq. mitigation scenario. Carbon capture and sequestration technologies (CCS) reduce emissions of coal combustion near zero and lead to negative emissions in combination with biomass combustion (in total 440 GtC are stored underground by CCS which would be emitted additionally in the BAU scenario). Fossil energy stocks are converted to carbon dioxide emissions by using emission factors from IPCC (2006, Ch. 1, Tab. 1.3). *Sources:* Reserves BGR (2009); historic consumption Boden et al. (2010); scenarios Edenhofer et al. (2010).

poor countries. Olmstead and Stavins (2006, 2010) argue that although many economists advocate carbon taxes, political support is low and harmonization of taxes has so far been difficult. Most importantly, emissions trading allows to separate the efficiency issue of reducing carbon emissions at least costs from the distributional issue of burden sharing: The allocation of allowances gives an additional degree of freedom to redistribute costs (or more exactly: rents) across firms, households and countries. An emissions trading scheme is, thus, the only way to combine efficiency and equity aspects in one instrument. While Nordhaus (2007) suggests to compensate developing countries that implement an internationally harmonized carbon tax, Hepburn and Stern (2008) are skeptical about separate transfers due to the evidence of broken commitments to Overseas Development Assistance.

Besides the need for a carbon price, some economists demand for innovation policies to foster the development and cost decrease of low-carbon technologies (e.g. Stern (2007, Ch. 10) or Aghion et al. (2009)). The basic argument is that innovation causes positive externalities because new knowledge about technologies is a public good. Patents can transform this knowledge to a certain extent into a private good (not all knowledge can be patented effectively) and reduce the free-rider incentive for non-innovators. By the same time, however, patents reduce efficiency due to the temporal monopoly power of the patent holder. Hence, either there is too few innovation (if innovations cannot be protected) or the innovation spreads out too slowly (if patents monopolize innovation). Several economists therefore argue that climate change is related to a double market failure: One regarding the GHG emissions, the other regarding the innovation process (Jaffe et al. 2005; Stern 2007; Acemoglu et al. 2009). According to the Tinbergen (1952) rule, two separate instruments have to be applied to address them: One carbon pricing policy and one technology policy.

Nevertheless, there are also critics of this view. Nordhaus (2009) accepts the market failure for innovation, but rejects its prominent role for the climate problem. As innovation spillovers affect all economic sectors, a generic policy has to be implemented which does not discriminate between dirty, clean or neutral innovations. Sinn (2008a, Ch. 3) argues along similar lines but also emphasizes that the costs of technology policies will always be higher than their benefits, because regulators have too little information and are highly influenced by lobbyists. A 'strong' ETS will – by definition – always reduce emissions and foster innovation into alternative technologies. Thus, the innovation market failure becomes small or even obsolete. Finally, technology policies under an emissions trading scheme are criticized as they do not reduce emissions, distort price signals and promote pollution-intensive technologies indirectly (i.e. Böhringer and Rosendahl 2010).

The economic debate about policy instruments focuses mainly on efficiency aspects. Policy makers and regulators are, however, usually concerned with political acceptance and feasibility, which comprises distributional issues (perceived fairness), commitment and credibility issues, administrative feasibility as well as possible side-effects and co-benefits to related problems (Bennear and Stavins 2007). One problem with carbon pricing is that it increases energy prices which might affect poor households and energy-intensive industries over-proportionally. In contrast, command-and-control policies as well as technology policies allow to combine innovation and industry policy with environmental policy. As governments can hardly commit to future carbon prices – which is essential to drive investments into clean technologies – technology policies can also serve as practical alternative to direct investments (Ulph and Ulph 2009). Furthermore, proponents of renewable energy technologies have argued that costs will decline fast enough and co-benefits (beside mitigation) are so high that one should abandon carbon pricing policies and concentrate on renewable energy policies (e.g. Weber 2010).

Finally there is an important rent transformation aspect associated to climate policy. The available resources of fossil carbon in the ground exceeds the amount of carbon that can be deposited in the atmosphere by a multitude (see Fig. 1.3). While in a business-as-usual world conventional oil and gas are scarce resources with a considerable scarcity rent, climate policy makes fossil resources abundant: They become worthless. Currently, the value of fossil resource consumption amounts to 5–6% of the world GDP with oil contributing alone four percentage points.[12] Climate policy does not only affect fossil scarcity rents but also almost everything else in the economy by influencing the value of (fossil-related) human and physical capital, energy prices, food prices, financial assets etc. (see Fullerton 2011, for more details). No matter how it is implemented, climate policy will remain a huge and conflict-laden rent transformation program, provoking high resistance from wide parts of the society. At the same time, carbon pricing explicitly creates a new rent associated to the scarcity of the atmosphere. Barnes et al. (2008) claim in their proposal for an 'Atmospheric Trust' that these rents should be managed by an independent institution. One fraction should be transferred to each individual reflecting that fact that every person has the equal property right on the common natural resources, the remaining fraction should be invested into low-carbon technologies on order to accelerate the transformation. The issue of rent transformation and an Atmospheric Trust institution will be re-examined in the synthesis chapter of this thesis.

1.2 Objective

The previous sections emphasized the high controversy about optimal mitigation targets and policy instruments to achieve them. The aim of this thesis is to analyze how carbon taxes, emissions trading schemes and technology policies can contribute to mitigating global warming. It takes as given that society wants to reduce carbon emissions to a certain extent and that a regulatory institution exists to implement concrete policy measures.

The thesis takes up current economic and political debates about efficient and effective policies as shaped in Sec. 1.1.3: Are price instruments better than quantity instruments? Is an ambitious emissions trading scheme sufficient to foster innovation in low-carbon technologies? Are technology policies appropriate to reduce emissions and, if so, what technologies should be supported?

Policy makers are often confronted with multiple objectives and constraints (Bennear and Stavins 2007). This serves as motivation to consider not only efficient (text-book) instruments but also second-best policies. In doing so, this thesis concentrates on three central research questions:

1. How robust are carbon taxes, emissions trading and technology policies regarding

[12] This number represents the *flow* value of fossil resources and is obtained by multiplying current fossil resource consumption according to BP (2011) with the corresponding market prices. Hence, extraction costs are already considered and the pure rents should be lower.

their (environmental) effectiveness? In particular, can ‘green paradoxes’ occur that imply acerbating global warming due to imperfect implementation of policies?

2. Can technology policies be efficiency-improving and reduce mitigation costs if a ‘perfect’ emissions trading scheme already exists? Is there an outstanding role of technology policies in the energy sector compared to other parts of the economy?

3. Can technology policies be a reasonable second-best policy if carbon prices are missing, introduced in the future or implemented at suboptimal levels?

The analysis is performed within theoretical partial equilibrium models as well as numerical general equilibrium models. The theoretical models give a general understanding of the performance of policy instruments under explicit assumptions and circumstances. In contrast, the numerical model exercise allows to consider complex dynamic aspects that are hardly solvable analytically as well as a quantitative assessment of policies. In most cases, it will be convenient to formulate the mitigation target as upper bound for cumulative emissions – the ‘carbon budget’ (WBGU 2009). The level of this carbon budget is an appropriate indicator for the expected temperature increase (Meinshausen et al. 2009). Within this cost-effectiveness approach an explicit assessment of climate damages is not necessary although damage estimations (and their normative valuation) by all means influence the mitigation target. Each chapter considers at least one, often two of these questions in a different technological or economic setting. To provide answers, policy instruments are usually evaluated with respect to efficiency and robustness. The latter is often done by emphasizing the impact of (small) deviations from the optimal policy on the outcome. The second-best policy analysis is partly motivated by distributional concerns and therefor the impact of policies on energy prices and fossil resource rents is also evaluated.

1.3 Outline

The thesis consists of five self-contained articles (chapters) and is divided into two parts. Part I (Chapter 2 and 3) analyzes carbon taxes and emissions trading within a series of partial-equilibrium Hotelling models. Part II (Chapter 4–6) develops the integrated policy assessment model PRIDE (Policy and Regulatory Instruments in a Decentralized Economy) to study intertemporal general equilibrium effects of policy instruments.

In Chapter 2, the original green paradox paper of Sinn (2008b) is reconsidered. Sinn’s well-known analysis based on cash-flow or ad-valorem taxes led to the conclusion that increasing carbon taxes and other demand-reducing policies accelerate resource extraction and, thus, emissions rather than reducing them. As carbon taxes are, however, related to the carbon content of fossil resources independently of their market value, they are unit taxes rather than ad-valorem or cash-flow taxes. Chapter 2 shows that such a green paradox occurs only under specific conditions if (increasing) *unit* taxes are used. By referring on existing carbon tax calculations of integrated assessment models, it concludes that a green paradox is possible but not very likely to occur if an appropriate carbon tax would be implemented. The chapter has been published in *Energy Policy*.[13]

Chapter 3 focuses on further aspects regarding the robustness of price and quantity instruments. It shows how suboptimal (green paradox provoking) taxes can evolve from a political process that responses to increasing climate damages. It also elaborates how robust carbon taxes and emissions trading are if resource owners discount future payoffs at a rate higher than the social discount rate, i.e. due to risk premiums. Finally, the 'division of labor' between the regulator and the market is studied: The design of price and quantity instruments determines who ultimately manages intertemporal allocation decisions – be it in a cost-benefit or in a cost-effectiveness (carbon budget) mode. The analysis shows that the intertemporal allocation problem (how much emissions when to release in the atmosphere) is difficult decentralize. Therefore, climate policy relies on a well-designed (public) institution to manage the atmosphere. The chapter has been published as *CESifo Working Paper*[14] and is in preparation for publication in *Ecological Economics*.

The first chapter of the second part introduces the climate policy assessment model PRIDE. Chapter 4 takes up the economic debate about the role of innovation and technology policies when ambitious carbon pricing policies already exist. Existing models find that additional policies fostering innovation are often welfare-increasing. However, the quantitative effect of these policies is usually moderate if an appropriate carbon pricing policy is implemented. The achievement of Chapter 4 is to elaborate that the small welfare impact of technology policies depends on two crucial assumptions made in most models: The heterogeneity of low-carbon technologies is suppressed by assuming one generic carbon-free technology (i.e. renewable energy) or the elasticity of substitution between energy technologies is moderate. Chapter 4 relaxes these two critical assumptions by considering two carbon-free technologies, one learning and one non-learning technology, as an alternative to fossil-based energy technologies. Additionally, an extensive parameter study is conducted emphasizing the role of the elasticity of substitution between technologies in exacerbating market failures. The model shows how a lock-in into an intertemporally inferior technol-

[13] Edenhofer, O. and Kalkuhl, M. (2011): When Do Increasing Carbon Taxes Accelerate Global Warming? A Note on the Green Paradox. *Energy Policy*, 39(4), 2208–2212.

[14] Kalkuhl, M. and O. Edenhofer (2010): Prices vs. Quantities and the Intertemporal Dynamics of the Climate Rent. *CESifo Working Paper* No. 3044.

ogy can occur although firms have perfect information and optimize intertemporally. Such a lock-in had so far only been described qualitatively (Unruh 2000; Stern 2007), but not shown within a computable general equilibrium model. Finally, several policies are analyzed to prevent lock-ins which differ in their degree of technology discrimination and re-financing mechanism. The chapter has been published in *Resource and Energy Economics*.[15]

While Chapter 4 focuses on efficiency arguments for subsidizing innovative low-carbon technologies as e.g. renewable energy, Chapter 5 takes an explicit second-best policy perspective. If governments cannot implement optimal carbon pricing policies, can they use renewable energy policies to decrease emissions? Only few scholars discuss this as economists usually tend to recommend the first-best policy (carbon pricing) instead of an inefficient second-best policy. However, the second-best perspective is of particular relevance with respect to the political constraints regarding carbon prices as well as the popularity of technology policies due to their local and national benefits. The model analysis is novel insofar as it considers the impact of renewable energy subsidies on the supply-side dynamics of fossil resource extraction. It provides a comprehensive assessment of several second-best policies on a global scale. The chapter has been submitted to *Resource and Energy Economics*.[16]

Chapter 6 is motivated equally but extends the PRIDE model by a carbon capture and sequestration sector (CCS) and appropriate CCS policies. Although many policy-makers and environmentalists favor renewable energy policies as second-best (or sometimes even 'best') policy for transforming the energy system, they are skeptical regarding CCS. As CCS is a mitigation option that can decrease emissions by simultaneously using fossil resources, it has quite opposite characteristics as renewable energy subsidies. The chapter explores the capability of pure CCS policies as well as hybrid CCS, renewable energy and carbon pricing policies to reduce emissions. Following an analytical consideration how CCS subsidies can replace a carbon tax without efficiency losses in a partial equilibrium model, the PRIDE model is modified. Several second-best scenarios are considered as well as a broad variation of parameters. This chapter has been submitted to the *Journal of Public Economics*.[17]

The main findings of the thesis are summarized in Chapter 7. In particular, the relevance of the research for the current climate policy is emphasized and further research topics explored.

[15] Kalkuhl, M., Edenhofer, O. and Lessmann, K. (2012): Learning or Lock-in: Optimal Technology Policies to Support Mitigation. *Resource and Energy Economics*, 34(1), 1–23.

[16] Kalkuhl, M., Edenhofer, O. and Lessmann, K.: Renewable Energy Subsidies: Second-best Policy or Fatal Aberration for Mitigation? Submitted to *Resource and Energy Economics*.

[17] Kalkuhl, M., Edenhofer, O. and Lessmann, K.: The Role of Carbon Capture and Sequestration Policies for Climate Change Mitigation. Submitted to the *Journal of Public Economics*.

Bibliography

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2009). The environment and directed technical change. *NBER Working Paper* (15451).

Adler, J. (2009). Taking property rights seriously: The case of climate change. *Social Philosophy and Policy 26*(02), 296–316.

Aghion, P., R. Veugelers, and C. Serre (2009). Cold start for the green innovation machine. *Bruegel Policy Contribution 12*, 2009.

Anthoff, D., C. Hepburn, and R. Tol (2009). Equity weighting and the marginal damage costs of climate change. *Ecological Economics 68*(3), 836–849.

Barnes, P., R. Costanza, P. Hawken, D. Orr, E. Ostrom, A. Umaña, and O. Young (2008). Creating an earth atmospheric trust. *Science 319*(5864), 724b.

Barrett, S. (1997). The strategy of trade sanctions in international environmental agreements. *Resource and Energy Economics 19*(4), 345–361.

Bennear, L. and R. Stavins (2007, May). Second-best theory and the use of multiple policy instruments. *Environmental and Resource Economics 37*(1), 111–129.

BGR (2009). Energierohstoffe 2009. Reserven, Ressourcen, Verfügbarkeit. Technical report, Bundesamt für Geowissenschaften und Rohstoffe, Hannover, Germany.

Boden, T., G. Marland, and R. Andres (2010). Global, regional, and national fossil-fuel CO2 emissions. Technical report, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Böhringer, C. and K. Rosendahl (2010). Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. *Journal of Regulatory Economics 37*(3), 316–325.

BP (2011). Statistical review of world energy. Technical report.

Dawson, G. (2011). Free markets, property rights and climate change: How to privatize climate policy. *Libertarian Papers 3*, 10.

Edenhofer, O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos, M. Leimbach, K. Lessmann, B. Magne, S. Scrieciu, H. Turton, and D. P. van Vuuren (2010). The economics of low stabilization: Model comparison of mitigation strategies and costs. *The Energy Journal 31*(Special Issue), 11–48.

Edenhofer, O., R. Pietzcker, M. Kalkuhl, and E. Kriegler (2011). Tax instrument for reducing emissions: An overview. In F. Gang, L. N. Stern, O. Edenhofer, X. Shanda, K. Eklund, F. Ackerman, L. Lailai, and K. Hallding (Eds.), *The Economics of Climate Change in China. Towards a Low Carbon Economy*, Chapter 6, pp. 167–211. London and Washington, D.C.: Earthscan.

Friedlingstein, P., R. Houghton, G. Marland, J. Hackler, T. Boden, T. Conway, J. Canadell, M. Raupach, P. Ciais, and C. Le Quéré (2010). Update on CO2 emissions. *Nature Geoscience 3*(12), 811–812.

Fullerton, D. (2011). Six distributional effects of environmental policy. *Risk Analysis 31*(6), 923–929.

Heitzig, J., K. Lessmann, and Y. Zou (2011). Self-enforcing strategies to deter free-riding in the climate change mitigation game and other repeated public good games. *Proceedings of the National Academy of Sciences 108*(38), 15739–15744.

Hepburn, C. and N. Stern (2008). A new global deal on climate change. *Oxford Review of Economic Policy 24*(2), 259–279.

Horowitz, J. and A. Lange (2008). What's wrong with infinity – a note on Weitzman's Dismal Theorem. *University of Maryland, Working Paper*.

IPCC (2006). *IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 1 Energy. Hyama, Japan: Institute for Global Environmental Strategies.

IPCC (2007a). *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

IPCC (2007b). *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

IPCC (2007c). *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

Jaffe, A. B., R. G. Newell, and R. N. Stavins (2005). A tale of two market failures: Technology and environmental policy. *Ecological Economics 54*(2-3), 164–174.

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber (2008). Tipping elements in the earth's climate system. *Proceedings of the National Academy of Sciences 105*(6), 1786–1793.

Lessmann, K. and O. Edenhofer (2011). Research cooperation and international standards in a model of coalition stability. *Resource and Energy Economics 33*(1), 36–54.

Lessmann, K., R. Marschinski, and O. Edenhofer (2009). The effects of tariffs on coalition formation in a dynamic global warming game. *Economic Modelling 26*(3), 641–649.

Luderer, G., V. Bosetti, M. Jakob, M. Leimbach, J. Steckel, H. Waisman, and O. Edenhofer (2011). The economics of decarbonizing the energy system–results and insights from the RECIPE model intercomparison. *Climatic Change*. in press.

Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature 458*(7242), 1158–1162.

Millner, A. (2011). On welfare frameworks and catastrophic climate risks. *University of California, Berkeley, Working Paper*.

Newell, R. G. and W. A. Pizer (2003, March). Regulating stock externalities under uncertainty. *Journal of Environmental Economics and Management 45*(2, Supplement 1), 416–432.

Nordhaus, W. (2007). To tax or not to tax: Alternative approaches to slowing global warming. *Review of Environmental Economics and Policy 1*(1), 26–44.

Nordhaus, W. (2008). *A Question of Balance. Weighing the Options on Global Warming Policies.* New Haven, USA: Yale University Press.

Nordhaus, W. (2010). Economic aspects of global warming in a post-copenhagen environment. *Proceedings of the National Academy of Sciences 107*(26), 11721.

Nordhaus, W. D. (2009). Designing a friendly space for technological change to slow global warming. *Snowmass Conference on Technologies to Combat Global Warming, Snowmass (CO), August 3-4*.

Olmstead, S. and R. Stavins (2006). An international policy architecture for the post-kyoto era. *The American economic review 96*(2), 35–38.

Olmstead, S. and R. Stavins (2010). Three key elements of post-2012 international climate policy architecture. *Fondazione Eni Enrico Mattei Working Papers*, 486.

Oppenheimer, M. and A. Petsonk (2005). Article 2 of the UNFCCC: Historical origins, recent interpretations. *Climatic Change 73*(3), 195–226.

Parry, I. and R. Williams III (2010). What are the costs of meeting distributional objectives for climate policy? *The BE Journal of Economic Analysis & Policy 10*(2), 9.

Posner, E. (2007). Climate change and international human rights litigation: a critical appraisal. *University of Chicago Law & Economics, Olin Working Paper No. 329, University of Chicago, Public Law Working Paper No. 148*.

Rahmstorf, S. (2010, April). A new view on sea level rise. *Nature Reports Climate Change*, 44–45.

Randalls, S. (2010). History of the 2 C climate target. *Wiley Interdisciplinary Reviews: Climate Change 1*(4), 598–605.

Reuters (2009). India will reject greenhouse gas emission targets. June 30.

Sen, A. (1985). *Commodities and capabilities*. North-Holland.

Shahar, D. (2009). Justice and climate change: Toward a libertarian analysis. *Independent Review 14*, 219–237.

Sinn, H.-W. (2008a). *Das Grüne Paradoxon: Plädoyer für eine illusionsfreie Klimapolitik*. Berlin: Econ.

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

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

Sterner, T. and U. Persson (2008). An even Sterner review: Introducing relative prices into the discounting debate. *Review of Environmental Economics and Policy 2*(1), 61–76.

Stiglitz, J. (2007). *Making globalization work*. WW Norton & Company.

Tinbergen, J. (1952). *On the theory of economic policy*. Amsterdam: North-Holland.

Toman, M. T. and B. Jemelkova (2003). Energy and economic development: An assessment of the state of knowledge. *The Energy Journal 24*(4), 93–112.

Ulph, A. and D. Ulph (2009). Optimal climate change policies when governments cannot commit. *Discussion Paper Series, Department of Economics University of St. Andrews* (0909).

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

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy 28*(12), 817–830.

WBGU (2009). Solving the climate dilemma: The budget approach. Special report, German Advisory Council on Global Change, Berlin.

Weber, E. (2010). Emissionen verringern? Klingt furchtbar. *Süddeutsche Zeitung*. 11 June 2010.

Weitzman, M. (2009). On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics 91*(1), 1–19.

Weitzman, M. (2010). GHG targets as insurance against catastrophic climate damages. NBER Working Papers 16136, National Bureau of Economic Research, Inc.

Weitzman, M. (2011). Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy 5*(2), 275–292.

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

Part I

The Supply-side Dynamics of Climate Policy

Chapter 2

When Do Increasing Carbon Taxes Accelerate Global Warming? A Note on the Green Paradox

Abstract: The "green paradox" by Hans-Werner Sinn suggests that increasing resource taxes accelerate global warming because resource owners increase near-term extraction in fear of higher future taxation. In this note we show that this effect does only occur for the specific set of carbon taxes that increase at a rate higher than the effective discount rate of the resource owners. We calculate a critical initial value for the carbon tax that leads to a decreased cumulative consumption over the entire (infinite) time horizon. Applying our formal findings to carbon taxes for several mitigation targets, we conclude that there is a low risk of a green paradox in case the regulator implements and commits to a permanently mal-adjusted tax. This remaining risk can be avoided by an emissions trading scheme as suggested by Sinn – as long as the emission caps are set appropriately and the intertemporal permit market works correctly.

2.1 Introduction

The green paradox of Sinn (2008) analyzes possible responses of intertemporally profit maximizing fossil resource owners to climate policy, which are omitted by many existing studies on climate policy instruments. The focus on the dynamics of fossil fuel supply leads to important implications regarding the effectiveness and robustness of policy instruments. By examining several tax schemes, Sinn concludes that "measures to reduce carbon demand, ranging from taxes on fossil fuel consumption to the development of alternative energy sources [. . .] will not mitigate the problem of global warming" (Sinn 2008, p. 388). The analysis of Sinn is in particular based on a formal examination of increasing *ad-hoc*[1] cash-flow taxes for resource owners within a Hotelling model. Increasing cash-flow taxes raise the value of resources extracted in the present relative to the resources extracted in the far-distant future. As such taxes, for Sinn's model assumptions, always exhaust the entire stock within infinite time, such a relative up-valuation of early extracted fossil resources leads to higher near-term extraction compared to the zero-tax case. Thus, increasing cash-flow taxes accelerate extraction and worsen global warming (the "green paradox"). Therefore, Sinn proposes several other policies like decreasing cash-flow taxes, constant unit taxes, *in-situ* subsidies, emissions trading, or capital source taxes which slow down and postpone extraction.

In this note, we focus on the impact of increasing unit taxes on resource extraction instead of cash-flow taxes because the economic and political debate mainly centers on CO_2 or carbon taxes as unit taxes which are not linked to actual prices of fossil resources (e.g. IPCC 2007, pp. 755-756; Nordhaus 2008; Stern 2008; Edenhofer et al. 2010). As it turns out, the denomination 'increasing taxes' has a very different meaning and incentive effect for unit and cash-flow taxes. This comes from the intertemporal dynamics of the resource extraction model which generates increasing resource prices due to increasing scarcities. We use basically the same model as Sinn (2008) and extend the original model by a formal analysis of unit taxes. While Sinn focuses only on a pure timing effect of policies (i.e. a pure intertemporal reallocation of resource extraction without affecting the cumulative amount of extraction), we will also take into account a volume effect (i.e. a lower cumulative amount of extraction within an infinite time horizon).

2.2 The effect of increasing resource taxes

In order to keep the analysis simple, we assume constant extraction costs $c \geq 0$ and focus on the tax and price dynamics of the standard Hotelling (1931) problem for a competitive resource industry as presented in Sinn (2008). There, resource owners maximize profit according to:

$$\begin{aligned}
&\max \int_0^\infty (1-v(t))(p(t)-c)q(t)e^{-rt}\,dt \\
&\dot{S}(t) = \frac{dS(t)}{dt} = -q(t) \\
&S(0) = S_0
\end{aligned}$$

[1] The tax is *ad-hoc* because it is not derived from an optimality or efficiency criterion.

where $p(t)$ is the resource price, $q(t)$ the resource extraction, r the interest rate, $S(t)$ the resource stock in the ground and $0 < S_0 < \infty$ the initial stock size. The resource price is determined by the demand function $q(p)$ with $q'(p) = \frac{\partial q(p)}{\partial p} < 0$ and $q(p) > 0$ for all $p > 0$.[2] In contrast to Sinn's increasing cash-flow tax $v(t) = 1 - \psi_0 e^{\sigma t}$ with $\sigma \geq 0$ we will in the following consider the unit tax $\tau(t) = \tau_0 e^{\theta t}$ which increases at a constant rate θ. The maximization problem, hence, reads:

$$\max \int_0^\infty (p(t) - \tau(t) - c)q(t)e^{-rt}\, dt$$
$$\dot{S}(t) = \frac{dS(t)}{dt} = -q(t)$$
$$S(0) = S_0$$

By setting up the Hamiltonian (in the following, we suppress the explicit time-dependency of the variables p, q, τ, λ and S)

$$H = (p - \tau - c)q + \lambda \dot{S}$$

we obtain as first-order conditions:

$$\lambda = p - \tau - c$$
$$\dot{\lambda} = r\lambda$$

These lead to the Hotelling rule

$$r = \frac{\dot{p} - \dot{\tau}}{p - \tau - c} = \frac{\dot{p} - \dot{\tau} + r\tau}{p - c} = \frac{\dot{p} + (r - \theta)\tau}{p - c} \tag{2.1}$$

and to the transversality condition

$$0 = \lim_{t \to \infty} \lambda S e^{-rt} = \lim_{t \to \infty} (p - \tau - c) S e^{-rt}$$

The resource price cannot be lower than the sum of the tax and the extraction costs, $p \geq \tau + c$. We define τ_0^* as the initial tax level where a pure tax-and-extraction-cost-price would

[2] Sinn's model assumptions imply a positive demand for fossil resources for arbitrarily high resource prices – i. e. there is no backstop-technology as a perfect substitute. Several working papers which relax this assumption and consider the impact of backstop energy and/or subsidies on backstop energy have recently been published (i.e. Gerlagh 2011; Grafton et al. 2010; Van der Ploeg and Withagen 2010). However, we neglect this modification because our aim is to concentrate on the impact of carbon taxes within the original Sinn (2008) model.

equalize cumulative demand with the entire resource stock, i.e.[3]

$$\int_0^\infty q(\tau_0^* e^{\theta t} + c)\, dt = S_0 \tag{2.2}$$

Proposition 2.1. *(a) If $\tau_0 \leq \tau_0^*$, the entire resource stock will be depleted in infinite time, i.e. $S_\infty := \lim_{t\to\infty} S = 0$. (b) If $\tau_0 > \tau_0^*$, the stock will not be exhausted in infinite time, i.e. $S_\infty > 0$; we say the tax provokes a volume effect.*

Proof. Solving the inhomogeneous linear differential equation (2.1) for the resource price p with $p_0 := p(0)$, we obtain:

$$p = \tau_0 e^{\theta t} + (p_0 - \tau_0 - c)e^{rt} + c \tag{2.3}$$

The transversality condition reads:

$$(p_0 - \tau_0 - c)S_\infty = 0 \tag{2.4}$$

The final size of the resource stock S_∞ is characterized by the cumulative demand $q(p)$ with the consumer price p given by (2.3):

$$S_\infty = S_0 - \int_0^\infty q\left(\tau_0 e^{\theta t} + (p_0 - \tau_0 - c)e^{rt} + c\right)\, dt \tag{2.5}$$

(a): Suppose that $S_\infty > 0$. Then the transversality condition (2.4) implies that $p_0 - \tau_0 - c = 0$. Hence, final resource stock equation (2.5) reads:

$$S_\infty = S_0 - \int_0^\infty q(\tau_0 e^{\theta t} + c)\, dt \leq S_0 - \int_0^\infty q(\tau_0^* e^{\theta t} + c)\, dt = 0$$

as $\tau_0 \leq \tau_0^*$, $q'(p) < 0$ and τ_0^* is according to (2.2) the stock-depleting tax level. This is, however, a contradiction to the assumption $S_\infty > 0$.
(b): If $\tau_0 > \tau_0^*$, with equation (2.5) follows:

$$\begin{aligned} S_\infty &= S_0 - \int_0^\infty q(\tau_0 e^{\theta t} + (p_0 - \tau_0 - c)e^{rt} + c)\, dt \\ &> S_0 - \int_0^\infty q(\tau_0^* e^{\theta t} + (p_0 - \tau_0 - c)e^{rt} + c)\, dt \\ &\geq S_0 - \int_0^\infty q(\tau_0^* e^{\theta t} + c)\, dt = 0 \end{aligned}$$

[3] In a recent working paper, Hoel (2010) provides a similar definition describing a "large" tax that reduces cumulative extraction below a certain threshold. We differ from Hoel by assuming an exponential tax because we focus in the following on the initial tax level and the tax growth rate as two relevant variables for policy choices.

	Tax increases at discount rate $\theta = r$		**Slowly increasing tax** $\theta < r$		**Fast increasing tax** $\theta > r$	
	τ_0 small $\tau_0 \leq \tau_0^*$	τ_0 large $\tau_0 > \tau_0^*$	τ_0 small $\tau_0 \leq \tau_0^*$	τ_0 large $\tau_0 > \tau_0^*$	τ_0 small $\tau_0 \leq \tau_0^*$	τ_0 large $\tau_0 > \tau_0^*$
Timing effect	none	none	postpone extraction	postpone extraction	accelerate extraction	accelerate extraction
Volume effect	none	conservative	none	conservative	none	conservative
Green paradox	none	none	none	none	yes	ambiguous
Impact on damages	none	–	–	– –	+ +	+/–

Table 2.1: Assessment of resource unit taxes with respect to the zero-tax case. r – effective discount rate of the resource owners; θ – rate of the tax increase, τ_0 – initial tax level. Impact on damages: "–" denotes a reduction of damages; "+" an increase of damages.

as $\tau_0 > \tau_0^*, p_0 \geq \tau_0 + c, q'(p) < 0$ and τ_0^* is the stock-depleting tax level. $\square$

Hence, if the initial resource tax level is set higher than τ_0^*, the cumulative extraction will always be reduced and the stock will be prevented from exhaustion, i.e. $S_\infty > 0$.

From (2.3) and (2.4) follows immediately:

Corollary 2.1. *If $\tau_0 > \tau_0^*$, the resource price will be completely determined by the tax and the extraction costs: $p = \tau_0 e^{\theta t} + c$. The resource owners reap zero profits.*

In case the tax provokes a volume effect, the carbon tax reflects the scarcity rent for the de facto resource stock $S_0' := S_0 - S_\infty$. In contrast, if the initial resource tax level was set equal or below τ_0^*, there would be no volume effect of the tax and the entire resource stock would be exhausted despite an increasing resource tax, i.e. $S_\infty = 0$.

With respect to the time path of the resource extraction, we can now distinguish three cases concerning the term $r - \theta$ in (2.1):

1. The carbon tax grows at the discount rate
2. The carbon tax grows at a rate lower than the discount rate
3. The carbon tax grows at a rate higher than the discount rate

Case 1: The carbon tax grows at the discount rate If $\theta - r = 0$, the increasing tax will not influence the relative time path of the resource price and, hence, resource extraction. If the initial tax level τ_0 is equal or below τ_0^* as defined by (2.2), the resource tax will simply absorb the scarcity rent without any distortions (Dasgupta and Heal 1979, p. 364). The initial consumer price p_0 is at the level that equalizes the total resource stock with the cumulative demand over an infinitive time horizon. If, in contrast, the initial tax level τ_0 is above τ_0^*, the consumer price for resources will equal the tax and is at each point in time strictly higher than in the no-tax case. Thus, a unit tax that increases with the discount rate has no timing effect – but it can have a substantial volume effect in decreasing demand and conserving the resource stock. With such a unit tax, a green paradox cannot occur.

Case 2: The carbon tax grows with a rate lower than the discount rate If $\theta < r$, the resource tax will have a clear timing effect. The price path in (2.1) is flattened and, thus, extraction is postponed to the future. Whether the cumulative amount of the extracted resources is affected, however, depends on the initial tax level. If it was set equal or below τ_0^*, the entire resource stock would be depleted. In contrast, if the initial tax level was set above τ_0^*, the resource tax would decrease the cumulative demand below the initial stock size. In this case, the resource stock will not be completely depleted. In any case, the tax postpones carbon extraction and therefore reduces climate damages by the timing affect and – if $\tau_0 > \tau_0^*$ – additionally by the volume effect.

Case 3: The carbon tax grows with a rate higher than the discount rate If $\theta > r$, the resource tax will have a clear timing effect. The price path is steepened according to (2.1) and, thus, extraction is accelerated. The volume effect, however, depends once more on the initial tax level. An initial level below τ_0^* does not decrease the cumulative extraction. Climate damages increase compared to the zero-tax case because the resources are extracted too early. This is the case for the classical green paradox as described in Sinn (2008). If, in contrast, the tax level is above τ_0^*, the cumulative extraction will be lowered and the stock will be prevented from exhaustion. In this case, we have two driving forces on climate damages with an antithetic impact. While the volume effect leads to lower long-term extraction, near-term extraction could actually increase due to the timing effect. The higher the initial tax level, the stronger is the volume effect and, thus, the timing effect diminishes. In principle, every value of S_∞ could be achieved if the initial tax level was set appropriately high.

Tab. 2.1 summarizes these cases. In a related study, Hoel (2010) argues that a carbon tax of 179 \$/tCO_2 (656 \$/tC) will definitely reduce carbon emissions from the beginning and that such immediate emissions reduction are likely to occur for carbon taxes higher than 367 \$/tC. Due to the heterogeneity of fossil resources in extraction costs and demand, it is difficult to calculate exactly the critical initial tax level leading to sufficient lower (cumulative) extraction. In the following, we will therefore focus on the timing effect of carbon tax proposals and their impact on resource extraction.

2.3 The role of the discount rate

The previous considerations revealed that the green paradox does only occur for a special subset of increasing *ad-hoc* carbon taxes, namely where the initial tax level is low and the growth rate of the tax is higher than the effective discount rate of the resource owners for the entire time horizon. At this point, it is important to emphasize that the discount rate resource owners actually use is decisive – and not one based on normative considerations about the choice of an appropriate social discount rate. The latter is important to quantify and evaluate costs and benefits of mitigation and to determine optimal mitigation targets (the "normative" approach). However, when determining optimal carbon taxes the incentive effect of policies has to be considered which relies on a correct modeling of the behavior of economic actors (the "descriptive" approach). In this sense, integrated assessment models need a careful and explicit interpretation depending on their specific research question.[4]

What carbon taxes do integrated assessment models suggest? In general, carbon taxes are very sensitive to many parameters concerning the climate system, damages and technological progress (Edenhofer et al. 2006). Fig. 2.1 shows carbon taxes calculated by several models. Tab. 2.2 gives also the initial tax level and growth rate of the respective exponential carbon taxes which are approximated to the models' taxes. Even for ambitious mitigation targets (450 ppm) most of the taxes have moderate growth rates between zero and three percent and are lower than the risk-free interest rates within these models. Only in the MERGE model the tax growth rate is with 5.8% on a very high level.

Resource owners discount their resource rent usually at the market interest rate which differs with respect to region and risk of financial assets. While the long-run rate of return of UK or US government bonds is about 1.5%, long-run rates of private equity are around 6–7% (Stern 2008). Sinn (2008) argues that resource owners may add an additional risk premium if the ownership of their resources in the ground is insecure due to (geo)political instability – an analogous argument will hold if futures markets for fossil resources are incomplete. Adelman (1986) estimated that effective discount rates of OPEC countries exceed 25% partly due to poor diversification of OPEC's economies and other political economy aspects – while in industrialized countries discount rates are estimated to be around 10%. Even if these numbers differ from current discount rates, it is very likely that discount rates of resource owners exceed market interest rates significantly.

[4]Although social planer models can – according to the welfare theorems – mimic market dynamics if no externalities and market failures exists, both models lead to different results in second-best worlds. This is, for example, relevant if the discount rate of a social planner differs from the rate of private households (see Heal (2009) for the debate on normative vs. positive discounting).

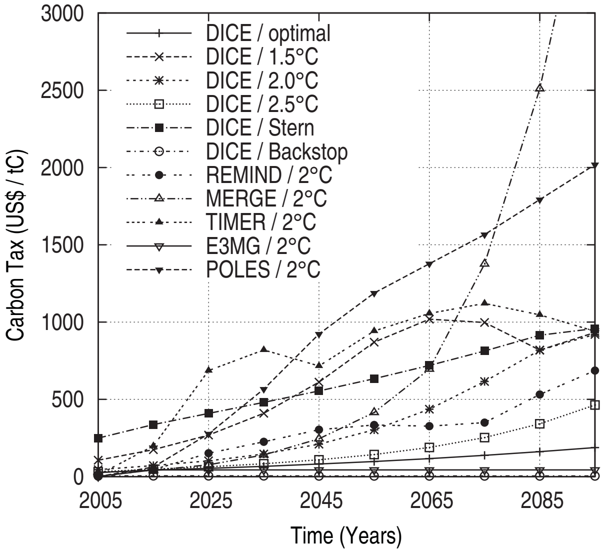


Figure 2.1: Carbon taxes in 2005-US$ per ton of carbon as calculated for several temperature scenarios by the integrated assessment models DICE-2007 (Nordhaus 2008, pp. 92-93), REMIND, MERGE, TIMER, E3MG and POLES (Edenhofer et al. 2010).

Model / Scenario	τ_0	$\theta[\%]$	R^2	$r[\%]$
DICE-2007				
Optimal (586 ppm CO_2)	37.2	1.9	0.994	5.5
1.5°C (420 ppm CO_2)	209.2	2.1	0.774	5.5
2°C (465 ppm CO_2)	54.2	3.3	0.992	5.5
2.5°C (544 ppm CO_2)	36.0	2.8	0.999	5.5
Stern Review (404 ppm CO_2)	316.0	1.3	0.985	5.5
Low-cost backstop (340 ppm CO_2)	5.0	−0.2	0.999	5.5
REMIND 2°C (450 ppm CO_2-eq.)	72.1	2.6	0.802	5.0
MERGE 2°C (450 ppm CO_2-eq.)	23.9	5.8	0.999	5.0
TIMER 2°C (450 ppm CO_2-eq.)	375.6	1.4	0.530	
E3MG 2°C (450 ppm CO_2-eq.)	43.5	0.0	0.525	0.0
POLES 2°C (450 ppm CO_2-eq.)	121.6	3.7	0.790	8.0

Table 2.2: Initial tax level τ_0 and tax growth rate θ for the approximated exponential carbon tax $\tau = \tau_0 e^{\theta t}$. The approximation of Fig. 2.1 models' ten-year taxes (from 2015 to 2095) is calculated by linear regression of the log-values with the least square method. The R² values measure how good the approximated tax fits to the models' tax. The last column shows – when available – the average discount rate r (return on capital) which applies in the models.

2.4 Policy implications

So far, we focused on the incentive effect of an arbitrarily set carbon tax. An optimal carbon tax as calculated in Chapter 3 follows a complex dynamics and requires a precise understanding of the damages of global warming. While such an optimal tax does not provoke an accelerated extraction, the consideration of second-best taxes as done by Sinn (2008) and by this paper gives important hints on the robustness of carbon taxes. As the mere possibility of an accelerated resource extraction exists in case the carbon tax is (and permanently remains) mal-adjusted, this instrument could be perceived too risky to prevent dangerous climate change. An emissions trading scheme as suggested by Sinn (2008) can avoid this risk – as long as the emission caps are set appropriately and the intertemporal permit market works correctly.

As an alternative to a global cap-and-trade scheme, Sinn (2008) proposes a capital income tax harmonization within OECD countries as a robust fool-proof instrument. Extraction is always slowed down because such a tax reform lowers the effective discount rate of resource owners. This instrument, however, is in practice not capable to achieve ambitious mitigation targets: Firstly, capital tax rates cannot be set very high as they lead to distortions in investment decisions implying lower welfare. Second, capital taxes cannot reduce cumulative extraction, i.e. they cannot provoke a volume effect (see Appendix for proof).

By the specific choice of resource and capital tax instruments, Sinn (2008) completely rules out the volume effect. This is a strong limitation: The volume effect could become relevant if policy makers commit to concentration targets or cumulative carbon emissions in order to prevent the crossing of tipping points in the climate system (see WBGU (2009) for the carbon budget proposal). An optimal carbon tax under such a carbon budget grows at the discount rate and the initial tax level is set such that cumulative extraction equals the carbon budget (see Chapter 3 for a formal analysis). However, a mal-adjusted tax can again provoke an accelerated extraction and an emissions trading scheme may be the superior alternative.

2.5 Conclusion

By implementing carbon (unit) taxes in Sinn's (2008) model, we have shown that an accelerated resource extraction due to increasing carbon taxes (green paradox) is limited to specific conditions: The initial tax level has to be lower than a certain threshold and the tax has to grow permanently at a rate higher than the discount rate of resource owners. We showed that a prominent set of carbon taxes for several mitigation targets is not at high risk to provoke a green paradox. However, in order to avoid the small risk of a green paradox, quantity instruments might be preferable if they are implemented appropriately and markets work correctly. The capital income tax proposed by Sinn can be useful to slow down extraction, but it is not capable to achieve low stabilization targets. If regulators nevertheless rely on carbon taxes (i.e. due to political constraints) the initial tax level should be high enough and the long-run tax-growth rate equal or below market interest rates.

2.A Capital tax incidence

Introducing a constant capital tax $\kappa < 1$ changes the effective discount rate of resource owners' maximization problem to $\tilde{r} = r(1-\kappa)$. The resulting Hotelling rule is then:

$$r(1-\kappa) = \frac{\dot{p}}{p-c} \tag{2.6}$$

Solving the differential equation (2.6) for $p(t)$ gives:

$$p = (p_0 - c)e^{r(1-\kappa)t} + c \tag{2.7}$$

Putting (2.7) into the transversality condition $0 = \lim_{t\to\infty}(p-c)Se^{-r(1-\kappa)t}$ yields

$$0 = \lim_{t\to\infty}(p_0 - c)S.$$

Hence, either the entire resource stock has to be exhausted (i.e. $\lim_{t\to\infty} = 0$) or the resource price equals always the extraction costs, i.e. $p = c$ due to (2.7). The latter condition, however, contradicts the stock clearing condition because with positive demand, the cumulative demand exceeds the initial resource stock: $\int_0^\infty q(p)\,dt = \int_0^\infty q(c)\,dt = \infty > S_0$.

Bibliography

Adelman, M. A. (1986). Oil producing countries' discount rates. *Resources and Energy 8*(4), 309–329.

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

Edenhofer, O., M. Grubb, C. Kemfert, K. Jonathan, and K. Lessmann (2006). Induced technological change: Exploring its implications for the economics of atmospheric stabilization: Synthesis report from the innovation modeling comparison project. *The Energy Journal 27*, 57–107.

Edenhofer, O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos, M. Leimbach, K. Lessmann, B. Magne, S. Scrieciu, H. Turton, and D. P. van Vuuren (2010). The economics of low stabilization: Model comparison of mitigation strategies and costs. *The Energy Journal 31*(Special Issue), 11–48.

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

Grafton, R., T. Kompas, and N. Van Long (2010). Biofuels subsidies and the green paradox. *CESifo Working Paper* (2960).

Heal, G. (2009). Climate economics: A meta-review and some suggestions for future research. *Review of Environmental Economics and Policy 3*(1), 4–21.

Hoel, M. (2010). Is there a green paradox. *CESifo Working Paper* (3168).

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

IPCC (2007). *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

Nordhaus, W. (2008). *A question of balance. Weighing the Options on Global Warming Policies.* New Haven, USA: Yale University Press.

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

Stern, N. (2008). The economics of climate change. *The American Economic Review 98*(2), 1–37.

Van der Ploeg, F. and C. Withagen (2010). Is there really a green paradox? *CESifo Working Paper* (2963).

WBGU (2009). Solving the climate dilemma: The budget approach. Special report, German Advisory Council on Global Change, Berlin.

Chapter 3

Managing the Climate Rent: How Can Regulators Implement Intertemporally Efficient Mitigation Policies?

Abstract:

This paper provides a formal survey of several intertemporal price and quantity instruments for mitigating global warming. We ask under what conditions and to what extend the regulator can shift the complex and daunting intertemporal optimization of fossil resource use to markets. Mitigation always generates an intertemporal *climate rent* which reflects the stock-dependent damages and emerging scarcities of the atmospheric carbon deposit. In order to calculate and to manage this climate rent appropriately, perfect information about resource demand, extraction costs, reserve sizes and damages for the entire planning horizon is necessary. In this paper we analyze the differing information requirements for the regulator and decentralized agents for several policy instruments under a (i) cost-benefit framework as well as a (ii) cost-effective carbon budget approach. It turns out that the intertemporal allocation decision can be decentralized only under restrictive assumptions. Hence, a public institution might be unavoidable for the intertemporal management of the atmosphere. Furthermore, we discuss which instruments can obtain an optimal allocation even if resource owners employ discount rate mark-ups (i.e. due to imperfect commitment or insecure property rights). While an emissions trading scheme without banking and borrowing is robust against discount rate mark-ups, resource taxes have to be modified in order to achieve an optimal allocation.

3.1 Introduction

Global warming is a stock-pollutant externality caused by the accumulation of greenhouse gases in the atmosphere. A main component of a successful climate policy consists of pricing global emissions – primarily from burning fossil fuels as they provide the main contribution to global warming (IPCC 2007, p. 28). This price signal can be obtained by taxes or quantity instruments like emission trading schemes (ETS). Many of the successfully regulated environmental problems are more or less static problems. Sulfur emissions and particulate matters, for example, are easily measurable and citizens experience the impacts on environmental quality and health within short time horizons. The same applies to river and ground water quality. Environmental regulation is usually an iterative process where environmental policies are introduced and evaluated within few years. Evaluation of these problems is made by indicators describing the environmental quality and by the improvement directly perceived by citizens. At the same time, the impact of economic costs of environmental measures can be assessed. These short evaluation periods allow for a tightening or alleviating of environmental regulation – depending on the experienced costs and benefits.

With respect to global warming, however, this proceeding is not appropriate: The response of the climate system takes several decades and a fast "correction" of temperature levels is impossible due to this high inertia (Solomon et al. 2009). Additionally, the stakes are high: The impacts of temperature increases are probably severe and long-lasting, as well as the impacts on the economy due to ambitious mitigation (Stern 2007). Above all it is interfered with the fossil resource economy: regulating emissions directly affects fossil resource extraction. If fossil resource owners intertemporally maximize profits, they sensitively respond to announced and implemented climate policies (Sinn 2008). As the expectations about future regulation strongly influence extraction and investment decisions, the "success" of already implemented policies with respect to achieved emission reductions can hardly be assessed. Hence, an iterative "muddling-through" policy based on a static externality concept is hardly feasible. Policies have to explicitly take into account the intertemporal dimension of the stock-pollutant problem.

The aim of this paper is to explore the institutional and informational requirements for achieving efficient allocation of resource extraction (and, hence, emissions). In contrast to existing works on resource extraction and global warming that focus on a social planner perspective (eg. Hoel and Kverndokk 1996; Farzin 1996) we explicitly consider the incentive, information and rent structure of this optimization problem as motivated by the green paradox (Sinn 2008). We go beyond Sinn's analysis by providing a systematic comparison of optimal intertemporal price and quantity instruments. In particular, we draw on the literature on the intertemporal management of exhaustible resources (eg. Hotelling 1931; Dasgupta and Heal 1979; Dasgupta et al. 1981) and intertemporal emissions trading (eg. Kling and Rubin 1997; Leiby and Rubin 2001) when exploring designs of efficient and effective climate policy instruments in presence of profit maximizing fossil resource suppliers. We discuss several Hotelling-like models from a social planner and decentralized market perspective. The social planner model serves as a benchmark for the socially optimal solution. In the decentralized model, we study the incentive effect and the rent incidence on the resource sector that anticipates the policy instrument of the regulator. Furthermore, we perform our analysis within a cost-benefit (CBA) framework as well as in a cost-effectiveness (carbon budget) framework where the cumulative amount of emissions has been set as environmental target exogenously. Maximizing expected welfare under a cost-benefit approach is not possible if catastrophic impacts have a sufficiently high probability (i.e. if they are described by a fat-tailed probability distribution) (Weitzman 2009). Such fat-tails evolve due to highly convex damages or due to the uncertainty about the parameters describing the probability distribution of the climate sensitivity (deep uncertainty). If the expected value of climate damages does not converge, greenhouse gas concentration targets could be derived by using an exogenous value-of-statistical-life parameter. In this case, concentration targets can be interpreted as an insurance against catastrophic climate change (Weitzman 2010).

As it turns out, efficient climate policy has, in any case, to generate a dynamic *climate rent* which arises from increasing damages or environmental scarcities. This climate rent dynamic can be induced by an optimal resource tax as well as by optimal emission trading schemes – with and without intertemporal flexibility (banking and borrowing of permits). However, the informational requirements for the regulator are immense: She needs *ex ante* perfect information about extraction costs and fossil resource demand as well as climate damages for the entire time horizon (e.g. for the entire 21st century). Additionally, she needs to credibly commit to the announced policy. As the efficient level of carbon taxes or emission caps is not constant in time the regulator has to continuously revise her policy to remain on the optimal trajectory. In practice, however, such revisions are costly as they might provoke wasteful rent-seeking behavior which may dilute the commitment and credibility of climate policy. Hence, implementing the efficient Pigouvian tax may be very difficult for the regulator. Within the cost-benefit framework, we derive an alternative stock-dependent taxation rule which achieves optimality at least for the case of identical resource owners. This tax rule differs from the other instruments as it shifts the task of evaluating climate damages and finding an optimal allocation completely to the resource sector. Hence, the government does only need to know the general functional form of damages – which is the lowest imaginable informational requirement. Such a tax rule provides an incentive-compatible alternative to the muddling-through approach mentioned above. Within the carbon budget framework, an emissions trading scheme with free banking and borrowing allows to unburden the regulator from making complex decisions on intertemporal allocation. Both proposals shift the intertemporal management from the regulator to decentralized agents. The latter may have a better access on important information (e.g. regarding resource supply, extraction costs, resource demand and backstop technologies). Furthermore, the regulator has only to commit to the taxation rule or the carbon budget, respectively, and not to a complex trajectory adjusting the policy incrementally.

Finally, we discuss optimal policies when the suppliers of fossil resources use higher discount rates than the regulator. This is the case when property rights are insecure, futures markets are incomplete, governments may not perfectly commit to future policies or normative considerations lead to different social and private discount rates. In any case, optimal carbon taxes have to be modified to consider this additional distortion. In contrast, emissions trading schemes (without banking and borrowing) are fairly robust against discount rates; only the permit price increases if resource owners use higher discount rates. Hence, within our Hotelling model, quantity instruments without intertemporal flexibility can achieve an optimal allocation even if no commitment for future caps exists.

The remainder of the paper is structured as follows: Section 2 starts with an analysis of optimal instruments within a cost-benefit analysis. Section 3 provides a similar analysis of cost-effective instruments within carbon budget framework. The implications of the theoretical findings are finally discussed in the Conclusions.

3.2 The cost-benefit approach

The analysis in this section is based on the modified Hotelling model presented in Sinn (2008). We focus only on that part of the economy that generates intermediate or final goods (or services) from fossil energy use. Hence, $f(R)$ describes a partial production function from fossil resources R (or, how fossil resources contribute to overall economic output). These reseources are extracted from a (finite) resource stock S at marginal extraction costs $c(S)$.[1] We use the common assumption that production is increasing and concave in R, i.e. $f_R > 0$ and $f_{RR} < 0$.[2] As easily accessible resource sites are exploited first, we assume that

[1] To improve the readability of this paper, we will usually suppress the time-dependency of flow and stock variables like $R(t)$, $S(t)$ and so forth.

[2] In the following, we use the notation g_x for the partial derivative of g with respect to x, thus: $g_x := \frac{\partial g(x)}{\partial x}$. Likewise, $\dot{g} := \frac{dg}{dt}$ denotes the derivative of g with respect to time.

extraction costs rise with depletion and are convex, thus $c_S < 0, c_{SS} \geq 0$. Focusing on the supply side, we neglect decay rates of carbon dioxide in the atmosphere and carbon dioxide storage technologies. We assume that by burning fossil resources a proportional amount of carbon dioxide is emitted into the atmosphere which remains there for a long time; thereby we describe (expected) damages $d(S)$ as function increasing in cumulative extraction of fossil fuels, implying $d_S < 0$.[3] We abstract from terminal scrap values of the resource stock in the final period T in a world without climate damages. Instead, we consider a social scrap value function $F(S(T)), F_S \geq 0$ which reflects irreversible and persistent damages of global warming that are not valued by individual resource owners.[4] In this paper, we always assume that fossil reserves are abundant in the sense that they are not fully extracted within the planning horizon (i.e. $S(T) > 0$) even if no damages exist. This can be justified by convex marginal extraction costs (Farzin 1992; Hoel and Kverndokk 1996), the existence of backstop technologies providing substitutes for R, or by the relative abundance of subterranean fossil carbon (eg. BGR 2009) in comparison to the limited demand of carbon within the planning horizon. The Assumption 3.1 gives a more restrictive formal condition that always leads to abundant resource stocks:

Assumption 3.1. *There exists $\tilde{S} \geq 0$ such that $c(\tilde{S}) > f_R(0)$. In words, if a certain amount of resources has been extracted, marginal extraction costs of resources $c(S)$ exceed marginal productivity f_R. This implies that extraction is ceased and the stock of fossil resources is not fully extracted within the planning horizon.*

This set of simplifying assumptions helps to clarify and highlight the supply-side dynamics by pointing out the intertemporal dimension of the control problem.

3.2.1 The social planner economy

The social planner maximizes the net present value of output $f(R)$ minus extraction costs $c(S)R$ and damages $d(S)$ with respect to the discount rate r. The optimization problem constrained by the scrap value function $F(S(T))$ and the initial resource stock size $S(0) = S_0$

[3] Archer (2005) estimates that 17-33% of the emitted carbon dioxide remains in the atmosphere within approximately 1,000 years. Solomon et al. (2009) reports even higher numbers: After stopping carbon emissions immediately, atmospheric carbon concentration will fall to 40% after 1,000 years. These numbers suggest that carbon uptake rates should lie between 0.04% and 0.18%. Thus, for a policy analysis within a time-horizon of one century, uptake rates might be negligible.

[4] Indeed, we could extend our analysis by considering one scrap value function $F^R(S(T))$ for resource owners and another scrap value function $F^S(S(T))$ describing the valuation of the final stock by the society. As it turns out, the policy implications do only depend on the differences between the scrap value functions $F(S(T)) := F^S(S(T)) - F^R(S(T))$. Hence, assuming $F^R(S(T)) \equiv 0$ simplifies the formal analysis without constraining the generality of our results.

reads:

$$\max_R \int_0^T (f(R) - c(S)R - d(S))\, e^{-rt}\, dt + F(S(T))e^{-rT} \tag{3.1}$$

subject to:

$$\dot{S} = -R \tag{3.2}$$

$$S(0) = S_0 \tag{3.3}$$

The solution of the intertemporal optimization problem is characterized by:

Proposition 3.1. *(Socially optimal resource extraction) If a social planner maximizes intertemporal output according to (3.1–3.3), then: (a) the optimal solution (R^*, S^*) is determined by the following system of equations:*

$$r = \frac{\dot{f}_R(R^*) - d_S(S^*)}{f_R(R^*) - c(S^*)} \tag{3.4}$$

$$\dot{S}^* = -R^* \tag{3.5}$$

$$F_S(S^*(T)) = f_R(R^*(T)) - c(S^*(T)) = \lambda^*(T) \tag{3.6}$$

$$S(0) = S_0 \tag{3.7}$$

(b) the shadow price λ^* for the stock S^* is given by:

$$\lambda^*(t) = F_S(S^*(T))e^{-r(T-t)} - \int_t^T (c_S(S^*)R^* + d_S(S^*))e^{r(t-\xi)}\, d\xi \tag{3.8}$$

Proof. (a) We set up the corresponding Hamiltonian function $H = f(R) - c(S)R - d(S) - \lambda R$. Application of the maximum principle leads to the first-order condition with respect to R, the equation of motion for the shadow price λ, and the transversality condition:

$$\lambda = f_R(R) - c(S) \tag{3.9}$$

$$\dot{\lambda} = r\lambda - H_S = r\lambda + c_S(S)R + d_S(S) \tag{3.10}$$

$$0 = (\lambda(T) - F_S(S(T)))S(T) \tag{3.11}$$

By substituting (3.9) and its derivative with respect to time into (3.10) we obtain the social Hotelling rule (3.4). Furthermore, the transversality condition (3.11) together with Assumption 3.1 implies that $\lambda(T) = F_S(S(T))$. (b) Solving the differential equation (3.10) for given

$\lambda(T)$ yields:

$$\lambda(t) = \lambda(T)e^{-r(T-t)} - \int_t^T (c_S(S)R + d_S(S))e^{r(t-\xi)}\, d\xi \tag{3.12}$$

□

For a zero scrap value function ($F(S(T)) \equiv 0$), Proposition 3.1 implies that marginal extraction costs increase up to marginal resource productivity. If the marginal scrap value is positive ($F_S(S(T)) > 0$), however, resources in the ground are assigned this additional value in the final period. This may be the case if society considers persistent and irreversible damages due to resource extraction after the planning period T. Equation (3.8) resembles the well-known rent dynamics for exhaustible resources with stock-dependent extraction costs (eg. Farzin 1992). However, the familiar formula is extended by the term $d_S(S)$ under the integral reflecting the stock-pollutant dynamics of resource extraction and the marginal scrap value term $F_S(S(T))$. Hoel and Kverndokk (1996) derive a similar result for an infinite time horizon.[5] As we will show below, the rent dynamics in Equation (3.8) has to be induced by policy instruments in order to achieve an optimal decentralized solution.

3.2.2 Resource taxes in a decentralized market economy

The resource sector takes resource prices $p(t) = f_R(R(t))$ and resource taxes $\tau(t)$ as given and maximizes intertemporal profit according to:

$$\max_R \int_0^T (p - c(S) - \tau)R)\, e^{-rt}\, dt \tag{3.13}$$

subject to:

$$\dot{S} = -R \tag{3.14}$$

$$S(0) = S_0 \tag{3.15}$$

In contrast to the social objective function (3.1), the resource sector does not consider social damages due to extraction during and after the planning horizon. By applying the maximum principle with λ as shadow price for the resource stock, we obtain (just along the lines of

[5] Hoel and Kverndokk (1996) assume extraction costs that rise without any bound implying that the optimal tax converges to zero in the long run: $\lim_{T\to\infty} \tau(T) = 0$. Within the infinite time horizon, such a resource tax aims at reallocating resource extraction and shifting it towards the future; within the finite time horizon, it may also be necessary to reduce cumulative extraction if $F_S(S(T) > 0$.

the proof of Proposition 3.1):

$$0 = p - c(S) - \tau - \lambda \tag{3.16}$$

$$\dot{\lambda} = r\lambda + c_S(S)R \tag{3.17}$$

$$0 = \lambda(T)S(T) \tag{3.18}$$

which leads to the private Hotelling rule and terminal condition:

$$r = \frac{\dot{p} - \dot{\tau} + r\tau}{p - c(S)} \tag{3.19}$$

$$\tau(T) = p(T) - c(S(T)) \tag{3.20}$$

because $S(T) > 0$. Without climate damages (i.e. $d(s) \equiv 0$), the decentralized market economy leads to the same extraction path as the social planner economy. In the presence of damages, however, the Hotelling rules in social planner and decentralized market economy (3.4) and (3.19) diverge for a zero tax level. In the decentralized market economy, the social optimum can be achieved by introducing a resource tax according to:

Proposition 3.2. *(Optimal resource tax) If the regulator knows the socially optimal extraction path S^* according to Proposition 3.1 and if she can commit at $t = 0$ to the tax path $\tau(t)$ over the entire planning horizon, then (a) the resource tax*

$$\tau(t) = F_S(S^*(T))e^{-r(T-t)} - \int_t^T d_S(S^*)e^{r(t-\xi)}\, d\xi \tag{3.21}$$

achieves the optimal extraction path and (b) the rent in the resource sector is given by:

$$\lambda(t) = -\int_t^T c_S(S^*)R^* e^{r(t-\xi)}\, d\xi \tag{3.22}$$

Proof. (a) Differentiating (3.21) with respect to time, we obtain $\dot{\tau} = r\tau - d_S(S^*)$. Substituting this into the private Hotelling rule (3.19) and considering the fact that in the market equilibrium prices equal marginal productivities, i.e. $p = f_R(R)$, we obtain the socially optimal Hotelling rule (3.4). Furthermore, $\tau(T) = F_S(S^*(T))$ ensures that the private transversality condition (3.20) equals the social transversality condition (3.6). (b) The equation for λ follows from the solution of the differential equation (3.17) with $\lambda(T) = 0$ due to $S(T) > 0$. □

Note that the sum of the resource owners' scarcity rent λ and the resource tax τ describes the entire rent dynamics and is expressed by:

$$\tau(t) + \lambda(t) = F_S(S^*(T))e^{-r(T-t)} - \int_t^T (c_S(S^*)R^* + d_S(S^*))e^{r(t-\xi)}\, d\xi \tag{3.23}$$

which is exactly the resource shadow price in the social planner model as expressed in Eq. (3.8). The first summand denotes the (cumulative) scarcity of resources due to high stock externalities ($F_S(S^*(T)) > 0$). The second summand describes the dynamics of extraction costs and climate damages. In the following, we will denominate the rent component associated with τ *climate rent* as it evolves due to the stock-pollutant dynamics $d_S(S)$ and the cumulative scarcity by future damages expressed in $\tau(T) = F_S(S(T))$. Proposition 3.2 confirms that τ is indeed incentive-compatible in a decentralized economy as suggested by the social planner model of Hoel and Kverndokk (1996): The tax achieves that intertemporally maximizing resource owners adjust their extraction path to the social optimum. Proposition 3.2 also makes the *informational requirement* for the government explicit: Implementing the optimal tax requires to solve the social planner problem as stated by Proposition 3.1. In an economy without climate damages, governments can delegate the task of determining an optimal allocation of resources completely to private resource owners: Proposition 3.2 confirms that without a climate externality no additional tax nor other government intervention is necessary. In contrast, under climate damages, implementing an optimal resource tax requires extensive amounts of information as well as a great ability to commit on a time-dependent tax, both of which are difficult to achieve:

- Calculating the optimal tax requires a full assessment of the resource stock size, extraction costs, resource demand, climate damages and the discount rate.

- Additionally, the regulator will have to commit to this tax for now and forever to incentivize the resource sector correctly. As the tax changes in time, it will provoke continuous public debates about the appropriate level as well as wasteful rent-seeking behavior to change the tax in favor of organized lobby groups.

Thus, the informational and commitment requirements for the regulator are quite high which makes deviations from the social optimum likely. A suboptimal tax can lead to an acceleration of extraction if the tax growth rate is high and the initial tax level is too low (Sinn 2008). The conventional Pigouvian tax to internalize stock-pollutant damages is therefore difficult to implement in reality.

3.2.3 Stock-dependent resource taxes

Usually, regulators cannot and do not commit *ex ante* to a time-dependent tax path $\tau(t)$ for long time horizons. Instead, regulation is more an iterative process where the resource tax is dependent on the estimation of marginal damages from the cumulative resource extraction. When concentrations rise, the regulator increases the tax to account for higher social damages. In this section we ask whether the regulator can achieve the optimal extraction path by implementing a resource tax $\tau(S)$ which is adjusted to the current concentration of carbon in the atmosphere. The regulator announces explicitly how she modulates the tax and the resource sector responds to this tax adjustment rule. Under rather restrictive assumptions, such a tax rule can indeed achieve the optimal allocation path:

Proposition 3.3. *(Stock dependent tax) If the regulator imposes a resource tax $\tau(S)$ which increases with cumulative emissions, thus $\tau_S(S) \leq 0$, then:*
(a) if there are $n > 1$ resource owners, the tax induces a flatter (steeper) extraction path R^i of the i-th resource owner than in the social optimum if

$$\tau_S(S) \underset{(<)}{>} \frac{-d_S(S) - r\tau(S)}{\sum_{j=1,j\neq i}^{n} R^j} \tag{3.24}$$

(b) if there are $n > 1$ resource owners, the tax rule

$$\tau(S) = \frac{-d_S(S)}{r} \tag{3.25}$$

leads to a steeper (flatter) resource price path compared to the optimal extraction if damages are strictly convex (concave).
(c) Implementing the tax rule (3.25) leads to the socially optimal Hotelling rule (3.4) if (i) damages are linear or (ii) if there is only one (competitive) resource owner. In order to meet the socially optimal transversality condition, the regulator has furthermore to commit to the terminal-period payment rule $\varsigma(S(T))$

$$\varsigma(S(T)) = \frac{d(S(T))}{r} - F(S(T)) \tag{3.26}$$

The combined rent and tax dynamics is as follows:

$$\lambda(t) + \tau(t) = F_S(S(T))e^{-r(T-t)} - \int_t^T (c_S(S^*)R^* + d_S(S^*))e^{r(t-\xi)}\, d\xi \tag{3.27}$$

Proof. (a) Setting up the Hamiltonian for the i-th resource owner reads $H^i = (p - c^i(S^i) - \tau(S))R^i - \lambda^i R^i$. The first order condition $\lambda^i = p - c^i(S^i) - \tau(S)$ and the equation of motion

$\dot{\lambda}^i = r\lambda^i + c_s^i(S^i)R^i + \tau_S(S)R^i$ lead to the Hotelling rule:

$$r = \frac{\dot{p} + \tau_S \sum_{j=1,j\neq i}^n R^j}{p - c^i(S^i) - \tau(S)} = \frac{\dot{p} + r\tau(S) + \tau_S \sum_{j=1,j\neq i}^n R^j}{p - c^i(S^i)} \tag{3.28}$$

The socially optimal extraction for n heterogeneous resource stocks $S^1, ...S^n$ is derived by solving

$$\max_{R^i} \int_0^T \left(f(R) - \sum_{i=1}^n c^i(S^i)R^i - d(S) \right) e^{-rt}\ dt + F(S(T))e^{-rT} \tag{3.29}$$

subject to $R = \sum_{i=1}^n R^i, S = \sum_{i=1}^n S^i, \dot{S}^i = -R^i$. The resulting Hotelling rule reads:

$$r = \frac{\dot{f}_R(R) - d_S(S)}{f_R(R) - c^i(S^i)} \tag{3.30}$$

By comparing (3.28) with (3.30), (a) follows.

(b) Substituting (3.25) into (3.24) implies that the right-hand-side of (3.24) equals zero and (b) follows directly from (a).

(c) Substituting (3.25) into (3.28) leads to the socially optimal Hotelling rule (3.30) if damages are linear (i.e. $\tau_S(S) \equiv 0$) or if only one resource owner exists (i.e. $\sum_{j=1,j\neq i}^n R^j = 0$). In the case of one (competetive) resource owner, the transversality condition under a payment rule $\varsigma(S)$ reads $\lambda(T) = \varsigma_S(S(T))$. Together with the first-order condition, this leads to $\varsigma_S(S(T)) + \tau(S) = p(T) - c(S(T))$. Substituting (3.26), we obtain the socially optimal Hotelling rule (3.6).

Solving the equation of motion for λ , we obtain:

$$\lambda(t) = \lambda(T)e^{-r(T-t)} - \int_t^T c_S(S)Re^{-r(\xi-t)}d\xi - \int_t^T \tau_S(S)Re^{-r(\xi-t)}d\xi \tag{3.31}$$

Using partial integration for $\int_t^T \tau_S(S)Re^{-r(\xi-t)}d\xi$ yields:

$$\lambda(t) + \tau(S) = (\lambda(T) + \tau(S(T)))e^{-r(T-t)} - \int_t^T c_S(S)Re^{-r(\xi-t)}d\xi + r\int_t^T \tau(S)e^{-r(\xi-t)}d\xi$$

Substituting the tax rule $\tau(S) = -d_S(S)/r$ and using $F_S(S(T)) = \lambda(T) + \tau(T)$ due to the final payment rule, we finally obtain (3.27) $\square$

The insight from Proposition 3.3a is that regulators who adjust the carbon tax with the actually observed cumulative emissions can induce an accelerated or postponed resource extraction, depending on the tax rule $\tau(S)$. If the tax rule reacts strongly on S, i.e. if $|\tau_S(S)|$ is large, an accelerated extraction becomes more likely. Proposition 3.3b transfers this to a specific tax rule (3.25) which turns out to be optimal under certain (restrictive) conditions in the last part of Proposition 3.3. Proposition 3.3c describes how the intertemporal climate externality is successfully shifted to the resource owner who internalizes the stock-pollutant dynamics and calculates the optimal intertemporal allocation. In this case, the informational requirements for the regulator are relatively low: The regulator neither needs to know the optimal stock size $S^*(t)$ nor marginal productivity or extraction costs of resources along the optimum in advance. She only has to know the functional form of the damage function $d(S)$ and to commit to the tax and terminal-period payment rule. The resulting tax depends entirely on the extraction path chosen by the resource owner. Hence, this tax rule allows unburdening the regulator completely from the task of finding an intertemporally optimal extraction path. However, if there are several resource owners, such a tax rule suffers from an additional externality between different resource owners. If damages are convex, a high aggregated stock S leads to a low resource tax which benefits all resource owners in the same way. Thus, if the i-th resource owner postpones extraction, all resource owners will benefit from lower resource taxes. At the same time, he has to carry an elevated tax burden for these resources caused by all resource owners together. Hence, he has an incentive to extract as fast as possible (as long as taxes are low). Proposition 3.3 gives an explanation, how the anticipation of an announced tax rule can lead to inefficient extraction paths due to a coordination problem in the resource sector. If damages are convex and the tax increases with cumulative extraction (i.e. $\tau_S < 0$), resource owners will react with an accelerated extraction which can lead to higher climate damages if the cumulative amount of extracted resources is not reduced appropriately. In order to overcome the coordination problem of the resource sector responding to a tax which is adjusted to the aggregate stock size S, the regulator has to link the tax rule to the *individual* resource stock of each resource owner:

Proposition 3.4. *(Individually adjusted optimal stock-dependent taxes) If there are n identical resource owners (i.e. with the same extraction cost function and initial resource stock) and the regulator announces to the i-th resource owner the resource tax rule $\tau^i(S^i)$ and the terminal-period payment rule $\varsigma^i(S^i)$*

$$\tau^i(S^i) = \frac{-d_S(nS^i)}{r} \tag{3.32}$$

$$\varsigma^i(S^i(T)) = \frac{1}{n}\left(\frac{d(nS^i(T))}{r} - F(nS^i(T))\right) \tag{3.33}$$

which depends explicitly on the i-th resource owners' cumulative extraction S^i, resource owners extract along the socially optimal extraction path.

Proof. The proof follows directly from the proof of Proposition 3.3. The individual tax rule leads for each resource owner to the Hotelling rule (cf. Eq. 3.28)

$$r = \frac{\dot{p} + r\tau^i(S^i)}{p - c(S^i)} = \frac{\dot{p} - d_S(nS^i)}{p - c(S^i)} \tag{3.34}$$

As all resource owners are identical, $S = nS^i$ and thereby the socially optimal Hotelling rule (3.30) applies. The terminal-period payment guarantees the socially optimal transversality condition. □

The tax rule extrapolates the stock-damage caused by each resource owner's extraction behaviour through multiplication with factor n. Although each resource owner only causes the fraction $1/n$ of social damage, he internalizes the entire stock-pollutant dynamic as if timing and extend of the externality would solely depend on himself. The underlying assumption of identical resource owners is still very restrictive. In the more realistic case of heterogeneous resource owners, there is no simple tax rule that internalizes the stock externality appropriately (and without knowing already the socially optimal allocation (R^*, S^*)). The reason is that the share of each resource owner's cumulative extraction S^i on total cumulative extraction S is in general not constant. This makes it impossible to determine the contribution of individual resource owners to global damages (as in (3.32)) without using information about other resource owners' extraction paths.

3.2.4 Emissions trading schemes

Proposition 3.2 proves that the informational requirements to implement a socially optimal resource tax are daunting. As a suboptimal tax can lead to an accelerated resource extraction worsening global warming, Sinn (2008) suggests a global emissions trading scheme as a fool-proof alternative. Below, we elaborate the informational requirements and possible designs of efficient emissions trading schemes (ETS). We explicitly consider the interplay of quantity instruments with the resource sector in order to study the extraction and rent dynamics.

Emissions trading without banking and borrowing

We first focus on a conventional ETS where permits for resource extraction $C(t)$ which are only valid for one time period are issued. If a resource owner wants to sell a unit of resource, he has to use one permit. Thus, the regulator can effectively limit the resource use to C. This does, however, not imply that resource extraction always equals the permit path (it could be profitable for resource owners to extract less than the cap allows). We do not study the conditions under which such an undersupply of resources can occur as it requires rather tedious calculations. Instead, we assume that optimal extraction under climate policy is always lower than the business-as-usual extraction:

Assumption 3.2. *(Scarcity of permits) In each period, there are fewer permits issued than resources extracted in the zero-damage (BAU) case, i.e.*

$$C(t) < R^B(t) := R^*(t)_{|d(S)\equiv 0} \tag{3.35}$$

As we will show, this assumption guarantees that all permits are used at each point in time and no undersupply of resources occurs. The optimal ETS is characterized by the following proposition:

Proposition 3.5. *(Optimal ETS without banking) If the regulator issues permits $C(t) = R^*(t)$ along the socially optimal extraction path of Proposition 3.1, then (a) the optimal extraction is achieved, (b) the resource rent is given by $\lambda + \theta$ according to:*

$$\lambda(t) = -\int_t^T c_S(S^*)R^* e^{r(t-\xi)}\, d\xi \tag{3.36}$$

$$\theta(t) = F_S(S^*(T))e^{-r(T-t)} - \int_t^T d_S(S^*)e^{r(t-\xi)}\, d\xi \tag{3.37}$$

Proof. (a) We have to show that all permits are used, i.e. that $R(t) = C(t) = R^*(t)$. The optimization problem of the resource sector is given by $\max_R \int_0^T (p - c(S))Re^{-rt}\, dt$ subject to the constraints $\dot{S} = -R$, $S(0) = S_0$, $R(t) \leq C(t)$. The Hamiltonian function then reads $H = (p-c(S))R - \lambda R - \theta(C-R)$, where θ denotes the shadow price for the binding constraint $R \leq C$. Applying the maximum principle leads to the following first-order condition, equation of motion, transversality and Kuhn-Tucker condition, respectively:

$$0 = p - c(S) - \lambda - \theta \tag{3.38}$$

$$\dot{\lambda} = r\lambda + c_S(S)R \tag{3.39}$$

$$0 = \lambda(T)S(T) \tag{3.40}$$

$$0 = \theta(C-R) \tag{3.41}$$

Assumption 3.1 and Eq. (3.40) imply that $\lambda(T) = 0$. Solving the differential equation (3.39) with $\lambda(T) = 0$ we obtain

$$\lambda(t) = -\int_t^T c_S(S)Re^{r(t-\xi)}\, d\xi \tag{3.42}$$

From assumption 3.2 follows that $R \leq R^* < R^B$ and therefore $S > S^B$ and $c_S(S) > c_S(S^B)$

as $c_{SS}(S) > 0$ (the superscript B denotes the BAU case where damages are neglected). This implies that

$$\lambda(t) = -\int_t^T c_S(S)Re^{r(t-\xi)}\,d\xi < -\int_t^T c_S(S^B)R^B e^{r(t-\xi)}\,d\xi = \lambda^B(t) \tag{3.43}$$

With (3.38) we obtain $\lambda = p - c(S) - \theta$ and with (3.16) and $\tau = 0$ (in BAU) we have $\lambda^B = p^B - c(S^B)$. The inequality (3.43) therefore reads:

$$p - c(S) - \theta < p^B - c(S^B) \tag{3.44}$$

which can be rearranged to

$$(p - p^B) + c(S^B) - c(S) < \theta \tag{3.45}$$

As p decreases with higher R (because $p = f_R$ and $f_{RR} < 0$) and $R < R^B$ it follows $p > p^B$. Likewise, $S^B < S$ and $c_S < 0$ imply $c(S^B) > c(S)$. Therefore, (3.45) leads to $\theta > 0$ and due to the Kuhn-Tucker condition (3.41), we have $R(t) = C(t)$. (b) As R follows the socially optimal path R^*, (3.36) directly follows from (3.42). From (3.38) follows that the rent in the resource sector is given by $p - c(S) = \lambda + \theta$. In particular, $p(T) = c(S(T)) + \theta(T)$. As $R(t) = R^*(t)$ and $p = f_R$, the difference $p - c(S)$ is the same as in the social Hotelling model (3.9) which implies together with (3.8):

$$\lambda + \theta = p^* - c(S^*) = F_S(S^*(T))e^{-r(T-t)} - \int_t^T (c_S(S^*)R^* + d_S(S^*))e^{r(t-\xi)}\,d\xi \tag{3.46}$$

Substituting λ from (3.36) into (3.46), we finally obtain (3.37). □

The shadow price θ for permits exactly equals the optimal resource tax (3.21) and thus reflects the climate rent. It is worthwhile to note that it has not been specified which party profits from the new climate rent – the resource sector or the regulator. If the regulator issues permits for free to the resource sector, the resource sector receives the extraction rent λ and adds the user cost θ to the resource price. His rent is then given by $\lambda + \theta$. Alternatively, the regulator can sell (or auction) the permits with a price up to θ and absorb the climate rent completely. In accordance with conventional wisdom this rent can be captured by the regulator without any intertemporal efficiency losses.

Emissions trading with banking and borrowing

Instead of controlling the time path of permits in each period, banking and borrowing of permits gives markets the flexibility to decide when to use the issued permits. A free intertemporal permit trade would result in a Hotelling path. Within this market, permits are treated like an exhaustible resource – one permit used now is not available in the future. This Hotelling-path is not socially optimal because the intertemporal allocation of marginal damages is not taken into account properly (Kling and Rubin 1997). This problem could be resolved by introducing intertemporal trading rates. Leiby and Rubin (2001) have calculated intertemporal trading rates (ITR) which change the effective size of the pollution allowance held by a permit owner from one period to the next and lead to an optimal intertemporal reallocation of permits. We apply this approach to our problem to study whether the regulator can shirk the information and commitment problems as raised under the previous ETS without banking and borrowing. In order to analyze banking and borrowing within our framework, only small modifications are required. The objective function and equation of motion for the resource stock remain unchanged. However, we add an equation of motion for the permit stock b. The permit stock decreases by one unit for one unit of resource use and grows at $\gamma(t)$ – the intertemporal trading rate (ITR).

$$\dot{b} = -R + \gamma b \tag{3.47}$$

To keep our analysis simple, we restrict it to the case where the regulator issues b_0 permits once in the initial period for the entire time horizon.

Proposition 3.6. *(Optimal ETS with banking) If the regulator knows the optimal extraction path S^* of Proposition 3.1, then (a) she can achieve the socially optimal extraction path by issuing b_0 permits in the beginning and allowing for banking of permits with the intertemporal trading rate γ according to:*

$$b_0 = S_0 + \frac{\int_0^T e^{-r\xi} d_S^* S^* \, d\xi - S^*(T) F_S(S^*(T)) e^{-rT}}{-\int_0^T e^{-r\xi} d_S^* \, d\xi + F_S(S^*(T)) e^{-rT}} \tag{3.48}$$

$$\gamma = \frac{-d_S^*}{F_S(S^*(T)) e^{-r(T-t)} - \int_t^T d_S^* e^{r(t-\xi)} d\xi} \tag{3.49}$$

(b) the rent in the resource sector is given by $\lambda + \mu$ where:

$$\lambda = -\int_t^T c_S^* R^* e^{r(t-\xi)}\, d\xi \tag{3.50}$$

$$\mu = F_S(S^*(T))e^{-r(T-t)} - \int_t^T d_S^* e^{r(t-\xi)}\, d\xi \tag{3.51}$$

Proof. See Appendix 3.A. □

As it turns out, the formula for the ITR γ is in accordance with the formula given by Leiby and Rubin (2001). We extend their analysis by giving a formula for the optimal size of the initial permit stock. In principle, optimal intertemporal permit trading requires two regulating screws. Besides the ITR, the regulator has to issue the optimal number of permits in the first period which can be traded over the entire time horizon. While the ITR γ enforces the optimal timing of extraction, b_0 enforces the optimal cumulative resource consumption in accordance with the transversality condition of the social planner problem. As the regulator has to calculate *ex ante* the damages and the extraction along the social optimum $d_S(S^*(t))$ and $S^*(t)$, respectively, the informational requirements of Propositions 3.2 remain unchanged. Introducing banking and borrowing cannot discharge the regulator from difficult intertemporal optimization decisions by using market mechanisms. The ETS with banking resembles the resource rent dynamics with a stock externality as given by (3.8). It becomes apparent that the regulator could capture the rent associated with the shadow price of permits μ. Applying an auctioning mechanism, she could sell permits in the first period at maximum price μ_0, which equals the discounted value of the cumulative tax income from the optimal resource tax (3.21).

3.2.5 Performance of policies under suboptimal discount rates

The analysis above assumes that the regulator's task is limited to the internalization of the climate externality. Due to the intertemporal dynamics of the problem, however, discount rates of agents and of the society play a crucial role. In particular, when property rights for resources are insecure, capital or futures markets are incomplete, or regulatory uncertainty to imperfect commitment of governments, agents' effective discount rate could be higher than in the representative-household economy (eg. Sinn 2008). However, the choice of discount rates from the social planner's perspective has also to be discussed in a normative framework (eg. Stern 2007; Heal 2009; Roemer 2011): while individuals discount utility during their life-time due to impatience or uncertainty over the individual's income stream, the society might use a different rate to discount the utility of generations in the far-distant future. Hence, resource owners might use an additional discount markup υ which leads to the discount rate $r+\upsilon$. If suboptimal discount rates distort the intertemporal allocation, the optimal tax and ETS policy has to be adjusted according to:

Proposition 3.7. *(Suboptimal discount rates) If the resource sector discounts profits with rate $r+\upsilon$ which differs from the discount rate r of the social planner's problem, then: (a) the optimal resource tax from Proposition 3.2 has to be modified according to*

$$\tau(t) = F_S(S^*(T))e^{-(r+\upsilon)(T-t)} - \int_t^T d_S(S^*)e^{(r+\upsilon)(t-\xi)}\, d\xi \\ + \upsilon \int_t^T (p^* - c(S^*))e^{(r+\upsilon)(t-\xi)}\, d\xi \tag{3.52}$$

and (b) the efficiency of the ETS without banking is not affected. The shadow price for permits, however, changes according to:

$$\theta = F_S(S^*(T))e^{-r(T-t)} - \int_t^T d_S(S^*)e^{r(t-\xi)}\, d\xi \\ + \int_t^T c_S(S^*)R^* \left(e^{(r+\upsilon)(t-\xi)} - e^{r(t-\xi)}\right) d\xi \tag{3.53}$$

In particular, θ increases in υ for $0 \le t < T$.

Proof. (a) See Appendix 3.B.1. (b) The permit path $C(t)$ enforces the resource extraction path $R(t) = C(t)$ as permits are scarce (Assumption 3.2). Thus, the final price for resources $p^* = p(R^*)$ and the marginal extraction costs $c(S^*)$ follow the socially optimal path. The shadow price for resources λ, however, changes to:

$$\lambda(t) = -\int_t^T c_S(S^*)R^* e^{(r+\upsilon)(t-\xi)}\, d\xi \tag{3.54}$$

With (3.38), it follows that $\theta = p^* - c(S^*) - \lambda$. For $p^* - c(S^*)$ we can substitute the right-hand-side of Eq. (3.46) which gives us together with (3.54) the shadow price for θ under the discount rate $r+\upsilon$ (3.53). Finally, for $0 \le t < T$:

$$\frac{\partial \theta}{\partial \upsilon} = \upsilon \underbrace{\int_t^T (t-\xi)c_S(S^*)R^* e^{(r+\upsilon)(t-\xi)}\, d\xi}_{>0} \tag{3.55}$$

as $c_S(S^*) < 0$. □

Proposition 3.7 states that the resource tax has to change in order to achieve the optimal allocation while the permit path of the ETS without banking and borrowing remains unaffected. As long as the permit constraint is binding only the user cost for permit scarcity is affected. The higher the private discount rate markup $\upsilon > 0$, the higher is the valuation of the user cost θ. If permits are grandfathered, suboptimal discount rates make no difference in final resource prices. If permits are auctioned, the resource sector's willingness to pay for permits changes due to the modified user costs. Although suboptimal discount rates do not change the efficient extraction path, they lead to a different climate rent level. Suboptimal discount rates in an ETS with banking and borrowing, however, are hard to correct as they affect both intertemporal arbitrage conditions for the permit as well as the resource path. The solution of Leiby and Rubin (2001) to simply add υ to the ITR γ does not lead to an optimal allocation if the fossil resource supply is integrated. Nevertheless, a higher ITR should always give an incentive to postpone permit and resource use. For the stock-dependent tax rule derived in Proposition 3.4 we could not find a modification that eliminates the impact of higher discount rates. Although both instruments, the resource tax and the ETS without banking and borrowing, can achieve the optimal allocation even under distorted discount rates, the informational requirements differ: For the tax policy, the regulator has additionally to know the discount rate markup υ that resource owners actually use.

3.3 The carbon-budget approach

The cost-benefit-approach requires a balancing of the damages from the use of fossil resources against the opportunity costs of postponed resource extraction. Quantifying the damages of climate change, however, is a difficult and controversial task. There are deep uncertainties in the climate system, in regional market and non-market impacts and in normative parameters like discount rates, risk aversion or assumed substitution possibilities between physical capital and ecosystem services. Furthermore, tipping points in the earth system can lead to irreversible, abrupt and catastrophic impacts when certain thresholds of the temperature increase are crossed (Lenton et al. 2008). The controversy in the choice of many normative and uncertain parameters and the complexity of the damage dynamics might explain why many policy makers rather define concentration or temperature targets like the two-degree target. Although there is no scientific agreement on the two-degree target, there is an ongoing discussion within economics whether the possibility of catastrophic risks allows for applying cost-benefit analysis to climate change (Posner 2004; Weitzman 2009, 2010). Therefore, some researchers argue that defining emission targets or carbon budgets might be at least a pragmatic approach to reduce the likelihood of catastrophic risks substantially. As Meinshausen et al. (2009) show, achieving such a temperature target like the two-degree target depends mainly on the cumulative emissions until 2050. Hence, a more practical way of communicating and negotiating climate targets could be based on (global or national) caps for cumulative emissions – a so-called *carbon budget* (WBGU 2009). The carbon budget approach, however, does not directly imply a choice between different policy instruments in order to achieve the temperature limit in a cost-effective way. The purpose of this part is to clarify the precise requirements for the design of policy instruments.

3.3.1 The social planner economy

Implementing a carbon budget CB for cumulative extraction is only meaningful, if it enforces a binding constraint. We formulate a similar, albeit more general assumption than Assumption 3.2:

Assumption 3.3. *(Scarcity of the carbon budget) Cumulative extraction in the absence of the carbon budget (BAU) exceeds the carbon budget:*

$$CB < \int_0^T R^B \, dt < S_0 \tag{3.56}$$

A socially optimal allocation under the carbon budget approach is described by a small modification of the social planner economy formulated in Sec. 3.2.1. We remove the damage and scrap value terms and add instead the carbon budget constraint to the intertemporal optimization problem:

$$\max_R \int_0^T \left(f(R) - c(S)R\right) e^{-rt} \, dt \tag{3.57}$$

subject to:

$$\dot{S} = -R \tag{3.58}$$

$$\dot{C} = -R \tag{3.59}$$

$$S(0) = S_0 \tag{3.60}$$

$$C(0) = CB \tag{3.61}$$

The optimal allocation is described by:

Proposition 3.8. *(Socially optimal resource extraction) If a social planner maximizes intertemporal output according to (3.57–3.61), then: (a) The optimal solution $(R^\star, S^\star)$ is de-*

termined by the following system of equations:

$$r = \frac{\dot{f}_R(R^\star)}{f_R(R^\star) - c(S^\star)} \tag{3.62}$$

$$\dot{S}^\star = -R^\star \tag{3.63}$$

$$S(0) = S_0 \tag{3.64}$$

$$S(T) = S_0 - CB \tag{3.65}$$

(b) The shadow prices $\lambda^\star$ and $\mu^\star$ for S and C, respectively, are given by:

$$\lambda^\star(t) = -\int_t^T c_S(S^\star)R^\star e^{r(t-\xi)}\, d\xi \tag{3.66}$$

$$\mu^\star(t) = \mu_T^\star e^{-r(T-t)} \tag{3.67}$$

where $\mu_T^\star = f_R(R^\star(T)) - c(S^\star(T)) = f_R(R^\star(T)) - c(S_0 - CB)$.

Proof. (a) We set up the corresponding Hamiltonian function $H = f(R) - c(S)R - \lambda R - \mu R$. Applying the maximum principle leads to the following first-order and transversality conditions:

$$\lambda + \mu = f_R(R) - c(S) \tag{3.68}$$

$$\dot{\lambda} = r\lambda + c_S(S)R \tag{3.69}$$

$$\dot{\mu} = r\mu \tag{3.70}$$

$$0 = \lambda(T)S(T) \tag{3.71}$$

$$0 = \mu(T)C(T) \tag{3.72}$$

Differentiating (3.68) with respect to time and rearranging with (3.69) and (3.70), we obtain the social Hotelling rule (3.62). Assumption 3.1 and (3.71) imply that $\lambda(T) = 0$. As shown in Appendix 3.C, Assumption 3.3 implies that the entire budget is consumed, i.e. $C(T) = 0, \mu(T) > 0$ and, hence, $S(T) = S_0 - CB$. (b) Solving (3.69) with $\lambda(T) = 0$, we obtain (3.66). From $\lambda(T) = 0$ and (3.68) follows $\mu(T) = f_R(T) - c(S(T))$ – and with (3.70) we get (3.67). □

Hence, the optimal allocation under a carbon budget simply follows the Hotelling rule. The transversality condition is determined by the size of the carbon budget. The rent can be decomposed into a term reflecting increasing extraction costs λ and a term reflecting the scarcity of the carbon budget μ which we also denote as *climate rent*. Resembling the results of the cost-benefit framework, it will turn out that policies have to generate this climate rent term in order to achieve the optimal allocation.

3.3.2 Resource taxes in a decentralized market economy

As the decentralized market dynamics equals the one described in the CBA Sec. 3.2.2, we merely restate the private Hotelling rule and the terminal condition:

$$r = \frac{\dot{p} - \dot{\tau} + r\tau}{p - c(S)} \tag{3.73}$$

$$\tau(T) = p(T) - c(S(T)) \tag{3.74}$$

Proposition 3.9. *(Optimal resource tax) If the regulator knows $\mu_T^\star$ (according to Proposition 3.8) and if she can commit at $t = 0$ to the tax path $\tau(t)$ over the entire planning horizon, then (a) the resource tax*

$$\tau(t) = \mu_T^\star e^{-r(T-t)} \tag{3.75}$$

$$\mu_T^\star = f_R(R^\star(T)) - c(S_0 - CB), \tag{3.76}$$

where $R^\star(T)$ denotes the final resource extraction from the social planner optimum (Proposition 3.8), achieves the optimal extraction path. (b) The rent in the resource sector is given by:

$$\lambda(t) = -\int_t^T c_S(S) S e^{r(t-\xi)}\, d\xi \tag{3.77}$$

Proof. (a) Plugging τ from (3.75) and its derivative into the private Hotelling rule (3.73) and utilizing the fact that in the market equilibrium $p = f_R$, we obtain the social Hotelling rule (3.62). The transversality condition of the decentralized resource sector (3.74) implies that $p(T) - c(S(T)) = \mu_T^{CB}$ which equals the social transversality condition derived in Proposition 3.8. Hence, $S(T) = S_0 - CB$. (b) Same proof as in Proposition 3.2 (b). □

Similar to the cost-benefit framework, the regulator faces the same informational requirements in the social planner as well as in the decentralized market economy. The optimal resource tax is a pure budget scarcity price that reflects the scarcity of the (exhaustible) carbon budget according to the Hotelling rule. There is only a rent for reserves with low extraction costs (which diminishes if extraction costs are constant). Hence, the climate rent term μ from the social planner economy equals exactly the resource tax τ.

3.3.3 Emissions trading scheme

Emissions trading without banking and borrowing

An optimal emissions trading scheme where permits cannot be banked or borrowed is described by:

Proposition 3.10. *(Optimal ETS without banking) If the regulator issues permits $C(t) = R^\star(t)$ along the socially optimal extraction path of Proposition 3.8, then (a) the optimal extraction is achieved, (b) the resource rent is given by $\lambda + \theta$ according to:*

$$\lambda(t) = -\int_t^T c_S(S)Re^{r(t-\xi)}\, d\xi \tag{3.78}$$

$$\theta(t) = \mu_T^\star e^{-r(T-t)} \tag{3.79}$$

$$\mu_T^\star = f_R(R^\star(T)) - c(S_0 - CB) \tag{3.80}$$

Proof. The proof is along the lines of the proof of Proposition 3.5. □

Again, Proposition 3.10 requires that the regulator can calculate the socially optimal resource extraction path for the entire time horizon. The informational requirements are not lower than in the social planner economy or under a resource tax policy. The shadow price for permits θ (which would be observed on a market for tradable permits) equals the optimal tax in each period. Similar to the previous section where we studied CBA compatible instruments, we denote the scarcity price for carbon θ as *climate rent*. The regulator could absorb this rent by auctioning permits or she could shift this rent to resource owners by a grandfathering scheme.

Emissions trading with banking and borrowing

Alternatively, the regulator can allocate the permits from the carbon budget in the first period to the resource owners and allow for intertemporal flexibility when to use the permits. As objective function and constraints equal those of the social planner problem, the market reproduces the socially optimal solution:

Proposition 3.11. *(Optimal ETS with banking) If the regulator issues CB permits in the initial period which can be banked by resource owners, then (a) the optimal extraction is* *achieved, (b) the resource rent is given by $\lambda + \theta$ according to:*

$$\lambda(t) = -\int_t^T c_S(S)Re^{r(t-\xi)}\,d\xi \tag{3.81}$$

$$\theta(t) = \mu_T^\star e^{-r(T-t)} \tag{3.82}$$

$$\mu_T^\star = f_R(R^\star(T)) - c(S_0 - CB) \tag{3.83}$$

Proof. (a) and (b) follow directly from Proposition 3.8 with resource rent $p-(c(S)) = \lambda + \theta$ and $\theta = \mu$. □

The initial permit price θ_0 has to be set at the level which equals cumulative permit (or resource) demand under the carbon budget CB. As it turns out, the problem is equivalent to the emission tax problem (3.75) and $\theta_0 = \tau_0$. But in contrast to the taxation scheme, the market has to determine $\theta_0 = \mu_T^\star e^{-rT}$ by estimating the demand function and the extraction cost curve. This, however, requires a complete set of future markets to achieve an intertemporal market equilibrium (Dasgupta and Heal 1979, pp. 100–110). The regulator could issue permits for free (e.g. in a grandfathering mode to resource owners) or sell them at maximum price $\theta(t)$ – thus she can divide the scarcity rent in a non-distortionary way between several economic actors. As the regulator may not estimate $\theta(t)$ correctly, she could auction the entire permit stock in the first period. The rent left to the resource owner then reduces to λ.

3.3.4 The performance of policies under suboptimal discount rates

Equal to the analysis in the cost-benefit section, we briefly study how suboptimal discount rates influence the performance of the previously studied policy instruments.

Proposition 3.12. *(Suboptimal discount rates) If the resource sector discounts profits with rate $r+\upsilon$ which differs from the discount rate r of the social planner's problem and if the regulator furthermore knows the socially optimal extraction and price paths $S^\star, R^\star, p^\star$ and $\mu_T^\star$ of Proposition 3.8, then: (a) The optimal allocation can be achieved if the resource tax from Proposition 3.9 is modified according to*

$$\tau(t) = \mu_T^\star e^{-(r+\upsilon)(T-t)} + \upsilon\int_t^T (p^\star - c(S^\star))e^{(r+\upsilon)(t-\xi)}\,d\xi \tag{3.84}$$

(b) The efficiency of the ETS without banking is not affected; the shadow price for permits, however, changes according to:

$$\theta(t) = \mu_T^\star e^{-r(T-t)} + \int_t^T c_S(S^\star)R^\star\left(e^{(r+\upsilon)(t-\xi)} - e^{r(t-\xi)}\right)\,d\xi \tag{3.85}$$

In particular, θ increases in υ. (c) Under the ETS with banking and borrowing, the optimal allocation can be achieved if the the regulator introduces an additional resource tax according to:

$$\tau(t) = \upsilon \int_t^T (p^\star - c^\star(S)) e^{(r+\upsilon)(t-\xi)} \, d\xi \tag{3.86}$$

Proof. For (a) and (c) see Appendix 3.B.2 and 3.B.3; (b) follows basically along the lines of the proof of Proposition 3.7 (b). □

If the discount rate in the resource sector exceeds the social discount rate ($\upsilon > 0$), the resource tax has to increase at a lower rate compared to the case where $\upsilon = 0$ in order to provide an incentive for future extraction. In line with the findings obtained in the CBA framework, the ETS without banking and borrowing is the most robust instrument – as long as the regulatory institution uses the 'right' discount rate. In the latter case, suboptimal discount rates only affect the shadow price for permits and, thus, the distribution of the permit rent in case permits are auctioned by the regulator. In particular, the optimal permit price does not increase at a constant rate and is therefore not consistent with intertemporal maximization of the permit rent. This is the reason why an ETS with banking and borrowing is suboptimal: High discount rates of permit owners lead to a steeper permit price path and, thus, to an accelerated extraction. Within the banking-and-borrowing ETS, the regulator additionally has to tax resource extraction. This, however, requires the regulator to have all the necessary information on optimal timing and demand for resources for the entire time horizon.

3.4 Conclusion

Table 3.1 summarizes the main findings of our paper. Our analysis has emphasized that in a deterministic world price and quantity instruments can differ with respect to the distribution of informational requirements between market and regulator and their robustness against discount rate mark-ups. In particular, the cost-benefit approach has to deal with more complex intertemporal rent dynamics as the carbon budget approach due to its aim to allocate climate damages efficiently in time.

Due to the complexity of the stock-pollutant problem markets are hardly able to manage the climate rent intertemporally in an efficient way without substantial government intervention. It seems to be unavoidable to entrust a regulatory institution with the challenging task to find an extraction path that is 'close' to the social optimum. This requires perfect information about the availability of fossil resource, extraction costs, climate damages, fossil

	Informational requirement for government	Commitment requirement for government	Robustness against sub-optimal discounting
Cost-benefit approach:			
Tax path	high	high	low
Tax rule	low	high	low
ETS w/o banking	high	low	high
ETS with banking	high	high	low
Carbon budget approach:			
Tax path	high	high	low
ETS w/o banking	high	low	high
ETS with banking	low	high	low

Table 3.1: Comparison of policy instruments.

resource demand as well as the availability of backstop technologies. In contrast to static environmental problems an iterative adjustment process for the carbon tax will hardly be able to approach the optimal emission level. Adapting carbon taxes to observed cumulative emissions can indeed induce an accelerated extraction (green paradox). Only in the case of homogenous resource owners or linear stock-dependent damages, such a stock-dependent tax rule (together with a final-period payment rule) leads to an optimal emission level within the cost-benefit framework. In this case, the regulator is completely discharged from the task to calculate and to control optimal emission pathways. She does only need to know the functional form of climate damages and a credible commitment to the tax and final-period payment rule. In the carbon-budget approach, only an intertemporally flexible permit trade could dispense the regulator from finding the intertemporally efficient extraction path. All other instruments rely crucially on the performance of the regulatory institution to implement an intertemporally efficient allocation plan. However, delegating the task of intertemporal optimization to decentralized agents in a market environment requires a complete set of future markets. Until now, future markets for commodities or resources have not been established for planning horizons of many decades or even an entire century. Existing future markets for several decades (e.g. for fossil resources) are often thin and suffer from volatile prices due to high uncertainties and speculations. Hence, it is questionable whether intertemporally flexible permit markets are really capable to find an optimal allocation.

Intertemporal optimality crucially depends on the discount rate that economic agents use for their investment and saving decisions. Insecure property rights, incomplete future markets and uncertainty about climate policies lead to high risk premiums which are added to the discount rate of resource owners. Furthermore, the discount rate itself (as derived from the Ramsey rule) may be too high from a normative point of view. Theoretically, resource taxes could cure this additional market failure but depend on the precise evaluation of the extraction dynamics which becomes even more complex when the regulator's discount rate differs from the market discount rate. In contrast, an emissions trading schemes without intertemporal flexibility for resource owners always ensures an optimal extraction path regardless of the discount rate used by resource owners. If the supply of permits is lower than the resource supply under the absence of climate policy, resource owners will always extract resources up to the emission cap: No under-supply can occur. In this case, suboptimally high discount rates do only increase the permit price and reduce the scarcity rent associated with the in-situ resources.

These considerations indicate the need for an institution enabling a reasonable intertemporal management of the climate rent which takes into account the behavior of the owners of exhaustible resources. As all efficient policy instruments are in general non-constant in time, a continuous adjustment of taxes or emissions caps is necessary. Without a strong and credible commitment, such revisions provoke high transaction costs due to ongoing rent-seeking activities of affected actors. Hence, a 'carbon bank' or atmospheric trust as proposed by (Barnes et al. 2008) could – similar to central banks – improve the commitment to a long-term climate policy. If such an institution is capable to solve the intertemporal optimization problem, it could implement optimal emission caps or carbon taxes. If such an institution is not able to solve this problem, a pragmatic second-best approach would be to commit only to a fixed cumulative emissions budget. In this case, finding the intertermporal efficient outcome is delegated to the market. Even if the carbon budget cannot be derived by a cost-benefit analysis, there are reasons to apply emission targets when catastrophic risks can occur with a very low likelihood. Then, an intertemporally efficient allocation of permits within the budget is obtained if complete futures markets can be developed. The choice between quantity and tax instruments depends on empirical assumptions about the capability of governments to long-term commit compared to the capability of markets to ensure intertemporal efficiency. Answering these questions is a promising research question. However, it is beyond the scope of this paper.

3.A CBA-ETS with banking and borrowing

The quantity trading ratio changes the effective volume of emissions through banked permits b by rate $\gamma(t)$. The optimization problem for the resource sector with initial conditions $S_0 = S(0)$ and $b_0 = b(0)$ reads:

$$\max_R \int_0^T (p - c(S)) R e^{-rt} dt \tag{3.87}$$

$$\dot{S} = -R \tag{3.88}$$

$$\dot{b} = -R + \gamma b \tag{3.89}$$

From the the Hamiltonian $H = (p - c(S))R - \lambda R - \mu(R - \gamma b)$ we obtain the first order-conditions

$$\lambda = p - c(S) - \mu \tag{3.90}$$

$$\dot{\lambda} = r\lambda + c_S(S)R \tag{3.91}$$

$$\dot{\mu} = r\mu - \gamma\mu \tag{3.92}$$

and the transversality conditions:

$$S(T)\lambda(T) = 0 \tag{3.93}$$

$$b(T)\mu(T) = 0 \tag{3.94}$$

In the following, we derive the optimal value for b_0 and the optimal *policy trajectory* for $\gamma(t)$ that guarantees a socially optimal solution as characterized in Proposition 3.1.

3.A.1 The optimal intertemporal trading rate $\gamma(t)$

Differentiating (3.90) and substituting (3.92), we obtain:

$$\dot{\lambda} = \dot{p} + c_S(S)R - (r - \gamma)\mu \tag{3.95}$$

Equating (3.95) with (3.91) and using (3.90) yields:

$$\dot{p} = r(p - c(S)) - \gamma\mu \tag{3.96}$$

The socially optimal price path, however, from (3.4) is given by:

$$\dot{p} = r(p - c(S)) + d_S(S) \tag{3.97}$$

By equating (3.97) with (3.96) and using (3.92), we obtain:

$$-d_S(S) = \gamma\mu = r\mu - \dot{\mu} \tag{3.98}$$

Solving for μ, we get $\mu(t) = e^{rt}\int_0^t d_S(S)e^{-r\xi}d\xi + \mu_0 e^{rt}$. For known $\mu(T)$ we can calculate $\mu_0 := \mu(0) = -\int_0^T e^{-r\xi}d_S(S)\, d\xi + \mu(T)e^{-rT}$ and obtain for μ:

$$\mu = \mu(T)e^{-r(T-t)} - \int_t^T d_S(S)e^{r(t-\xi)}d\xi \tag{3.99}$$

Now, we can calculate γ by using (3.98) and (3.99):

$$\gamma = \frac{-d_S(S)}{\mu} = \frac{-d_S(S)}{\mu(T)e^{-r(T-t)} - \int_t^T d_S(S)e^{r(t-\xi)}d\xi} \tag{3.100}$$

For $S(T) > 0$, the transversality condition (3.93) implies $\lambda(T) = 0$ and with (3.90) $\mu(T) = p(T) - c(S(T))$. As in the optimum $f_R(R(T)) - c(S(T)) = F_S(S(T))$ (see Proposition 3.1), it follows with $p = f_R$ that $\mu(T) = F_S(S(T))$ for the social optimum.

3.A.2 The optimal initial permit stock b_0

Solving (3.89) yields

$$b(t) = e^{\int_0^t \gamma d\xi}\int_0^t \left(-Re^{-\int_0^\xi \gamma du}\right)d\xi + b_0 e^{\int_0^t \gamma d\xi} \tag{3.101}$$

By using the substitution $\phi := -\int_0^t \mu_0^{-1}e^{-rs}d_s(S)ds - 1$ we can re-write γ as $\gamma = \frac{\partial}{\partial t}(-\ln(-\phi)) = -\frac{\dot{\phi}}{\phi}$ and obtain for (3.101): $b(t) = \frac{-1}{\phi(t)}\left(\int_0^t \phi(\xi)R(\xi)\, d\xi + b_0\right)$. For given terminal value $b(T)$, we can calculate b_0 as follows:

$$b_0 = -b(T)\phi(T) - \int_0^T \phi(\xi)R(\xi)\, d\xi = -b(T)\phi(T) + \int_0^T \phi(\xi)\dot{S}(\xi)\, d\xi \tag{3.102}$$

For an optimal solution, $\mu(T) > 0$ for as otherwise the trading ratio $\gamma(T)$ in (3.100) is not defined. From the transversality condition (3.94) then follows that $b(T) = 0$. Using integration by substitution and the definition of ϕ, we get:

$$b_0 = \phi(T)S(T) - \phi(0)S(0) - \int_0^T \dot{\phi}(\xi)S(\xi)\, d\xi \tag{3.103}$$

$$= \phi(T)S(T) + S_0 + \frac{\int_0^T e^{-r\xi}d_S(S)S\, d\xi}{\mu_0} \tag{3.104}$$

By plugging in $\phi(T)$ and μ_0 from above, the initial permit stock is finally described by:

$$b_0 = S_0 + S(T)\frac{-\mu(T)e^{-rT}}{-\int_0^T e^{-r\xi}d_S\, d\xi + \mu(T)e^{-rT}} + \frac{\int_0^T e^{-r\xi}d_S(S)S\, d\xi}{-\int_0^T e^{-r\xi}d_S(S)\, d\xi + \mu(T)e^{-rT}} \tag{3.105}$$

$$= S_0 + \frac{\int_0^T e^{-r\xi} d_S(S) S \, d\xi - S(T)\mu(T)e^{-rT}}{-\int_0^T e^{-r\xi} d_S(S) \, d\xi + \mu(T)e^{-rT}} \tag{3.106}$$

3.A.3 The resource rent

The rent π in the resource sector is determined by resource prices minus extraction costs, i.e. $p - c(S)$. From (3.90) follows that $\pi = \lambda + \mu$. With the solution of the differential equation for λ (3.91) and the equation for μ (3.99),we obtain $\pi = (\mu(T) + \lambda(T))e^{-r(T-t)} - \int_t^T (d_S + c_S R)e^{r(t-\xi)} \, d\xi$

3.B Suboptimal discount rates

3.B.1 Optimal resource tax in the cost-benefit approach

If the resource sector uses the discount rate ρ instead of the socially optimal discount rate r, the re-arranged private Hotelling rule (3.19) reads:

$$\rho(p - c(S)) = \dot{p} - \dot{\tau} + \rho\tau \tag{3.107}$$

The re-arranged socially optimal Hotelling rule (3.4) with $p = f_R$ in the market equilibrium is:

$$r(p^* - c(S^*)) = \dot{p}^* - d_S^* \tag{3.108}$$

Substituting $\dot{p}$ from (3.108) into (3.107), we obtain for the optimal solution $\dot{\tau} = \rho\tau + d_S^* + (r - \rho)(p^* - c(S^*))$. Solving the ODE for given $\tau(T)$ yields:

$$\tau(t) = \tau(T)e^{-\rho(T-t)} - \int_t^T d_S^* e^{\rho(t-\xi)} \, d\xi - (r - \rho)\int_t^T (p^* - c(S^*))e^{\rho(t-\xi)} \, d\xi \tag{3.109}$$

In order to achieve the social transversality condition (3.11), we set $\tau(T) = F_S(S^*(T))$.

3.B.2 Optimal resource tax under a carbon budget without ETS

Under the budget approach applies the private Hotelling rule from (3.107). The re-arranged socially optimal Hotelling rule (3.62), however, does not contain a damage term and reads with $p = f_R$:

$$r(p - c(S)) = \dot{p} \tag{3.110}$$

Substituting $\dot{p}$ from (3.110) into (3.107) and solving the ODE for given $\tau(T)$, we obtain:

$$\tau(t) = \tau(T)e^{-\rho(T-t)} - (r-\rho)\int_t^T (p^* - c(S^*))e^{\rho(t-\xi)}\, d\xi \tag{3.111}$$

In order to achieve the social transversality condition within the budget approach, we set $\tau(T) = \mu_T^{CB}$.

3.B.3 Optimal resource tax under a carbon budget with ETS

Under the ETS with banking and borrowing, we have to consider the Hotelling rules (3.110) and (3.107) which yields to the same formula for the optimal tax as (3.111) without ETS. The social transversality condition, however, is already achieved by the limited permit stock, implying $\tau(T) = 0$, and thus:

$$\tau(t) = -(r-\rho)\int_t^T (p^* - c(S^*))e^{\rho(t-\xi)}\, d\xi \tag{3.112}$$

3.C Exhaustion of the entire carbon budget

Proof for $C(T) = 0$:

Let us assume, that the permit stock is not exhausted, i.e. $C(T) > 0$. From (3.72) follows that $\mu(T) = 0$ which implies that (with $\lambda(T) = 0$ and (3.68)) $f_R(R(T)) = c(S(T))$. As in the BAU case $S^B(T) > 0$ and thus, $\lambda^B(T) = 0$, it follows that $f_R(R^B(T)) = c(S^B(T))$ (where x^B denotes the corresponding variable in the BAU-scenario without binding carbon budget constraint, i.e. with $CB = S_0$). Thus, we have:

$$f_R(R(T)) = c(S(T)) \tag{3.113}$$
$$f_R(R^B(T)) = c(S^B(T)) \tag{3.114}$$

From Assumption 3.3 follows that

$$S(T) > S^B(T) \tag{3.115}$$

Equations (3.113–3.115) imply together with $f_{RR} < 0$ and $c_S < 0$ that $R(T) > R^B(T)$. As $\int_0^T R\, dt < \int_0^T R^B\, dt$ and $R(T) > R^B(T)$ there must exist a $t^* : 0 < t^* < T$ with:

$$R(t^*) = R^B(t^*) \tag{3.116}$$
$$R(t) \geq R^B(t) \quad \text{for } t^* \leq t \leq T \tag{3.117}$$

In particular, this implies $\int_0^{t^*} R\,dt < \int_0^{t^*} R^B\,dt$ and thus (considering $c_S < 0$)

$$c(S(t^*)) < c(S^B(t^*)) \tag{3.118}$$

The Hotelling rules for the budget and BAU probem read:

$$r = \frac{\dot{f}_R}{f_R - c(S)} = \frac{\dot{f}_R^B}{f_R^B - c(S^B)} \tag{3.119}$$

Using $\dot{f}_R = f_{RR}\dot{R}$, we get by rearranging (3.119) in $t = t^*$:

$$\underbrace{\dot{R}(t^*) - \dot{R}^B(t^*)}_{\geq 0 \;\; \text{from}(3.117)} = \underbrace{\frac{r}{f_{RR}}}_{<0} \underbrace{[c(S^B(t^*)) - c(S^B(t^*))]}_{>0 \;\; \text{from}(3.118)} \tag{3.120}$$

which leads to a contradiction as the right hand side is strictly negative while the left hand side is positive (or zero). Thus, the initial assumption $C(T) > 0$ is not valid and it follows that $C(T) = 0$.

Bibliography

Archer, D. (2005). Fate of fossil fuel CO2 in geologic time. *J. Geophys. Res. 110*(C9), C09S05.

Barnes, P., R. Costanza, P. Hawken, D. Orr, E. Ostrom, A. Umaña, and O. Young (2008). Creating an earth atmospheric trust. *Science 319*(5864), 724b.

BGR (2009). Energierohstoffe 2009. Reserven, Ressourcen, Verfügbarkeit. Technical report, Bundesamt für Geowissenschaften und Rohstoffe, Hannover, Germany.

Dasgupta, P., G. Heal, and J. E. Stiglitz (1981). The taxation of exhaustible resources. NBER Working Paper 436, National Bureau of Economic Research.

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

Farzin, Y. H. (1992). The time path of scarcity rent in the theory of exhaustible resources. *The Economic Journal 102*(413), 813–830.

Farzin, Y. H. (1996). Optimal pricing of environmental and natural resource use with stock externalities. *Journal of Public Economics 62*(1-2), 31–57.

Heal, G. (2009). Climate economics: A meta-review and some suggestions for future research. *Review of Environmental Economics and Policy 3*(1), 4–21.

Hoel, M. and S. Kverndokk (1996). Depletion of fossil fuels and the impacts of global warming. *Resource and Energy Economics 18*(2), 115–136.

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

IPCC (2007). *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

Kling, C. and J. Rubin (1997). Bankable permits for the control of environmental pollution. *Journal of Public Economics 64*(1), 101–115.

Leiby, P. and J. Rubin (2001). Intertemporal permit trading for the control of greenhouse gas emissions. *Environmental and Resource Economics 19*(3), 229–256.

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber (2008). Tipping elements in the earth's climate system. *Proceedings of the National Academy of Sciences 105*(6), 1786–1793.

Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature 458*(7242), 1158–1162.

Posner, R. (2004). *Catastrophe: risk and response*. Oxford University Press, USA.

Roemer, J. (2011). The ethics of intertemporal distribution in a warming planet. *Environmental and Resource Economics 48*, 363–390.

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

Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences 106*(6), 1704–1709.

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

WBGU (2009). Solving the climate dilemma: The budget approach. Special report, German Advisory Council on Global Change, Berlin.

Weitzman, M. (2009). On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics 91*(1), 1–19.

Weitzman, M. L. (2010). GHG targets as insurance against catastrophic climate damages. NBER Working Papers 16136, National Bureau of Economic Research, Inc.

Part II

PRIDE: An Integrated Policy Assessment Model

Chapter 4

Learning or Lock-in: Optimal Technology Policies to Support Mitigation

Abstract: We investigate conditions that amplify market failures in energy innovations, and suggest optimal policy instruments to address them. Using an intertemporal general equilibrium model we show that 'small' market imperfections may trigger a several decades lasting dominance of an incumbent energy technology over a dynamically more efficient competitor, given that the technologies are very good substitutes. Such a 'lock-in' into an inferior technology causes significantly higher welfare losses than market failure alone, notably under ambitious mitigation targets. More than other innovative industries, energy markets are prone to these lock-ins because electricity from different technologies is an almost perfect substitute. To guide government intervention, we compare welfare-maximizing technology policies including subsidies, quotas, and taxes with regard to their efficiency, effectivity, and robustness. Technology quotas and feed-in-tariffs turn out to be only insignificantly less efficient than first-best subsidies and seem to be more robust against small perturbations.

4.1 Introduction

Whether technology policy is needed in addition to carbon pricing to combat global warming efficiently is still debated controversially. The straight-forward approach suggests that addional externalities – for example innovation spillovers – require additional instruments (Fischer and Preonas 2010). In contrast, some economists have argued that existing, technology unspecific instruments like patents and research subsidies are sufficient to foster innovations in the energy sector (Nordhaus 2009). In particular, there is concern that the social costs of technology-specific policies (due to rent-seeking, transaction costs and information problems) outweigh the benefits.

Our paper takes this debate as starting point by focussing on three questions: (i) Are innovation-related market failures in the energy sector different from other sectors in the economy, in particular with respect to possible technology lock-ins? (ii) Is it likely for the social costs of innovation externalities to exceed the social costs of technology-specific instruments? (iii) In how far do policies with stronger technology discrimination outperform more general policies?

The first of our questions is addressed in Gerlagh et al. (2008), within a model of patents for innovations. The dynamic inefficiency of limited patent lifetime leads to a bias towards innovations with pay-back time during the patent lifetime. As climate change is a stock-pollutant problem, the benefits of innovation in energy technologies materialize in the distant future when atmospheric carbon concentration is high. Hence, investments into energy innovation may be less than into other innovations. Several modeling studies incorporating carbon externalities and innovation address the second and the third question. With regard to the technological structure, Kverndokk and Rosendahl (2007) and Rivers and Jaccard (2006) are close to our model but do not consider intertemporal resource extraction and endogenous savings dynamics. Fischer and Newell (2008) use a partial two-period equilibrium model calibrated to the US economy for very moderate mitigation targets. Gerlagh et al. (2004) and Gerlagh and Lise (2005) analyze the impact of constant ad-hoc carbon taxes under (perfectly internalized) technological change within an intertemporal general equilibrium model. Finally, Popp (2004, 2006) studies the impact of R&D expenditures on carbon prices and mitigation costs within a social planner model. Grimaud et al. (2010) use a similar technological structure to analyze carbon pricing and R&D policies in a decentralized economy.

Another strand of research has focused on the high inertia of energy markets due to long investment cycles, increasing returns to scale and networt externalities (Unruh 2000, 2002; Foxon and Pearson 2007; Schmidt and Marschinski 2009). This strand is partly based on the concept of 'lock-in' – a market dominance of an inferior incumbent technology at the expense of a superior contender technology (Arthur 1989, 1994). Well-known examples include keyboard layout and video recorders (David 1985; Cusumano et al. 1992) but also energy technologies (Cowan and Hulten 1996; Islas 1997). Due to the inertia of the energy sector, carbon pricing may have only little impact on investments and innovation, making additional instruments necessary.

We differ from these models in analyzing the possibility and intensity of technology lock-ins within an intertemporal general equilibrium model. Furthermore, we provide an extensive policy analysis considering first-best and several welfare maximzing second-best instruments. In the model we describe in Sec. 4.2, lock-ins rise due to imperfections in the innovation process and the competition between technologies that are almost perfect substitutes: Technological progress in the learning carbon-free sector is driven by learning-by-doing with intra-sectoral knowledge spillovers. We furthermore explore the possibility of high effective discount rates in the learning technology sector. The discount rate mark-ups might evolve from risk premiums due to uncertainty and imperfect commitment about future climate policy which effects the profitability of early learning-by-doing. We consider three energy technologies: (i) fossil energy, (ii) a learning carbon-free energy where significant learning-by-doing occurs as expected for many renewable energy technologies, and (iii) a mature (non-learning) carbon-free energy where technology has already experienced past learning and considerable up-scaling. Candidates for the mature carbon-free energy technology are nuclear power or hydropower.

We find that a possible lock-in into the inferior (non-learning) technology can be very costly compared to the costs of the innovation market failure alone, i.e. when the inferior technology would not be available at all (Sec. 4.3). Incomplete appropriation of the gains of innovation generally leads to higher prices. This is the case for all technology development that exhibits spillovers, but given sufficient product differentiation, consumers will buy new products even at higher prices. Impacts of spillovers will be small because the demand of variety-loving consumers triggers further technological progress and cost reductions. Electricity, however, is a very homogeneous good, and thus price competition dominates the market. The currently cheapest technology crowds out other technologies that may be dynamically more efficient. Hence, due to the very good substitutability between energy from technologies with different innovation potential markets suffer more from spillovers than many other innovative industries.

Due to the good substitutability, seemingly small market failures have a considerable impact on the energy mix, welfare and carbon prices. We therefore analyze the performance of different policies in preventing lock-ins by calculating optimal first-best and second-best policy instruments (Sec. 4.4). We distinguish the following policy instruments: (i) subsidies for the learning carbon-free technology; (ii) quotas (i.e. portfolio standards) with different degree of technology discrimination, (iii) feed-in-tariffs, (iv) taxes on the mature carbon-free technology, and (v) second-best carbon pricing. We find that only the subsidy achieves the social optimum, but feed-in-tariffs and quotas specifically targeting the learning technology only incur very small welfare losses. The other instruments exhibit larger welfare losses up to the point of showing no improvement compared to the laissez-faire market equilibrium with a carbon price only. Limited commitment and political-economy aspects motivate our analysis of policy stimuli, i.e. subsidies that are only available for a certain time (Sec. 4.5). It turns out, that an optimal subsidy stimulus of only a few decades reduces consumption losses substantially. Finally, by considering small perturbations of the optimal policies we find that the optimal feed-in-tariff and quota turn out to be fairly robust, while a deviation from the optimal subsidy of as little as one percent may render the subsidy ineffective in preventing a lock-in (Sec. 4.6).

4.2 The model

We use an intertemporal general equilibrium model that distinguishes household, production, fossil resource extraction and several energy sectors.[1] In addition to energy generated by combustion of fossil resources, there are two carbon-free energy sources: a mature energy sector, and a more expensive yet learning competitor technology. A further sector extracts fossil resources from a finite resource stock. For simplicity, we use labor only as input in the production sector and not in the energy sector as only a minor share of the labor force is allocated to the energy sector (in EU-27 approx. 3% (Eurostat 2009)). Furthermore, capital and fuel costs clearly dominate operation and maintenance costs (which include labor costs) for all major energy generation technologies (IEA 2010, Tab. 6.2). We assume standard constant elasticity of substitution (CES) production functions stated in detail in the appendix. The economic sectors are in a competitive market equilibrium within a closed economy. Global warming policy is addressed by a carbon bank – an independent institution that manages a given carbon (permit) budget intertemporally. The government, which anticipates the equilibrium response of the economy, imposes policy instruments on the economy to maximize welfare. Fig. 4.1 gives an overview of the equilibrium and the role of the government.

4.2.1 The decentralized economy

Here, we concentrate on the description of the agents' optimization problem and the interplay with government's policies; the mathematical description of production technology as well as the derivation of the first-order conditions can be found in Appendix 4.A and 4.B, respectively.

[1]The model is built to deal with a large set of climate policy issues like delayed carbon pricing, supply-side dynamics and double-dividend aspects which go beyond the research question of this paper.

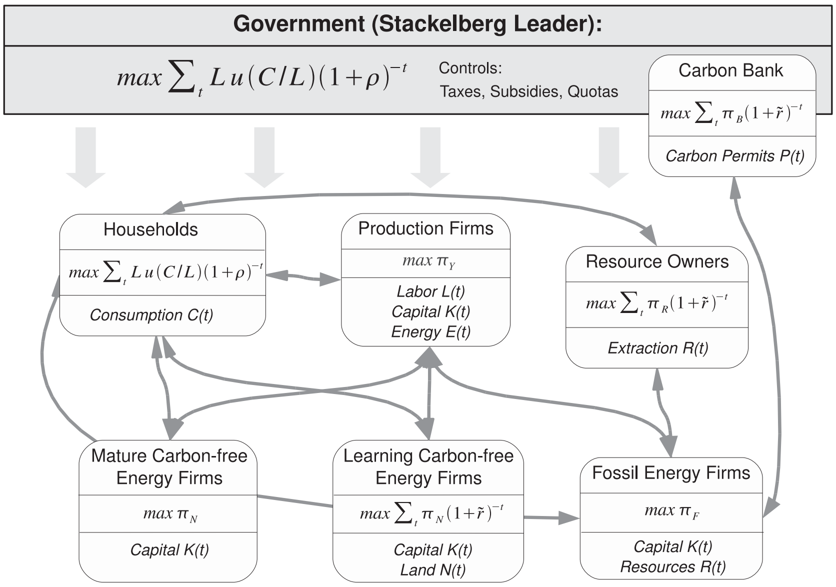


Figure 4.1: Overview of the modeling framework.

The representative household

We assume a representative household with the objective to maximize the sum of discounted utility U, which is a function of per-capita consumption C/L:[2]

$$\max_{C_t} \quad \sum_{t=0}^{T}(1+\rho)^{-t}L_t\mathbf{U}(C_t/L_t)$$

where ρ is the pure rate of time preference.

The household owns labor L, capital stocks K_j, and the firms, and therefore receives the factor incomes wL and rK_j, as well as the profits of all firms π_j, where $j \in \{Y,F,R,N,L\}$ enumerates the sectors (consumption good sector Y, fossil energy sector F, resource extraction sector R, mature (non-learning) carbon-free energy sector N, learning carbon-free energy sector L). Wage rate w, interest rate r, profits π_j and lump-sum transfers from the government Γ are taken as given from the household's perspective. The household is assumed to take the depreciation of capital at rate δ into account in its investment decision.[3]

[2] In the following, we often omit the time-index variables t in the main text to improve readability.

[3] Imposing the depreciation dynamics on the saving-side (households) instead of the investment-side (firms) is done for technical reasons. It does not change investment behavior but simplifies the capital dynamics within the economic model.

The household therefore faces the following constraints:

$$C_t = w_t L_t + r_t K_t - I_t + \pi_t + \Gamma_t \tag{4.1}$$

$$K_t = \sum_j K_{j,t}, \qquad I_t = \sum_j I_{j,t}, \qquad \pi_t = \sum_j \pi_{j,t} \tag{4.2}$$

$$K_{j,t+1} = K_{j,t} + I_{j,t} - \delta K_{j,t}, \qquad K_0 \text{ given} \tag{4.3}$$

The production sector

The representative firm in the consumption good sector maximizes its profit π_Y by choosing how much capital K_Y and labor L to rent, and how much energy to purchase from the various sources: fossil fuels sector, mature and learning carbon-free energy sectors (E_F, E_N, and E_L, respectively).[4] It has to consider the production technology $\mathbf{Y}(\cdot)$ and the given factor prices for capital (r), labor (w), fossil (p_F), mature carbon-free (p_N) and learning carbon-free (p_L) energy (the price of consumption goods is set to one). Furthermore, the production sector may need to consider government intervention in form of a feed-in tariff ς_F. The feed-in-tariff takes the form of a subsidy but is cross-financed by a tax τ_F on energy from the fossil and the mature carbon-free technology energy sectors.

$$\begin{aligned}\pi_{Y,t} = \mathbf{Y}(K_{Y,t}, L_t, E_{F,t}, E_{L,t}, E_{N,t}) - r_t K_{Y,t} - w_t L_t - (p_{F,t} + \tau_{F,t})E_{F,t} - (p_{L,t} - \varsigma_{F,t})E_{L,t} \\ - (p_{N,t} + \tau_{F,t})E_{N,t}\end{aligned} \tag{4.4}$$

The nested CES production function $\mathbf{Y}(\mathbf{Z}(K_Y, A_Y L), \mathbf{E}(E_F, \mathbf{E_B}(E_L, E_N)))$ combines a capital-labor intermediate with energy, assuming an elasticity of substitution of σ_1. Capital and labor are combined to an intermediate input Z using the elasticity of substitution σ_2; similarly, fossil energy and carbon-free energy are combined to final energy with the elasticity of substitution σ_3. Finally learning and mature carbon-free energy are combined to aggregate carbon-free energy E_B using the elasticity of substitution σ_4.[5] Population L and productivity level A_Y grow at an exogenously given rate.

Additionally, the government may impose quotas to influence the energy portfolio. Three quotas are included, differing with respect to how specifically they can foster energy from the learning carbon-free technology: Quotas of the first kind, ψ_L^T, set a minimum

[4] The intertemporal profit maximization problem of the production, fossil energy and mature carbon-free energy sector boils down to a static problem.

[5] We do not integrate fossil, learning and non-leaning energy on the same CES-level because we assume that substitutability between the two carbon-free energies E_L and E_N should be higher than between a carbon-free and a fossil energy E_F and E_L. This is due to the fact that carbon-free energy is usually considered in the electricity sector while fossil energy covers electric as well as non-electric energy consumption.

share of energy from the learning carbon-free (E_L) relative to total energy use. The second type ψ_L^B requires a minimum share of E_L relative to all carbon-free energy. Finally, the quota ψ_B^T determines the minimum share of energy from either carbon-free technology relative to total energy use.

$$E_{L,t} \geq \psi_{L,t}^T (E_{F,t} + E_{N,t} + E_{L,t}) \tag{4.5}$$

$$E_{L,t} \geq \psi_{L,t}^B (E_{N,t} + E_{L,t}) \tag{4.6}$$

$$E_{L,t} + E_{N,t} \geq \psi_{B,t}^T (E_{F,t} + E_{N,t} + E_{L,t}) \tag{4.7}$$

The fossil energy sector

The fossil energy sector maximizes profits π_F with respect to capital K_F and fossil resource use R, subject to the CES production technology E_F and given factor prices for fossil energy, capital and resources (p_R). Additionally, it may consider a carbon tax τ_R or carbon permit price p_C:

$$\pi_{F,t} = p_{F,t}\mathbf{E_F}(K_{F,t}, R_t) - r_t K_{F,t} - (p_{R,t} + \tau_{R,t} + p_{C,t})R_t \tag{4.8}$$

The fossil resource sector

The fossil resource sector extracts resources from an exhaustible stock S using capital K_R. Its objective is to maximize the sum of profits over time, discounted at the rate $r_t - \delta$[6]:

$$\max_{R_t} \sum_{t=0}^{T} \pi_{R,t} \Pi_{s=0}^{t} [1 + (r_s - \delta)]^{-1}$$

Resource owners rent the capital used in the extraction process at the market interest rate. The productivity of capital $\partial\mathbf{R}/\partial K_R$ decreases with ongoing depletion of the exhaustible resource stock (Rogner 1997; Nordhaus and Boyer 2000). The resource sector, therefore, has to consider the following constraints:

$$\pi_{R,t} = p_{R,t}\mathbf{R}(S_t, K_{R,t}) - r_t K_{R,t} \tag{4.9}$$

$$S_{t+1} = S_t - R_t, \qquad S_t \geq 0, \qquad S_0 \text{ given} \tag{4.10}$$

[6]As the interest rate already reflects depreciation of capital due to our formulation of the representative household (see Eqs. 4.1–4.3), consumption has to be discounted by the interest rate net of depreciation.

The learning carbon-free energy sector

The learning carbon-free sector maximizes profit π_L under capital input and with a fixed amount of land N. It considers interest rate, the price of the learning carbon-free energy as well as an output subsidy τ_L as given and may additionally consider a risk premium $v \geq 0$ which effectively increases the discount rate above the market interest rate. The risk premium reflects uncertainty and imperfect commitment regarding the stringency of future mitigation policies (and, thus, carbon prices). Another rationale for imperfect foresight is provided by Rivers and Jaccard (2006) who argue that the variance of learning investments is larger than for other investments. Risk premiums evolve if capital or insurance markets are not perfect (i.e. due to asymmetric information) or investors are risk-averse. As the learning-by-doing dynamics implies an additional inertia through the knowledge stock, the learning sector is more vulnerable to uncertainty than non-learning sectors.[7] The optimization problem of the sector reads:

$$\max_{K_{L,t}} \sum_{t=0}^{T} \pi_{L,t} \Pi_{s=0}^{t} \left[1 + (r_s + v - \delta)\right]^{-1}$$

$$\pi_{L,t} = (p_{L,t} + \tau_{L,t}) \mathbf{E_L}(\mathbf{A_L}(H_t) K_{L,t}, N) - rK_L \tag{4.11}$$

$$H_{t+1} = H_t + (E_{L,t} - E_{L,t-1}), \qquad H_0 \text{ given} \tag{4.12}$$

The productivity $\mathbf{A_L}$ depends on cumulative output H according to $A_L = \frac{A_{L,max}}{1+\left(\frac{\Omega}{H}\right)^{\gamma}}$ and converges to $A_{L,max}$ when $H \to \infty$. This formulation is based on Arrows's learning-by-doing approach (Arrow 1962) and widely used in energy economic models (e.g. Kverndokk and Rosendahl 2007; Fischer and Newell 2008). Ω is a scaling parameter, and γ is the learning exponent. It is related to the learning rate lr by $\gamma = -\ln(1-lr)/\ln 2$, which measures by how much productivity increases when cumulative capacity is doubled.

As shown in Appendix 4.B, the firms' internal value of learning μ_t is given by $\mu_{t-1} = \frac{1-\phi}{1+r_t+v+\delta}(p_{L,t} + \tau_{L,t} + \mu_t)\frac{\partial \mathbf{E_L}}{\partial H_t}$. The spillover rate $\phi \in [0,1]$ is introduced to indicate how much of the learning-by-doing effect is anticipated by the individual firm. This approach is in more detail explained in Fischer and Newell (2007) and relies on the learning-by-doing dynamics elaborated in Spence (1984) and Ghemawat and Spence (1985). It is consistent

[7] By the same token, imperfect commitment also concerns the fossil resource owners. Under a mitigation policy, however, high carbon prices dilute the intertemporal rent dynamics of the fossil resource sector. Fossil resource rents become almost zero under ambitious mitigation targets. Introducing high risk premiums does therefore not affect the resource extraction which is dominated by the carbon price (see Chapter 3 for an analytical analysis).

with econometric studies on external learning-by-doing spillovers which suggest that learning does not only depend on the individual firm's cumulative production but also – to some extent – on the other firms' cumulative output (Irwin and Klenow 1994; Barrios and Strobl 2004). From a social planner's perspective, all externalities are internalized and spillovers are irrelevant as cumulative output determines learning. In contrast, in a decentralized economy, only a share $(1-\phi)$ of learning is appropriated by the firm. Hence, ϕ describes an incentive problem.[8]

The learning carbon-free sector covers mainly renewable energy technologies requiring large amounts of land. As best sites (regarding solar radiation, wind speed etc.) are used first, marginal costs increase with ongoing deployment (if productivity is held constant) (cf. IPCC 2011, Ch. 10). The learning-by-doing effect may offset these diminishing returns in particular for the early deployment phase.

The mature carbon-free energy sector

The mature carbon-free sector sector maximizes profit π_N subject to capital input K_N:

$$\pi_{N,t} = (p_{N,t} - \tau_{N,t})\mathbf{E_N}(K_{N,t}) - r_t K_{N,t} \tag{4.13}$$

It takes interest rate and energy price as given and has to consider an output tax τ_N on energy generation if it is imposed by the government. Being a rather generic sector, we employ an AK-technology function where a change of the productivity level A_N changes the marginal productivity of capital.

The carbon bank

We assume that society's mitigation goal is formulated as an upper constraint on cumulative carbon extraction – a so-called carbon budget –, and that the government has appointed an institution, the carbon bank, to manage the corresponding carbon permits efficiently. Equivalently, the government could issue all available carbon permits to the market and allow for free intertemporal permit trade. The carbon bank has the objective to maximize the revenues π_C from a given carbon budget $B_0 \geq 0$. It decides how much carbon permits P to issue in each time period. As each unit of carbon R extracted by the fossil resource sector

[8]A spillover rate of 100 percent implies that firms perceive the productivity increase as fully exogenous. In contrast, a 0 percent spillover rates implies a perfect internalization of learning by firms. Learning then is a pure private good.

requires the purchase of one carbon permit, it follows that $P = R$.

$$\max_{R_t} \sum_{t=0}^{T} \pi_{B,t} \Pi_{s=0}^{t} \left[1 + (r_s - \delta)\right]^{-1}$$

$$\pi_{B,t} = p_{C,t} R_t \tag{4.14}$$

$$B_{t+1} = B_t - R_t, \qquad B_t \geq 0, \qquad B_0 \text{ given} \tag{4.15}$$

Similar to an exhaustible resource, the carbon budget is a stock of permits which can be used throughout the planning horizon. The resulting carbon price set by the bank therefore follows the Hotelling rule.

While there are some economists arguing for such an independent institution to increase commitment and reduce regulatory uncertainty (Barnes et al. 2008; Brunner et al. 2011) , we use this approach mainly for didactical reasons. If there are no further externalities, such a Hotelling price path leads always to an efficient abatement profile (Chapter 3; Goulder and Mathai (2000)). When market failures in other sectors, however, cannot be corrected, it can be beneficial to deviate from the Hotelling price path. As we want to study the potential of such second-best carbon pricing seperately (Sec. 4.4.5), we use the Hotelling carbon price as default implementation of the government's mitigation policy.

4.2.2 Equilibria of the economy

In this study, we distinguish three types of equilibria for the economy outlined above. The social optimum given by the choice of a benevolent social planner serves as the benchmark equilibrium. In the Stackelberg equilibria, a welfare-maximizing government selects the optimal trajectory of policy instruments from a pre-defined subset of available policy instruments given the implicit reaction functions of the economic sectors (see for example Dockner et al. (2000, p. 111)). Thirdly, we consider a laissez-faire market equilibrium with no government intervention.

Social optimum

The intention of considering the social optimum of our model economy, is to measure the extend to what second-best policies fall short of the first-best. The socially optimal allocation is determined by solving the welfare maximizing problem subject to investment, fossil extraction, carbon budget, technology and macroeconomic budget constraints according to:

$$\max_{\{K_{j,t}\}} \sum_{t=0}^{T}(1+\rho)^{-t}L_t\mathbf{U}(C_t/L_t) \tag{4.16}$$

subject to Eqs. 4.2, 4.3, 4.10, 4.12, 4.15, 4.20–4.32

and $C_t = Y_t - I_t$

Stackelberg equilibrium

The first-order conditions of the sectors described above (and spelled out in Appendix 4.B) define an intertemporal market equilibrium for given policy instruments. The government considers all technology constraints, budget constraints, equations of motion and first-order and transversality conditions and chooses policy instruments to maximize welfare (see Fig. 4.1).

Furthermore, the government balances incomes and expenditures in any time with households' lump-sum tax Γ. In case of the feed-in-tariff, the subsidy ς_F for the learning energy is financed by the tax for fossil and mature energy τ_F.

$$\Gamma_t = \tau_{N,t}E_{N,t} - \tau_{L,t}E_{L,t} + \tau_{R,t}R_t + \pi_{B,t} \tag{4.17}$$

$$\varsigma_{F,t}E_{L,t} = \tau_{F,t}(E_{F,t} + E_{N,t}) \tag{4.18}$$

Hence, the government's optimization problem is described by:

$$\max_{\Theta} \sum_{t=0}^{T}(1+\rho)^{-t}L_t\mathbf{U}(C_t/L_t) \tag{4.19}$$

subject to Eqs. 4.1–4.15, 4.17–4.18 , 4.20–4.32, 4.33–4.52

$\Theta = \{\tau_{L,t}, \tau_{N,t}, \tau_{R,t}, \varsigma_{F,t}, \psi^T_{L,t}, \psi^B_{L,t}, \psi^T_{B,t}\}$ is the set of government policies. For the purpose of our paper it will be convenient to restrict policies to a single instrument while all other instruments are set to zero.

Laissez-faire equilibrium

The laissez-faire market equilibrium is a special case of the Stackelberg equilibrium. Here we set all policy instruments to zero – thus, $\Theta \equiv \mathbf{0}$. Note that this does not include climate policy, as we always assume that climate policy in form of a carbon budget is implemented by the carbon bank setting p_C.

4.2.3 Calibration and implementation of the model

Model parameters are chosen to reproduce a global-economy baseline from a model comparison project in the social optimum without any carbon budget (Edenhofer et al. 2010). We use a carbon budget of 450 GtC for the mitigation scenario. This limits global warming to 2°C above the preindustrial level with a probability higher than 50 percent (Meinshausen et al. 2009). The endogenous fossil energy price starts at 4 ct/kWh in 2010 and increases up to 8 ct/kWh in 2100 (under business as usual) due to increasing extraction costs. The mature carbon-free technology refers to nuclear or hydropower as their learning rates are very low (1-9%) compared to renewable energy technologies like solar, wind and ethanol (8-35%) (IEA 2000; McDonald and Schrattenholzer 2001). The parameters describing the non-learning carbon-free technology are chosen to reproduce constant energy costs at 15 ct/kWh. This is at the upper bound of IEA's cost estimate for nuclear and gas (IEA 2010).[9] The recent IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation cites 41 learning rate estimations for renewable energy ranging from 0% to 45% with a mean of 16.4% (IPCC 2011, Ch. 10, Tab. 10-10). For the learning carbon-free energy we will mainly consider two parameterizations: a moderate learning parameterization with a 17% learning rate and 9 ct/kWh generation costs in 2100 (standard parameterization); and a high learning scenario with a 25% learning rate and 5 ct/kWh generation costs in 2100. Initially, the average costs are around 28 ct/kWh. The discounted consumption losses due to the consideration of the carbon budget (i.e. the mitigation costs) are 1.7% for the 25% learning rate and 4.0% for the 17% learning rate scenario.

The climate externality can be easily incorporated by a fixed carbon budget consistent with a certain temperature target. The magnitude of the innovation market failure, however, i.e. learning spillovers and risk premiums, seems to be difficult to quantify. Several econometric studies confirm the existence of learning-by-doing spillovers in the manufacturing and semiconductor industry; the estimated spillover rates are usually between 20% and 60% (Irwin and Klenow 1994; Gruber 1998; Barrios and Strobl 2004).[10] The literature on R&D and innovation externalities indicates that social rates of return into innovations exceed the private rates of return by the fourfold (cf. Nordhaus 2002). As only one fifth of the value of innovation can be appropriated by the innovator, the resulting spillover rate is 80%. In our

[9] We use a small negative external learning rate in Eq. 4.32 of $g_N = -0.4\%$ to obtain constant costs for the non-learning carbon-free energy because the interest rate falls over time. A negative learning rate can also be justified by increasing resource or site scarcities or increasing safety standards which raised capital costs for nuclear power plants in the past (Du and Parsons 2009). However, we ran our model also for $g_N = 0$ and did not observe qualitative differences in the economic dynamics.

[10] These spillover rates refer to countries that already have a comprehensive patent legislation. The knowledge transfer into countries with imperfect patent legislation should therefore be higher.

model, however, we do not consider R&D externalities explicitly to avoid the interference of too many innovation externalities. In order to still account for the high magnitude of innovation externalities, we chose a learning-by-doing spillover rate of 60%, but we consider also lower and higher values. Due to the lack of empiric evidence, we assume that the risk premium is zero ($\nu = 0$). Nevertheless, we elaborate the impact of deviations from these values in Sec. 4.3. We set $\sigma_3 = 3$, implying a good substitutability between fossil and carbon-free energy. As the carbon-free energy sector covers mainly electric energy, we assume a high substitutability and set $\sigma_4 = 21$.[11]

The optimization problems as defined by (4.16) and (4.19) form a non-linear program (NLP) which is solved numerically with GAMS (Brooke et al. 2005). All parameters of the model are listed in Appendix 4.D.

4.3 The lock-in effect

In this section, we compare the laissez-faire market equilibrium (with Hotelling carbon price) with the optimal solution. In order to compare the dynamic outcome of several equilibria we introduce two metrics: (i) *consumption losses* refer to the relative deviation of discounted consumption from the social optimum under the same technological parameters (we use a 3% discount rate); (ii) the *delay* of learning carbon-free generation (compared to the social optimum) is measured by the difference in years until the learning carbon-free energy achieves a share of 10% in the total energy.

4.3.1 Why the energy sector is highly vulnerable to lock-ins

Fig. 4.2a shows carbon-free energy generation and costs in the social optimum (which is equivalent to the laissez-faire equilibrium for $\phi = 0$ and $\nu = 0$, i.e. without market failures) for two different elasticities of substitution σ_4 between E_L and E_N. Energy from learning carbon-free technology is used significantly, although its average unit costs are initially higher compared to those of the mature technology. But when the learning curve and spillovers are internalized, future cost reductions for the learning technology are fully anticipated. Hence, the learning technology dominates the mature carbon-free technology.

[11] IAMs use different elasticities of substitutions between energy technologies. Some models assume perfect substitutability (Messner 1997; Kverndokk et al. 2004; Edenhofer et al. 2005; Kverndokk and Rosendahl 2007), others use values of 0.9 (Goulder and Schneider 1999), 2 (van der Zwaan et al. 2002; Böhringer and Rutherford 2008) or 8.7 (Popp 2006). Gerlagh and Lise (2005) use a variable elasticity of substitution ranging from 1 to 4. IAMs with differentiation between electric and non-electric energy usually assume high (Cian et al. 2009) or perfect (Manne et al. 1995; Leimbach et al. 2010) substitutability between electric energy technologies while using lower elasticities of substitution between electric and non-electric energy.

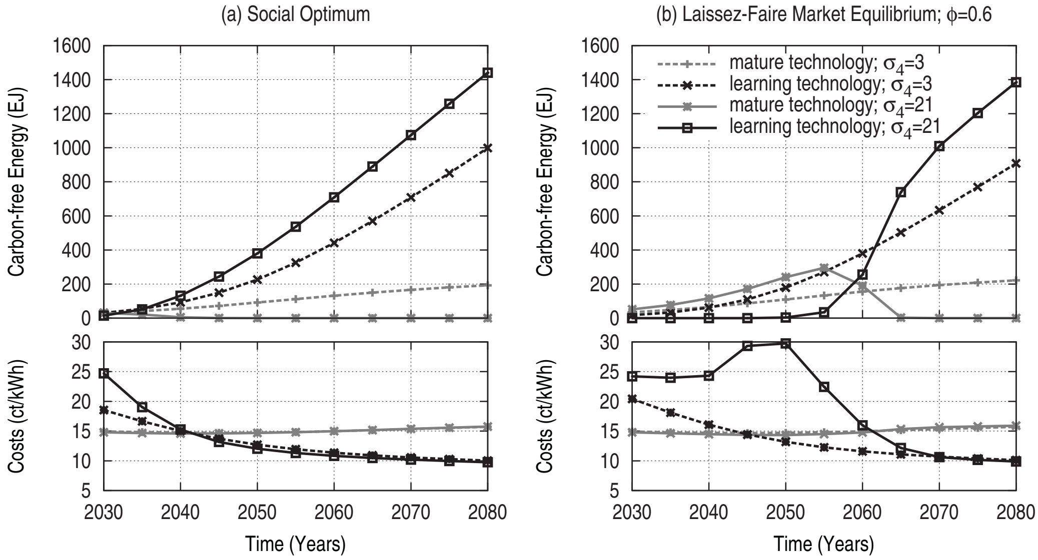
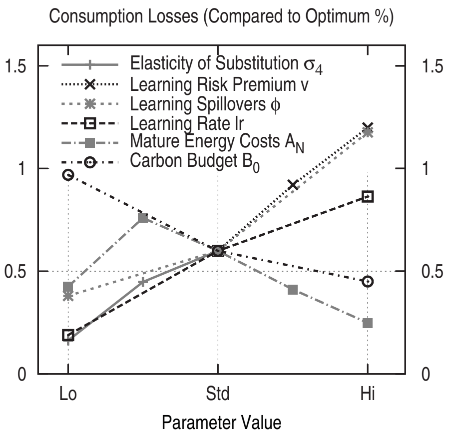


Figure 4.2: Carbon-free energy generation and costs (2030-2080) for two different elasticities of substitution ($\sigma_4 \in \{3,21\}$) between learning and mature carbon-free energy: (a) optimal outcome and (b) laissez-faire equilibrium with 60 percent spillovers and no additional technology policy instruments.

Fig. 4.2b shows the generation in the laissez-faire equilibrium with intrasectoral learning spill-overs. The spillovers lead to an imperfect anticipation of the future benefits of learning-by-doing. For a low elasticity of substitution ($\sigma_4 = 3$), the laissez-faire outcome does not differ significantly from the optimal solution. For a higher elasticity of substitution, however, this changes fundamentally: The learning carbon-free technology is delayed significantly and energy demand is met by energy from the mature carbon-free technology. This has a clear and intuitive explanation: a low elasticity creates a niche demand for the learning carbon-free energy even when it is more expensive than the mature carbon-free. Driven by such a niche demand the learning sector may gain experience and reduce production costs until it becomes competitive. But at high elasticities of substitution niche demand vanishes. In this case, the technology with the lowest market price wins.

Fig. 4.2 shows that a dynamically inferior technology dominates the dynamically efficient technology for many decades. The energy sector "locks-in" into the mature energy which competes with a learning technology that cannot internalize the value of future learning appropriately into its price. The energy sector is highly vulnerable to lock-in because electricity is an almost perfect substitute for consumers. In contrast, many innovations in the manufacturing or entertainment electronic sector provide a new product different from existing ones (e.g. flat screens vs. CRT monitor). The low substitutability implies a high niche demand and, thus, provokes ongoing learning-by-doing although considerable spillovers ex-



Parameter		Lo	Std	Hi
Elasticity of Substitution	σ_4	3	21	
Learning Risk Premium	v		0.0	0.15
Learning Spillovers	ϕ	0.5	0.6	0.75
Learning Rate	lr	0.1	0.17	0.25
	Ω	20000	200	60
	$A_{L,\max}$	0.6	0.6	0.8
Mature Energy Cost	A_N	0.3	0.2	0.1
Carbon Budget	B_0	200	450	700

Figure 4.3: Consumption losses due to lock-in for several parameter variations around the standard parameterization.

ist and market prices are distorted.

4.3.2 Economic impacts of lock-ins

In our standard parametrization the consumption losses due to the lock-in are 0.6%. Fig. 4.3 shows how this value changes if several parameters are modified. As we already argued, a high elasticity of substitution is an important condition for a lock-in to occur. A second important condition is that the generation cost of mature carbon-free energy is at a critical level: In the case of $0.2 \leq A_N \leq 0.25$, which corresponds to production costs between 12 and 15 ct/kWh, the mature carbon-free energy is an attractive option before learning has started and an expensive one after considerable learning took place. Thirdly, there must exist a market failure in the learning carbon-free sector, which is introduced by the spillover rate or the discount rate mark-up (risk premium). Beside these three necessary conditions, Fig. 4.3 indicates that learning rates and mitigation targets influence the magnitude of consumption losses. Hence, ambitious climate targets (like 200 GtC) become more expensive if energy markets do not perform well although an efficient carbon pricing instrument is applied.

Generally we can distinguish two sources of welfare losses. First, the intertemporally suboptimal deployment of the learning carbon-free energy causes consumption losses even if no competitive mature carbon-free technology is available (and no lock-in occurs). A doubling of the mature carbon-free production costs (i.e. $A_N = 0.1$) for example, makes the learning technology competitive even if high spillovers exist. In this case the mature carbon-free energy generation is virtually zero. The resulting consumption losses due to spillovers are smaller than 0.3% and there is almost no delay in learning carbon-free generation (< 5

	lr	ϕ	v	B_0	σ_4	Consumption losses	Delay (years)	Initial carbon price (1=optimal)
1	17%	25%	15%	450	21	0.4%	16	1.16
2	17%	25%	15%	200	21	0.7%	20	1.14
3	17%	50%	15%	450	21	0.9%	27	1.23
4	17%	50%	15%	200	21	1.4%	35	1.17
5	17%	75%	10%	450	16	1.5%	40	1.27
6	17%	75%	10%	200	16	2.2%	50	1.18
7	25%	25%	15%	450	21	0.6%	16	1.51
8	25%	25%	15%	200	21	0.7%	13	1.49
9	25%	50%	15%	450	21	1.1%	24	1.83
10	25%	50%	15%	200	21	1.3%	22	1.77
11	25%	75%	15%	450	13	2.0%	34	2.27
12	25%	75%	15%	200	13	3.4%	41	2.09
13	25%	100%	0%	200	13	8.0%	87	2.15

Table 4.1: Parameter values that provoke lock-ins: Impact on consumption losses, delay of achieving 10% learning carbon-free energy share and initial carbon price.

years). In contrast, the simply existence of a competitive non-learning technology delays the learning technology deployment due to lock-in substantially and reduces consumption even more. This second kind of welfare loss is more severe than the impact of suboptimal deployment in a world where no non-learning carbon-free energy is available.

In Fig. 4.3 only one parameter is varied at a time. This ignores that changes in multiple parameters may cancel each other out or may mutually reinforce their effect on the technology lock-in. Indeed, Tab. 4.1 shows further parameter sets that cause particularly severe lock-ins with consumption losses greater than one percent. Even if spillovers are only 25 percent, the existence of an additional high risk premium postpones learning carbon-free energy generation and provokes consumption losses of 0.7% under a carbon budget of 200 GtC. A (rather theoretically) upper bound for the consumption losses is given for the case where spillovers are 100% and the carbon budget is very ambitious. In this case, consumption losses increase to 8.0%.

The lock-in does not only provoke consumption losses and delayed learning carbon-free generation, it furthermore modifies the Hotelling carbon price by changing the interest rate and the initial carbon price. While the impact on the interest rate is small, the initial carbon price level increases by 22 percent to meet the carbon budget in our standard parameterization. The medium-learning parameterizations in Tab. 4.1 show similar figures. In contrast, if the learning rate is high the initial carbon price increases by 49–127 percent compared to the case where no market failures exist.

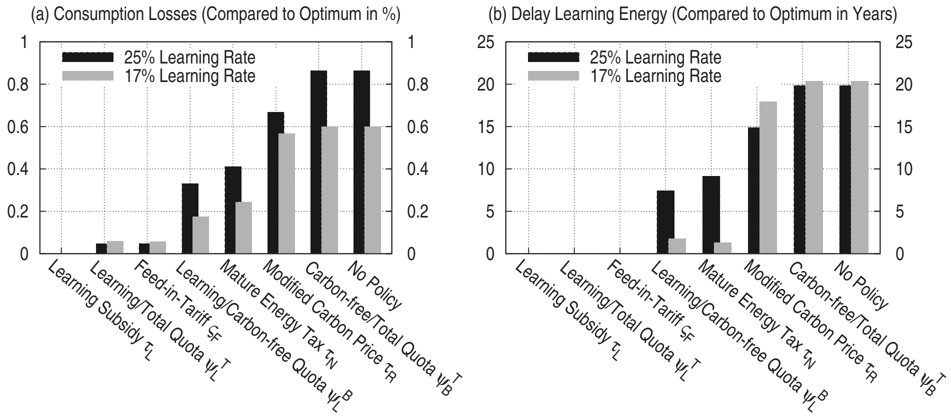


Figure 4.4: Performance of several policy instruments under the Stackelberg equilibrium: (a) Consumption losses relative to the optimal solution; (b) delay to achieve a share of 10% learning carbon-free energy.

4.4 Optimal policy instruments

The previous section showed that in absence of policy intervention there are significant consumption losses higher than one percent possible due to severe temporary lock-ins. This motivates the analysis of several policy instruments to prevent lock-ins and reduce welfare losses. We focus on two illustrative parameter settings: a high learning scenario (25% learning rate) and a medium learning case (17% learning rate). For a low learning rate (8%), innovation market failures cause only very small consumption losses (Fig. 4.3). As in this case technology policies hardly increase welfare, we omit the policy analysis for the 8% learning rate case. We calculate optimal policies for a 60% spillover rate and zero risk premiums; considering cases with lower spillover rates and additional risk premium leads to similar results.

In the Stackelberg equilibrium, we calculate the welfare maximizing time paths of (i) subsidies for the learning technology, (ii) feed-in-tariffs, (iii) carbon-free energy quotas, (iv) mature carbon-free taxes, and (v) a modified carbon price. The instruments differ in two aspects: First, they comprise a different degree regarding the technology discrimination: While the subsidy or feed-in-tariffs target the learning technology only, carbon prices and carbon-free quotas do not discriminate between carbon-free technologies. Secondly, they rely on different financing mechanisms: The financial flows of subsidies and taxes are balanced by lump-sum transfers; in contrast, feed-in-tariffs and quotas are income-neutral.

The performance of each of these instruments with respect to consumption losses and delay of learning carbon-free deployment is shown in Fig. 4.4. In the following we discuss these instruments in detail.

4.4.1 Subsidy for learning carbon-free energy

Due to the learning-by-doing spillovers, the social value of the learning technology is higher than its private value. By equating the learning technology sector's first-order conditions of the optimal economy (without spillovers) with the imperfect economy, we can calculate the optimal subsidy that internalizes the value of learning and achieves an efficient allocation (see Appendix 4.C). The optimal subsidy $\tau_{L,t} = \mu_t^* \left(1 - \frac{(1-\phi)(1+r_{t+1}+\delta)}{1+r_{t+1}+v+\delta}\right)$ basically adjusts the output price p_L by adding some fraction of the socially optimal value of learning μ_t^* (which can be obtained from the efficient intertemporal market equilibrium or the social planner optimum). Obviously, the subsidy increases in ϕ and in v. It converges to the maximum μ_t^* if $\phi \to 1$ or $v \to \infty$ and converges to zero if $\phi \to 0$ and $v \to 0$. In case of zero discount rate mark-ups ($v = 0$), the subsidy simplifies to $\tau_{L,t} = \phi \mu_t^*$; in case of zero spillovers and positive risk premiums, however, the optimal subsidy becomes $\tau_{L,t} = \mu_t^* \left(\frac{v}{1+r_{t+1}+v+\delta}\right)$. As the output subsidy is lump-sum financed, it does not cause further distortions in the economy.

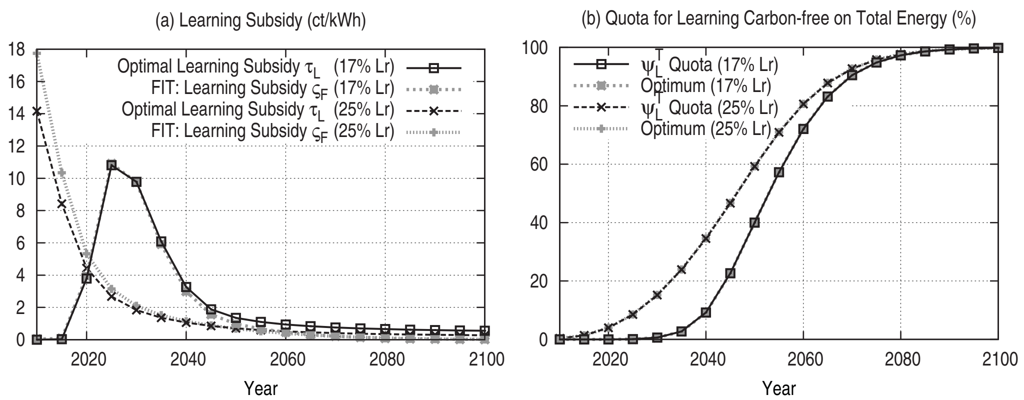


Figure 4.5: (a) Optimal subsidy and feed-in-tariff and (b) optimal quota for learning carbon-free energy on total energy.

The numerical calculation confirms that this subsidy is a first-best instrument. If learning rates are high, the subsidy is initially high as an early deployment of learning carbon-free energy is socially optimal (see Fig. 4.5a). For lower learning rates, fossil energy is more attractive in the first decades. Learning energy generation and the subsidy are delayed because postponed learning costs are lower due to discounting. Note that after an initial "activation" phase which shifts the energy generation from the niche to large-scale generation, the subsidy is declining because of diminishing learning with cumulative output.

4.4.2 Feed-in-tariff

Although a lump-sum financed subsidy is an efficient instrument, it is rarely employed in reality. Governments which prefer a price instrument to a quota widely choose feed-in-tariffs to encourage renewable energy generation. In contrast to the lump-sum-financed subsidy τ_L, the feed-in-tariff (ς_F) is a subsidy on learning carbon-free energy that is cross-financed by a tax on fossil and mature carbon-free energy τ_F. This captures the idea that the costs of feed-in-tariffs are borne by the entire energy sector.

The optimal path of the feed-in-tariff closely follows the lump-sum financed subsidy (Fig. 4.5a). As the cross-financing mechanism causes small distortions for fossil and mature carbon-free energy prices,[12] the feed-in-tariff converges faster to zero. Consumption losses, however, are small ($< 0.1\%$) and there is no delay in learning carbon-free energy deployment (Fig. 4.4).

4.4.3 Quota on the energy mix

Some governments use tradable quotas instead of subsidies to encourage renewable energy generation. In the following, we calculate the performance of several quota regimes which differ with respect to their degree of technological discrimination. In Eqs. (4.5–4.6), we introduced three different quota designs: (i) a minimum quota for the carbon-free energy on the total energy generation (ψ_B^T), (ii) a minimum quota for the learning energy on the total energy generation (ψ_L^T), and (iii) a minimum quota for the learning energy on the total carbon-free energy generation (ψ_L^B).

Quota for (total) carbon-free energy

A quota on E_B does not increase welfare compared to the laissez-faire equilibrium in our model. Hence, it is therefore optimal to keep it at zero. A positive quota encourages both the learning and the mature carbon-free technology relative to the fossil energy technology. Hence, this quota instrument has a similar effect as the carbon tax but induces a further distortion due to the implicit income-neutrality while the carbon tax generates lump-sum income for the household. As the instrument is too unspecific to prevent the lock-in into the mature carbon-free, consumption losses remain substantial.

[12]The difference between lump-sum subsidy τ_L and feed-in-tariff ς_F becomes apparent in the first-order conditions (4.37–4.39) in Appendix 4.B.

Quotas for learning carbon-free energy

This instrument is more specific. It can indeed increase the generation of learning carbon-free energy. However, we find that the reference point of the quota matters: if the quota is chosen relative to the shares of the two carbon-free energies (ψ_L^B), it can discriminate the mature against the learning technology and therefore prevent a (temporary) lock-in. Nevertheless, it cannot push the learning technology relative to the fossil energy which would be necessary to achieve an efficient timing of learning energy generation.

In contrast, the quota for learning energy relative to total energy (ψ_L^T) does not only prevent a lock-in, but also induces a more efficient learning energy generation at the expense of fossil energy generation. The optimal quota almost achieves the socially optimal energy generation (Fig. 4.5b). From the first-order conditions (4.37–4.39) follows that a binding quota ψ_L^T is equivalent to a feed-in-tariff if and only if the quota price $\phi_L^T = \tau_F/\psi_L^T = \varsigma_F/(1-\psi_L^T)$. Equally to the feed-in-tariff the quota operates like an implicit subsidy on E_L and an implicit tax on E_F and E_N while maintaining income neutrality. Overall consumption losses are small and of the same magnitude as for the feed-in-tariff.

4.4.4 Tax on the mature carbon-free energy

Instead of promoting the learning technology, the lock-in can alternatively be addressed by taxing the mature carbon-free technology which causes the lock-in. As shown in Fig. 4.4, this policy is relatively expensive compared to the optimal subsidy, the feed-in-tariff, or the optimal quota. However, consumption losses are mainly due to the delay of the learning carbon-free energy similar to the case where no (or only a prohibitively expensive) mature energy technology is available (as discussed in Sec. 4.3).

4.4.5 Modified carbon pricing

The management of the carbon budget by the carbon bank leads to a Hotelling carbon price. In a first-best setting (no technology failures) this is equivalent to an optimal carbon tax τ_R. However, when additional market failures such as learning spillovers are present, the second-best carbon price differs from the Hotelling carbon price. In our model the second-best carbon price deviates from the carbon bank's carbon price in the laissez-faire equilibrium only during the short transition phase when massive investments into the learning carbon-free technology are made. Nevertheless, the modified carbon tax cannot prepone this transition phase. A higher carbon price would primarily encourage the mature carbon-free technology. Hence, consumption losses remain almost unchanged compared to the laissez-faire outcome. Nevertheless, a second-best carbon price performs better than the

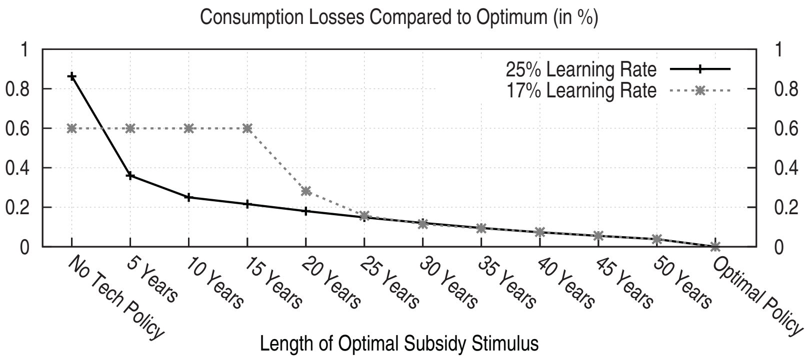


Figure 4.6: Consumption losses with respect to the length of optimal temporary subsidies (starting in 2010).

technology-unspecific quota for carbon-free energy. Although both instruments encourage carbon-free energy at the expense of fossil energy, the quota instrument causes an additional distortion due to the implicit income-neutrality property.

4.5 Policy stimulus

The policy instrument analysis in Section 4.4 calculated optimal first-best and second-best instruments for the entire time horizon (21st century). In reality such a long-lasting commitment by governments might be difficult to implement. Furthermore, long-term subsidies may have adverse side-effects if they cause rent-seeking behavior and transaction costs. A charming solution might be to limit the duration of policy intervention. We therefore calculated the optimal subsidy starting in 2010 for different time spans. The consumption losses of these policy stimuli are shown in Fig. 4.6. A policy stimulus of 25 years is sufficient to prevent lock-ins and decrease consumption losses below 0.2%. If learning is moderate the subsidy is relatively unimportant during the first 15 years as the large-scale learning energy deployment begins in 2030. Hence, it is important that the subsidy is implemented when the transition phase starts (under the high learning parametrization, this is immediately in 2010).

4.6 Robustness of optimal policy instruments

The previous analysis revealed that within our deterministic model setting there are only small differences between subsidies, feed-in-tariffs and technology-specific quotas. In particular, the latter two instruments are completely equivalent. This section provides some elementary considerations about the performance of these instruments when relaxing the assumption of perfect information. First, we study the behavior of the market equilibrium around the optimal instrument (sensitivity analysis). Second, we exemplarily consider the consequences of the government being wrong in its believe about the magnitude of the learning rate.

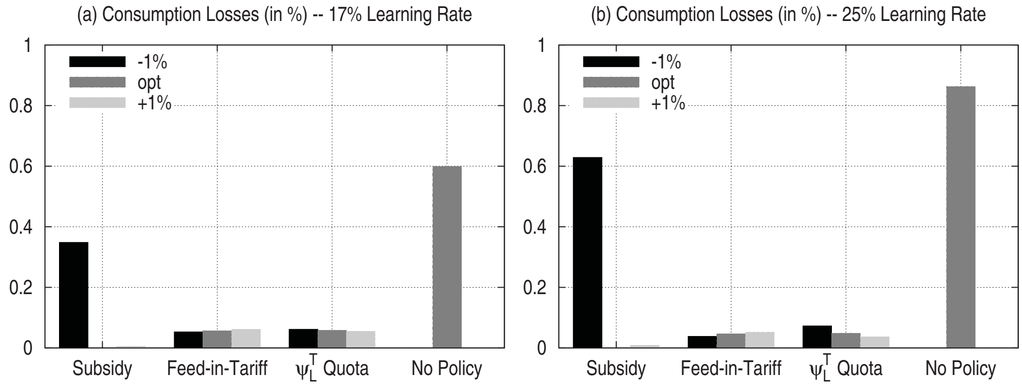


Figure 4.7: Consumption losses relative to the 1st-best optimum of optimal and 'close-to-be-optimal' ($\pm 1\%$) instruments.

To assess the sensitivity of the 'optimal policies' with respect to small errors in their implementation, we calculate the consumption losses of varying the instrument by one percent relative to its optimal use. As shown in Fig. 4.7, changes in discounted consumption are small with one exception: when the subsidy is set too low, significant consumption losses in the range of the laissez-faire outcome can result. Lowering the subsidy by one percent results in a strong lock-in into the mature carbon-free technology because the subsidy then fails to make the learning technology competitive. The high sensitivity is mainly due to the high substitutability. It leads to strong quantity responses if the learning technology is slightly more expensive than the mature technology. This flipping behaviour occurs only if the subsidy is slightly too low as in this case the lock-in dynamics prevails. If the subsidy is higher than optimal, firms simply use slightly more learning carbon-free energy. This sensitive behavior does not occur for the other instruments. As the 1%-lower-than-optimal feed-in-subsidy implies an additional taxation of fossil and mature carbon-free energy, it provides a greater buffer for the comparative advantage of the learning technology. For the quota, small perturbations translate directly into small deviations in production if the quota is binding; a lock-in cannot occur. Hence, the high sensitivity of the subsidy policy indicates that there may be a high risk of failure.

In our second analysis, we explore the consequences of imperfect information about the learning rate. To this end, we assume that the government derives its optimal policy based on the wrong learning rate and sticks to this assessment for the entire planning horizon. This

Actual learning rate (%)	Assumed learning rate (%) for subsidy			No policy
	8	17	25	
8	0.00 (0)	0.15 (23)	0.18 (26)	0.19 (30)
17	0.07 (9)	0.00 (0)	0.48 (17)	0.60 (20)
25	0.62 (18)	0.24 (-6)	0.00 (0)	0.86 (20)
Mean	0.23	0.13	0.22	0.55

Table 4.2: Consumption losses in % and delay in years (in parentheses) relative to optimal policy if the government implements a learning subsidy assuming a different learning rate than actually prevails.

is implemented by running the optimal policy from the presumed learning rate as an exogenously given policy for the 'true' learning rate. Tab. 4.2 shows the consumption losses if the government implements the optimal subsidy from the 8%, 17% and 25% learning scenario in all possible real-world learning scenarios. In all cases, consumption losses remain below the no-policy case. Expected consumption losses are lowest for the subsidy assuming a 17% learning rate (given that all three learning rates are equally likely). They are also lower than the expected losses in the no-policy scenario, hence imperfect information is no argument for non-action.

The reasons for the consumptions losses lie, of course, in the stringency of the policy, but also in its timing (see Fig. 4.5a). Consider, for example, implementing the subsidy from the 25% learning scenario: this subsidy path is initially high but declines rapidly, therefore influencing the learning technology use only in the first decade directly. If the actual learning rate is 25%, this subsidy induces a quick up-scaling of learning carbon-free energy which then displaces other energy technologies due to its high learning rate. At lower actual learning rates (e.g. 17%), however, the initial price advantage caused by the subsidy is too short to reduce costs below those of the incumbent technologies. Consequently, the non-learning carbon-free energy remains competitive for a long time and the deployment of learning carbon-free energy is delayed substantially. This causes consumption losses which are close to the no-policy case.

These considerations provide a first step regarding the robustness of policies. They also indicate the complexity of the intertemporal dynamics of learning spillovers. A profound stochastic analysis requires maximizing the expected intertemporal welfare for specific probability distributions of key parameters. Considering the long time horizon in this application, however, introducing learning for the government becomes crucial: realistically, part of the uncertainty about learning rates and spillovers will be resolved after a few decades giving the government ample reason to revise its formerly announced policy. In a consistent approach, the possibility to learning should itself be anticipated. A satisfying answer to the question whether quantity or price-based technology instruments perform better in an uncertain world is thus beyond the scope of this study, but an important topic for future work.

4.7 Conclusions

Our model provides important insights into the causes and implications of market failures for energy innovations (Sec. 4.3). We identified a *trio infernale* of necessary conditions that provoke a lock-in into a mature (non-learning) technology although a superior (learning) contender technology is available: (i) learning spillovers and/or risk premiums, (ii) a high substitutability between these two technologies, and (iii) a critical range of present and future generation costs of the competing technologies. The cost level must be such that the contender technology is more expensive than the mature technology in the short term, yet cheaper in the long run due to its learning potential. If only (i) and (ii) or (i) and (iii) hold, the market failure is small and the associated welfare losses may be exceeded by the transaction costs of addressing it. For example, if the high-cost carbon-free energy is prohibitively expensive, no lock-in occurs, and thus, consumption losses of only 0.3% are caused by suboptimal timing of innovation alone. Similarly, if substitutability is imperfect, the innovative technology gains experience in niche markets. In this case, consumption losses are also low (0.2%). If all three conditions hold, however, the innovation process may be delayed by several decades. For plausible parameters, this causes consumption losses ranging from 0.4% to 3.4% and carbon price increases by 14–127 percent. Hence, lock-ins between low-carbon technologies interfer with climate policy: Higher carbon prices and mitigation costs make it difficult for governments to seek for ambitious temperature targets.

Market failure due to spillovers may not only affect the energy sector but all innovative sectors in the economy. But in contrast to electronic, information and entertainment industries, energy – and in particular electricity – is a homogeneous good where almost no product differentiation is possible.[13] Thus, while in many economic sectors condition (i) and (iii) hold, condition (ii) is violated. Spillovers and discount rate mark-ups have only small impact on welfare and may not justify (technology-specific) policy intervention.

An optimal policy has to internalize spillovers. This can be done by a subsidy on learning carbon-free energy which is lump-sum financed (Sec. 4.4). Feed-in-tariffs and minimum quotas on learning carbon-free energy also provide a way to promote a technology.

[13] An exception might be niche markets due to imperfect grid access or benevolent consumers that are aware of the social costs of lock-ins and therefore purchase the more expensive learning technology at their own costs. However, consumers must be aware of choosing not only the carbon-free technology (which includes A_N), but the *learning* (carbon-free) technology at higher costs.

However, these are cross-financed by an implicit tax on mature carbon-free and fossil energy. The distortionary financing mechanism leads to the occurrence of small inefficiencies (around 0.1%). All these instruments require the regulator to pick the "winner", i.e. to support the dynamically more efficient technology while discriminating the other technologies. In reality, the regulator might not have this option due to information, incentive and political-economy problems. Instead of picking-the-winner, the regulator could "drop-the-losers", i.e. discriminate the non-learning technologies by a tax. In particular, this could be useful if it was easier to identify technologies which need to be avoided, than to determine which (maybe yet not existing) technology will be essential for future energy generation. This also enhances competition under several learning technologies. Technology-unspecific carbon-free energy quotas and modified carbon pricing are poor instruments resulting in negligible or zero welfare gains.

We performed our analysis within a global-scale economic model to analyse the dynamics and implications of technological market failures for climate change mitigation. The conditions for the occurence of lock-ins and their implications should be transferable to a regional or national economy with similar cost parameters, learning rates and technological substitutability. One crucial issue, however, concerns the nature of spillovers: On the one hand, the knowledge transfer could be higher on a regional level (e.g. due to higher mobility of skilled employees between firms); on the other hand, imperfect patent legislation may lead to higher knowledge transfers in respective countries. If spillovers are global (and experience is thus a global public good), a globally coordinated technology policy would become necessary. Such a policy would suffer from the common free-rider and enforcing problems as studied for other global public good problems. In contrast, if spillovers are national, it is in the interest of every government to internalize knowledge externalities by specific policies.

Regarding the robustness of instruments, the implementation of the subsidy carries the risk of being ineffective if it deviates only slightly from the optimal value. In contrast, the consumption losses for feed-in-tariffs and quotas are always small if realized implementation differs from the optimal values (Sec. 4.6) although they are never first-best in a deterministic setting. If the regulator does not know the actual learning rate, assuming a medium learning reate seems to be a good strategy. Nevertheless, implementing a subsidy based on a wrong belief in the learning rate leads to higher consumption than implementing no subsidy at all. A concluding evaluation of these risks requires a comprehensive stochastic analysis which considers uncertainties in several economic parameters and learning about uncertainty. While this is beyond the scope of this paper, it indicates an important question for future research.

4.A Technology

The following functional forms for utility and production are used:

$$\mathbf{U}(C/L) = \frac{\left(\frac{C}{L}\right)^{1-\eta}}{1-\eta} \tag{4.20}$$

$$\mathbf{Y}(Z,E) = \left(a_1 Z^{\frac{\sigma_1-1}{\sigma_1}} + b_1 E^{\frac{\sigma_1-1}{\sigma_1}}\right)^{\frac{\sigma_1}{\sigma_1-1}} \tag{4.21}$$

$$\mathbf{Z}(K_Y,L) = \left(a_2 K_Y^{\frac{\sigma_2-1}{\sigma_2}} + b_2 (A_Y L)^{\frac{\sigma_2-1}{\sigma_2}}\right)^{\frac{\sigma_2}{\sigma_2-1}} \tag{4.22}$$

$$\mathbf{E}(E_F,E_B) = \left(a_3 E_F^{\frac{\sigma_3-1}{\sigma_3}} + b_3 E_B^{\frac{\sigma_3-1}{\sigma_3}}\right)^{\frac{\sigma_3}{\sigma_3-1}} \tag{4.23}$$

$$\mathbf{E_B}(E_L,E_N) = \left(a_4 E_L^{\frac{\sigma_4-1}{\sigma_4}} + b_4 E_N^{\frac{\sigma_4-1}{\sigma_4}}\right)^{\frac{\sigma_4}{\sigma_4-1}} \tag{4.24}$$

$$A_{Y,t+1} = A_{Y,t}\left(1 + \frac{1}{1-g_0 e^{-\zeta t}}\right) \tag{4.25}$$

$$L_t = L_0(1-q_t) + q_t L^{max}, \qquad q_t = \frac{e^{ft}-1}{e^{ft}} \tag{4.26}$$

$$\mathbf{E_F}(K_F,R) = \left(a K_F^{\frac{\sigma-1}{\sigma}} + b R^{\frac{\sigma-1}{\sigma}}\right)^{\left(\frac{\sigma}{\sigma-1}\right)} \tag{4.27}$$

$$\mathbf{R}(S,K_R) = \kappa(S) K_R \tag{4.28}$$

$$\kappa(S) = \frac{\chi_1}{\chi_1 + \chi_2\left(\frac{S_0-S}{\chi_3}\right)^{\chi_4}} \tag{4.29}$$

$$\mathbf{E_L}(A_L,K_L,N) = A_L K_L^{\nu} N^{\nu-1} \tag{4.30}$$

$$\mathbf{A_L}(H) = \frac{A_{L,max}}{1+\left(\frac{\Omega}{H}\right)^{\gamma}} \tag{4.31}$$

$$\mathbf{E_N}(K_N) = A_N e^{1 g_N t} K_N \tag{4.32}$$

4.B First-order conditions of decentralized agents

Household sector Maximizing the Lagrangian $\mathscr{L}_H = \sum_{t=0}^{T}(L_t U(C_t/L_t)\,[1+\rho]^{-t} + \lambda_{H,t}(K_{t+1} - K_t - (I_t - \delta K_t)))$ with respect to C_t and K_t and by using the substitution (4.1) yields the following first-order conditions:

$$L_t \frac{\partial \mathbf{U}}{\partial C_t} = \lambda_{H,t} \tag{4.33}$$

$$\lambda_{H,t} - \lambda_{H,t-1}(1+\rho) = -\lambda_{H,t}(r_t - \delta) \tag{4.34}$$

$$0 = \lambda_{H,T} K_{T+1} \tag{4.35}$$

Production sector Maximizing the Lagrangian $\mathscr{L}_{Y,t} = \pi_{Y,t} + \phi^T_{B,t}(E_{L,t} + E_{N,t} - \psi^T_{B,t}(E_{F,t} + E_{N,t} + E_{L,t})) + \phi^B_{L,t}(E_{L,t} - \psi^B_{L,t}(E_{N,t} + E_{L,t})) + \phi^T_{L,t}(E_{L,t} - \psi^T_{L,t}(E_{F,t} + E_{N,t} + E_{L,t}))$ with respect to $K_{Y,t}, L_t, E_{F,t}, E_{L,t}$ and $E_{N,t}$ and using the substitutions (4.4) and (4.21–4.24) leads to the first-order conditions:

$$r_t = \frac{\partial \mathbf{Y}(\mathbf{Z},\mathbf{E})}{\partial K_{Y,t}}, \qquad w_t = \frac{\partial \mathbf{Y}(\mathbf{Z},\mathbf{E})}{\partial L_t} \tag{4.36}$$

$$p_{F,t} = \frac{\partial \mathbf{Y}(\mathbf{Z},\mathbf{E}(\mathbf{E_F},\mathbf{E_B}))}{\partial E_{F,t}} - \tau_{F,t} - \phi^T_{B,t}\psi^T_{B,t} - \phi^T_{L,t}\psi^T_{L,t}, \tag{4.37}$$

$$p_{L,t} = \frac{\partial \mathbf{Y}(\mathbf{Z},\mathbf{E}(\mathbf{E_F},\mathbf{E_B}(\mathbf{E_L},\mathbf{E_N})))}{\partial E_{L,t}} + \varsigma_{F,t} + \phi^T_{B,t}(1-\psi^T_{B,t}) + \phi^B_{L,t}(1-\psi^B_{L,t}) + \phi^T_{L,t}(1-\psi^T_{L,t}), \tag{4.38}$$

$$p_{N,t} = \frac{\partial \mathbf{Y}(\mathbf{Z},\mathbf{E}(\mathbf{E_F},\mathbf{E_B}(\mathbf{E_L},\mathbf{E_N})))}{\partial E_{N,t}} - \tau_{F,t} - \phi^B_{L,t}\psi^B_{L,t} - \phi^T_{L,t}\psi^T_{L,t} + \phi^T_{B,t}(1-\psi^T_{B,t}) \tag{4.39}$$

With the KKT conditions for the inequaltiy constraints (4.5–4.7):

$$0 = \phi^T_{L,t}(E_{L,t} - \psi^T_{L,t}(E_{F,t} + E_{N,t} + E_{L,t})) \tag{4.40}$$

$$0 = \phi^B_{L,t}(E_{L,t} - \psi^B_{L,t}(E_{N,t} + E_{L,t})) \tag{4.41}$$

$$0 = \phi^T_{B,t}(E_{L,t} + E_{N,t} - \psi^T_{B,t}(E_{F,t} + E_{N,t} + E_{L,t})) \tag{4.42}$$

Fossil energy sector By maximzing π_F given by (4.8), the common static conditions apply:

$$p_{R,t} + \tau_{R,t} + p_{C,t} = p_{F,t}\frac{\partial \mathbf{E_F}}{\partial R_t}, \qquad r_t = p_{F,t}\frac{\partial \mathbf{E_F}}{\partial K_{F,t}} \tag{4.43}$$

Fossil resource extraction sector Maximizing the Lagrangian $\mathscr{L}_R = \sum_{t=0}^{T}\left(\pi_{R,t}\Pi_{s=0}^{t}\left[1 + r_s - \delta\right]^{-1} + \lambda_{R,t}(S_{t+1} - S_t + R_t)\right)$ with respect to R_t and S_t and the substitutions (4.9) and (4.28–4.29) leads to the first-order conditions:

$$\lambda_{R,t} = p_{R,t} - r_t/\kappa_t \tag{4.44}$$

$$\lambda_{R,t} - \lambda_{R,t-1}(1 + (r_t - \delta)) = -(p_{R,t} - \lambda_{R,t})\frac{\partial \mathbf{R}}{\partial S_t} \tag{4.45}$$

$$\lambda_{R,T} S_{T+1} = 0 \tag{4.46}$$

Learning carbon-free energy sector Maximizing the Lagrangian $\mathscr{L}_L = \sum_{t=0}^{T}(\pi_{L,t}\Pi_{s=0}^{t}\left[1+r_s+v-\delta\right]^{-1}\lambda_{L,t}(H_{t+1}-H_t-(E_{L,t}-E_{L,t-1})))$ with respect to $K_{L,t}$ and H_t and introducing the spillover rate ϕ leads to the first-order conditions:

$$
\begin{aligned}
0 &= \left(p_{L,t}\frac{\partial \mathbf{E_L}}{\partial K_{L,t}} - r_t\right)\Pi_{s=0}^{t}\left[1+r_s+v-\delta\right]^{-1} + (\lambda_{L,t+1}-\lambda_{L,t})\frac{\partial \mathbf{E_L}}{\partial K_{L,t}}\\
0 &= (1-\phi)\frac{\partial \mathbf{E_L}}{\partial H_t}\left(p_{L,t}\Pi_{s=0}^{t}\left[1+r_s+v-\delta\right]^{-1} + \lambda_{L,t+1}-\lambda_{L,t}\right) - \lambda_{L,t} + \lambda_{L,t-1}\\
0 &= \lambda_T = \lambda_{T-1}
\end{aligned}
$$

With $\tilde{\mu}_t := \lambda_t\Pi_{s=0}^{t}\left[1+(r_s+v-\delta)\right]$ we can transform this into

$$
r_t = \left(p_{L,t} + \tau_{L,t} - \tilde{\mu}_t + \frac{\tilde{\mu}_{t+1}}{1+r_{t+1}+v-\delta}\right)\frac{\partial \mathbf{E_L}}{\partial K_{L,t}}
$$

and $\tilde{\mu}_t - \tilde{\mu}_{t-1}(1+r_t+v-\delta) = (1-\phi)\frac{\partial \mathbf{E_L}}{\partial H_t}\left(p_{L,t}+\tau_{L,t}-\tilde{\mu}_t+\frac{\tilde{\mu}_{t+1}}{1+r_{t+1}+v-\delta}\right)$. Finally, with $\mu_t = \tilde{\mu}_{t+1}(1+r_{t+1}+v+\delta)-\tilde{\mu}_t$, we obtain:

$$
r_t = (p_{L,t}+\tau_{L,t}+\mu_t)\frac{\partial \mathbf{E_L}}{\partial K_{L,t}} \tag{4.47}
$$

$$
\mu_{t-1} = \frac{1-\phi}{1+r_t+v+\delta}(p_{L,t}+\tau_{L,t}+\mu_t)\frac{\partial \mathbf{E_L}}{\partial H_t} \tag{4.48}
$$

$$
\mu_T = 0 \tag{4.49}
$$

Mature carbon-free energy sector The common static condition applies:

$$
A_N e^{g_N t}(p_{N,t}-\tau_{N,t}) = r_t \tag{4.50}
$$

Carbon bank Intertemporal optimization results in a Hotelling price:

$$
p_{C,t} = (1+r_t-\delta)p_{C,t-1} \tag{4.51}
$$

$$
p_{C,T}B_{T+1} = 0 \tag{4.52}
$$

4.C Optimal first-best subsidy

Let * denote the solution from the efficient intertemporal market equilibrium, i.e. where $\phi = 0$ and $v = 0$ and there is no subsidy $\tau_{L,t} = 0$. Hence, Eqs. (4.47–4.48) read

$$r_t^* = (p_{L,t}^* + \mu_t^*)\frac{\partial \mathbf{E_L^*}}{\partial K_{L,t}} \tag{4.53}$$

$$\mu_{t-1}^* = \frac{1}{(1+r_t^* - \delta)}\frac{\partial \mathbf{E_L^*}}{\partial H_t}\left(p_{L,t}^* + \mu_t^*\right) \tag{4.54}$$

Equating (4.53) with the original first-order condition (4.47) where $\phi, v, \tau_{L,t} \geq 0$ and solving for $\tau_{L,t}$ in the optimum yields:

$$\tau_{L,t} = \mu_t^* - \mu_t \tag{4.55}$$

Substituting (4.55) into the RHS of (4.48), we obtain for the optimum:

$$\mu_{t-1} = \frac{(1-\phi)}{(1+r_t+v-\delta)}\frac{\partial \mathbf{E_L^*}}{\partial H_t}\left(p_{L,t}^* + \mu_t^*\right) \tag{4.56}$$

Substituting (4.55) into the LHS of (4.56) as well as plugging (4.54) into the RHS of (4.56), we finally obtain for τ:

$$\tau_{L,t} = \mu_t^*\left(1 - \frac{(1-\phi)(1+r_{t+1}+\delta)}{1+r_{t+1}+v+\delta}\right) \tag{4.57}$$

4.D Parameters and initial values for numerical solution

Symbol	Parameter	Value
ρ	pure time preference rate of household	0.03
η	elasticity of intertemporal substitution	1
δ	capital depreciation rate	0.03
L^{max}	population maximum (bill. people)	9.5
f	population growth parameter	0.04
a_1	scale parameter in final good production	0.95
b_1	scale parameter in final good production	0.05
σ_1	elasticity of substitution energy–intermediate	0.5
a_2	scale parameter in intermediate production	0.3
b_2	scale parameter in intermediate production	0.7
σ_2	elasticity of substitution labor–capital	0.7
a_3, b_3, a_4, b_4	scale parameter (energy usage)	1
σ_3	elasticity of substitution fossil–carbon-free energy	3
σ_4	elasticity of substitution learning–mature carbon-free	21
g_0	productivity growth parameter	0.026
ζ	productivity growth parameter	0.006
a	scale parameter in fossil energy generation	0.8
b	scale parameter in fossil energy generation	0.2
σ	elasticity of substitution energy–intermediate	0.15
χ_1	scaling parameter	20
χ_2	scaling parameter	700
χ_3	resource base (GtC)	4000
χ_4	slope of Rogner's curve	2
ν	share parameter learning carbon-free energy generation	0.95
$A_{L,max}$	maximum productivity learning carbon-free energy	0.6
Ω	scaling parameter	200
γ	learning exponent	0.27
N	land	1
v	risk premium (learning technology)	0.0
ϕ	spillover rate (learning technology)	0.6
A_N	productivity mature energy technology	0.2
g_N	productivity change rate	-0.004
K_0	Initial total capital stock (trill. US$)	165
S_0	Initial stock of fossil resources (GtC)	4000
B_0	Carbon budget (GtC)	450
H_0	Initial experience stock	0.2
L_0	Initial population (bill. people)	6.5
$A_{Y,0}$	Initial productivity level	6
T	time horizon (in years)	150

Table 4.3: Parameters used for the numerical model.

Bibliography

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

Arthur, W. B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *The Economic Journal 99*(394), 116–131.

Arthur, W. B. (1994). *Increasing returns and path dependence in the economy*. University of Michigan Press.

Barnes, P., R. Costanza, P. Hawken, D. Orr, E. Ostrom, A. Umaña, and O. Young (2008). Creating an earth atmospheric trust. *Science 319*(5864), 724b.

Barrios, S. and E. Strobl (2004). Learning by doing and spillovers: Evidence from firm-level panel data. *Review of Industrial Organization 25*(2), 175–203.

Böhringer, C. and T. F. Rutherford (2008). Combining bottom-up and top-down. *Energy Economics 30*(2), 574–596.

Brooke, A., D. Kendrick, A. Meeraus, R. Raman, and R. E. Rosenthal (2005). *GAMS. A Users Guide*. GAMS Development Corporation.

Brunner, S., C. Flachsland, and M. Marschinski (2011). Credible commitment in carbon policy. *Forthcoming in Climate Policy*.

Cian, E. D., V. Bosetti, A. Sgobbi, and M. Tavoni (2009). The 2008 WITCH model: New model features and baseline. *FEEM Working Papers* (2009.85).

Cowan, R. and S. Hulten (1996). Escaping lock-in: The case of the electric vehicle*. *Technological Forecasting and Social Change 53*(1), 61–79.

Cusumano, M. A., Y. Mylonadis, and R. S. Rosenbloom (1992). Strategic maneuvering and mass-market dynamics: The triumph of VHS over beta. *The Business History Review 66*(1), 51–94.

David, P. A. (1985). Clio and the economics of QWERTY. *The American Economic Review 75*(2), 332–337.

Dockner, E., S. Jørgensen, N. van Long, and G. Sorger (2000). *Differential Games in Economics and Management Science*. Cambridge: Cambridge University Press.

Du, Y. and J. E. Parsons (2009). Update on the cost of nuclear power. *Massachusetts Institute of Technology, Center for Energy and Environmental Policy Research* (0904).

Edenhofer, O., N. Bauer, and E. Kriegler (2005). The impact of technological change on climate protection and welfare: Insights from the model mind. *Ecological Economics 54*(2-3), 277–292.

Edenhofer, O., B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, P. Criqui, M. Isaac, A. Kitous, S. Kypreos, M. Leimbach, K. Lessmann, B. Magne, S. Scrieciu, H. Turton, and D. P. van Vuuren (2010). The economics of low stabilization: Model comparison of mitigation strategies and costs. *The Energy Journal 31*(Special Issue), 11–48.

Eurostat (2009). Energy sector in europe. Technical Report 72, European Commission.

Fischer, C. and R. Newell (2007). Environmental and technology policies for climate mitigation. *RFF Working Papers* (DP-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.

Foxon, T. J. and P. J. G. Pearson (2007). Towards improved policy processes for promoting innovation in renewable electricity technologies in the UK. *Energy Policy 35*(3), 1539–1550.

Gerlagh, R., S. Kverndokk, and K. E. Rosendah (2008). Linking environmental and innovation policy. *FEEM Working Papers* (2008.53).

Gerlagh, R. and W. Lise (2005). Carbon taxes: A drop in the ocean, or a drop that erodes the stone? The effect of carbon taxes on technological change. *Ecological Economics 54*(2-3), 241–260.

Gerlagh, R., B. van der Zwaan, M. Hofkes, and G. Klaassen (2004). Impacts of CO2-taxes in an economy with niche markets and learning-by-doing. *Environmental and Resource Economics 28*, 367–394.

Ghemawat, P. and A. M. Spence (1985). Learning curve spillovers and market performance. *The Quarterly Journal of Economics 100*(5), 839–52.

Goulder, L. H. and K. Mathai (2000). Optimal CO2 abatement in the presence of induced technological change. *Journal of Environmental Economics and Management 39*(1), 1–38.

Goulder, L. H. and S. H. Schneider (1999). Induced technological change and the attractiveness of co2 abatement policies. *Resource and Energy Economics 21*(3-4), 211–253.

Grimaud, A., G. Lafforgue, and B. Magne (2010). Climate change mitigation options and directed technical change: A decentralized equilibrium analysis. *Resource and Energy Economics In Press*. doi:10.1016/j.reseneeco.2010.11.003.

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

IEA (2000). *Experience Curves for Energy Technology Policy*. International Energy Agency, Paris, France.

IEA (2010). *Projected Costs of Generating Electricity*. International Energy Agency, Paris, France.

IPCC (2011). *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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

Islas, J. (1997). Getting round the lock-in in electricity generating systems: the example of the gas turbine. *Research Policy 26*(1), 49–66.

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.

Kverndokk, S., K. E. Rosendahl, and T. F. Rutherford (2004). Climate policies and induced technological change: Which to choose, the carrot or the stick? *Environmental and Resource Economics 27*, 21–41.

Leimbach, M., N. Bauer, L. Baumstark, and O. Edenhofer (2010). Mitigation costs in a globalized world: Climate policy analysis with REMIND-R. *Environmental Modeling and Assessment 15*, 155–173.

Manne, A., R. Mendelsohn, and R. Richels (1995). MERGE - a model for evaluating regional and global effects of ghg reduction policies. *Energy Policy 23*(1), 17–34.

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

Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2C. *Nature 458*(7242), 1158–1162.

Messner, S. (1997). Endogenized technological learning in an energy systems model. *Journal of Evolutionary Economics 7*(3), 291–313.

Nordhaus, W. D. (2002). Modeling induced innovation in climate-change policy. In A. Grübler, N. Nakicenovic, and W. D. Nordhaus (Eds.), *Technological Change and the Environment*, Chapter 8, pp. 182–209. Washington, DC: RFF Press, Washington, DC.

Nordhaus, W. D. (2009). Designing a friendly space for technological change to slow global warming. *Snowmass Conference on Technologies to Combat Global Warming, Snowmass (CO), August 3-4*.

Nordhaus, W. D. and J. Boyer (2000). *Warming the World. Economic Models of Global Warming*. Cambridge, Massachusetts, London, England: The MIT Press.

Popp, D. (2004). ENTICE: Endogenous technological change in the dice model of global warming. *Journal of Environmental Economics and Management 48*(1), 742–768.

Popp, D. (2006). ENTICE-BR: The effects of backstop technology R&D on climate policy models. *Energy Economics 28*(2), 188–222.

Rivers, N. and M. Jaccard (2006). Choice of environmental policy in the presence of learning by doing. *Energy Economics 28*(2), 223–242.

Rogner, H.-H. (1997). An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment 22*(1), 217–262.

Schmidt, R. C. and R. Marschinski (2009). A model of technological breakthrough in the renewable energy sector. *Ecological Economics 69*(2), 435–444.

Spence, M. (1984). Cost reduction, competition, and industry performance. *Econometrica 52*(1), 101–121.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy 28*(12), 817–830.

Unruh, G. C. (2002). Escaping carbon lock-in. *Energy Policy 30*(4), 317–325.

van der Zwaan, B. C. C., R. Gerlagh, G., Klaassen, and L. Schrattenholzer (2002). Endogenous technological change in climate change modelling. *Energy Economics 24*(1), 1–19.

Chapter 5

Renewable Energy Subsidies: Second-best Policy or Fatal Aberration for Mitigation?

Abstract: This paper evaluates the consequences of renewable energy policies on welfare, resource rents and energy costs in a world where carbon pricing is imperfect and the regulator seeks to limit emissions to a (cumulative) target. We use a global general equilibrium model with an intertemporal fossil resource sector. We calculate the optimal second-best renewable energy subsidy and compare the resulting welfare level with an efficient first-best carbon pricing policy. If carbon pricing is permanently missing, mitigation costs increase by a multiple (compared to the optimal carbon pricing policy) for a wide range of parameters describing extraction costs, renewable energy costs, substitution possibilities and normative attitudes. Furthermore, we show that small deviations from the second-best subsidy can lead to strong increases in emissions and consumption losses. This confirms the rising concerns about the occurrence of unintended side effects of climate policy – a new version of the green paradox. We extend our second-best analysis by considering two further types of policy instruments: (1) temporary subsidies that are displaced by carbon pricing in the long run and (2) revenue-neutral instruments like a carbon trust and a feed-in-tariff scheme. Although these instruments cause small welfare losses, they have the potential to ease distributional conflicts as they lead to lower energy prices and higher fossil resource rents than the optimal carbon pricing policy.

5.1 Introduction

Policies to promote renewable energy technologies have a long tradition in many OECD countries. Even before carbon pricing instruments (like the EU-ETS in 2005) were implemented to reduce carbon emissions, many countries had used subsidies, feed-in-tariffs (FIT) or public research and development spending to increase the share of renewable energy (IEA 1997). As concerns about global warming intensify due to new research results such as the latest IPCC (2007b) report and the Stern (2007) Review, politicians and economists are debating about the most effective mitigation policy. Many economists recommend putting a price on carbon in form of taxes or emissions trading schemes (ETS) to mitigate emissions at least costs (e.g. IPCC 2007a, p. 747). The academic popularity of carbon pricing has given rise to a controversial debate on how this instrument relates to renewable energy policies: Are both instruments necessary to achieve mitigation targets at least costs or does the policy mix increase compliance costs?

Basically, there are two strands of argumentations for implementing renewable energy specific policies: one is based on efficiency grounds, the other relies on pragmatic considerations promoting second-best policies that are politically more feasible (see Bennear and Stavins (2007) for a general discussion of the use of second-best instruments). The first argumentation claims that the energy sector is subject to multiple externalities like carbon emissions, local air pollution, innovation and learning spillovers, imperfect competition, network effects or energy security concerns (e.g. Fischer and Preonas 2010; Sorrell and Sijm 2003; Unruh 2000). If the regulator implements only Pigouvian carbon taxes, emissions will be higher than under the first-best optimum (Grimaud et al. 2011). Likewise, if the regulator seeks to achieve a certain emission target (by an ETS or by appropriate carbon taxes) without further policy instruments, compliance costs will be higher than socially optimal (Fischer and Newell 2008; Kalkuhl et al. 2012; Kverndokk and Rosendahl 2007). The second, pragmatic argumentation stresses that distributional concerns and missing stakeholder support for (efficient) carbon pricing may constitute political constraints which prevent the implementation of the first-best policy: High carbon prices reduce profits and income primarily in the fossil energy industry and lower-income households (Burtraw et al. 2009; Metcalf 2008; Parry 2004; Parry and Williams III 2010). Additionally, unilateral carbon pricing can induce relocation of energy-intensive industries (e.g. Markusen et al. 1993). A uniform global carbon tax or a global ETS solves the relocation problem, but might be Utopian in the short term as there is no practical experience how to negotiate and distribute rent incomes and cost burdens. Ideological attitudes against carbon pricing policies also play an important role: Carbon taxes face high opposition as taxes in general are unpopular in wide parts of the US society (Newell et al. 2005). The alternative to taxes, emissions trading, is criticized similarly by many environmentalists and developing countries as being institutionally infeasible or unfair. Distributional concerns and practical and information constraints for compensation may be the most important reason why carbon pricing has not yet been stringent if imposed at all. If exogenous constraints impede the implementation of the first-best instrument, a second-best approach can be a valuable alternative (Bennear and Stavins 2007). In particular, technology-optimistic considerations about the progress of the learning renewable energy technologies might lead to the perception that a temporary renewable deployment stimulus could be a more manageable way to foster mitigation.[1]

It is difficult to estimate to what extent existing renewable energy policies are efficiency-based (i.e. addressing further externalities besides carbon pricing) or driven by pragmatic second-best considerations to reduce emissions. Nevertheless, existing renewable energy policies are also criticized by economists as being inefficient or ineffective. Nordhaus (2009) advocates to treat technologies and innovations in all sectors of the economy equally, i.e. avoid technology discrimination. He advises to concentrate on establishing a global carbon price. Sinn (2008b,a) criticizes ‘demand-side policies’ like renewable energy subsidies as they could lead to an accelerated fossil resource extraction. Generally, many economists recommend to favor an efficient first-best policy over an inefficient second-best approach – without quantifying the respective efficiency losses of the latter.[2]

This paper steps into this gap by considering second-best alternatives to carbon pricing and weighing (theoretical) efficiency against (practical) feasibility aspects. We conduct a cost-effectiveness analysis which takes a certain mitigation target as exogenously given. On the one hand, cost-benefit-analysis depends highly on the assumed damage function and probability distribution of uncertain parameters. As Weitzman (2010) elaborated, this may not only lead to a wide range of optimal temperature targets but may also make cost-benefit analysis impossible if probability distributions are fat-tailed. On the other hand, governments focus in international negotiations and national implementations often on temperature or emissions targets as they are less abstract than cost-benefit analysis.

In order to focus on the welfare effects of second-best policies, we assume that possible secondary market failures like innovation spillovers or network effects are completely internalized by firms or already addressed by an efficient policy instrument. Hence, renewable energy technologies are not subject to uncorrected additional market failures besides the

[1] Farmer and Trancik (2007), for example, estimate that the “costs of reaching parity between photovoltaics and current electricity prices are on the order of $200 billion” – which is 1.4% of U.S. GDP in 2009.

[2] Fischer and Newell (2008) are a notable exception as they calculate the costs of achieving certain emission reductions with second-best policies. Likewise, Galinato and Yoder (2010) focus on revenue-neutral second-best tax-subsidy combinations to reduce carbon emissions.

climate target which rules out the implementation of renewable energy subsidies for efficiency reasons. Instead, we consider a second-best (i.e. the welfare maximizing) renewable energy subsidy when carbon pricing is missing, delayed or imperfect. We further analyze a second-best feed-in-tariff system and carbon trust scheme where fossil tax income is used to cross-finance renewable energy subsidies. We evaluate these instruments with respect to their impact on welfare, resource rents and energy prices compared to an optimal carbon pricing scheme as efficient first-best benchmark. By calculating optimal second-best instruments we provide a valuable numerical estimation of the (optimistic) least-cost potential of these emission mitigation instruments. Furthermore, we assess the robustness of renewable energy subsidies and elaborate the risk of 'green paradoxes' due to slightly maladjusted subsidies. One of the key findings of our paper is that permanent renewable energy subsidies are a very poor and risky substitute for missing or imperfect carbon prices. Mitigation costs increase by a multiple if no carbon price is available for variations in a wide range of plausible parameters. Additionally, subsidies that deviate only slightly from the optimal subsidy can lead to a severe increase in emissions or to high consumption losses. Hence, although high carbon prices are hard to establish in reality, permanent subsidies are no practical alternative. However, feed-in-tariff systems, carbon trusts or temporary subsidies combined with long-term carbon pricing can be designed in a way to ease distributional conflicts at reasonable additional costs.

We perform our analysis within the integrated policy assessment model described in Chapter 4. The model provides a consistent and flexible framework to calculate optimal policies and to conduct a precise welfare analysis. Sec. 5.2 introduces the economic sectors and the relevant basic equations. In our intertemporal general equilibrium model, we consider three stylized energy technologies: (i) a fossil energy technology causing carbon emissions, (ii) a renewable energy technology with high learning-by-doing potential, and (iii) a nuclear power technology as a capital-intensive non-learning carbon-free technology. An intertemporal fossil resource extraction sector is integrated to account for possible supply-side responses to climate policies as motivated by Sinn (2008b). The model is parameterized on a global-economy scale to reproduce business-as-usual and mitigation scenarios from typical integrated assessment models. The global dimension is crucial for appropriately considering the intertemporal supply-side dynamics of fossil resource owners. Although policies have to be implemented nationally, considering the global perspective gives a useful upper bound for the efficiency of second-best instruments. In contrast to Chapter 4, we assume no additional market failures for learning technologies. Instead, we explore the potential of several renewable energy subsidies (presented in Sec. 5.3) to compensate for missing or suboptimal carbon prices in order to achieve ambitious mitigation targets. In Sec. 5.4, the impact of these second-best policies on welfare, rents and energy prices is discussed. Subsequently, the sensitivity and robustness of second-best subsidies is analyzed. Finally, we conclude our paper by summing up important insights and implications for climate policy.

5.2 The model

We use an intertemporal general equilibrium model that distinguishes a household, a production sector, fossil resource extraction and several energy sectors. In addition to energy generated by combustion of fossil resources that causes carbon emissions, there are two carbon-free energy sources: a non-learning nuclear energy sector, and a more expensive yet learning renewable technology with a high cost-decreasing potential. A further sector extracts fossil resources from a finite resource stock. We assume standard constant elasticity of substitution (CES) production functions (see Fig. 5.1 for an overview of the technology used).

For our cost-effectiveness analysis, the mitigation target is expressed by an upper bound for cumulative extraction. In contrast to Chapter 4, there is no emissions trading scheme or 'carbon bank' that provides a first-best carbon price according to the Hotelling rule. The government, which anticipates the equilibrium response of the economy, imposes policy instruments on the economy to maximize welfare subject to the mitigation target.

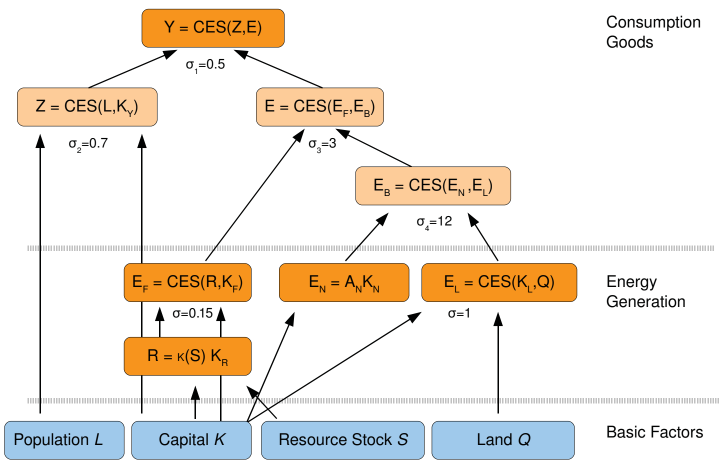


Figure 5.1: Technology of the model and key elasticities of substitution σ_i between production factors.

5.2.1 The economic sectors

In the following, we concentrate on a short description of the agents' optimization problem and the interplay with the government's policies. A detailed and more formal description of production technology, market equilibrium and parameter choices can be found in Chapter 4.

The representative household

We assume a representative household with the objective to maximize the sum of discounted utility U, which is a function of per-capita consumption $U(C/L) = (C/L)^{1-\eta}/(1-\eta)$ with η being the risk aversion or (intertemporal) inequality aversion parameter.[3]

$$\max_{C_t} \quad \sum_{t=0}^{T} (1+\rho)^{-t} L_t \mathbf{U}(C_t/L_t)$$

where ρ is the pure rate of time preference.

The household owns labor L, capital stocks K_j, and the firms, and therefore receives the factor incomes wL and rK_j, as well as the profits of all firms π_j, where $j \in \{Y,F,R,N,L\}$ enumerates the sectors (consumption good sector Y, fossil energy sector F, resource extraction sector R, nuclear energy sector N, renewable energy sector L). Wage rate w, interest rate r, profits π_j and lump-sum transfers from the government Γ are taken as given. The capital stock changes due to investments I net of depreciation of capital at rate δ. The household therefore faces the following constraints:

$$C_t = w_t L_t + r_t K_t - I_t + \pi_t + \Gamma_t \tag{5.1}$$

$$K_t = \sum_j K_{j,t}, \qquad I_t = \sum_j I_{j,t}, \qquad \pi_t = \sum_j \pi_{j,t} \tag{5.2}$$

$$K_{j,t+1} = I_{j,t} + (1-\delta) K_{j,t}, \qquad K_0 \text{ given} \tag{5.3}$$

The production sector

The representative firm in the consumption good sector maximizes its profit π_Y by choosing how much capital K_Y and labor L to deploy, and how much energy to purchase from the various sources: fossil fuels, nuclear power and renewable energy (E_F, E_N, and E_L, respectively). It has to consider the production technology $\mathbf{Y}(\cdot)$ and the given factor prices for capital (r), labor (w), fossil (p_F), nuclear (p_N) and renewable (p_L) energy (the price of consumption goods is normalized to one). Furthermore, the production sector may need to consider government intervention in form of a subsidy on renewable energy τ_L or a feed-in

[3] In the following, we often omit the time-index variables t in the main text to improve readability.

tariff ς_F. The latter takes the form of a subsidy but is cross-financed by a tax τ_F on energy from the fossil and the nuclear energy sectors.

$$\begin{aligned}\pi_{Y,t} = \mathbf{Y}(K_{Y,t}, L_t, E_{F,t}, E_{L,t}, E_{N,t}) - r_t K_{Y,t} - w_t L_t - (p_{F,t} + \tau_{F,t})E_{F,t} \\ - (p_{L,t} - \varsigma_{F,t} - \tau_{L,t})E_{L,t} - (p_{N,t} + \tau_{F,t})E_{N,t}\end{aligned} \quad (5.4)$$

The nested CES production function $\mathbf{Y}(\mathbf{Z}(K_Y, A_Y L), \mathbf{E}(E_F, \mathbf{E_B}(E_L, E_N)))$ combines the inputs capital-labor intermediate and energy, assuming an elasticity of substitution of σ_1. Capital and labor are combined to an intermediate input Z using the elasticity of substitution σ_2; similarly, fossil energy and carbon-free energy are combined to final energy with the elasticity of substitution σ_3. Finally renewable and nuclear energy are combined to an aggregate carbon-free energy E_B using the elasticity of substitution σ_4 (see also Fig. 5.1 for a condensed overview). Population L and labor productivity A_Y grow at an exogenously given rate.

The fossil energy sector

The fossil energy sector maximizes profits π_F with respect to capital K_F and fossil resource use R, subject to the CES production technology $\mathbf{E_F}$ and given factor prices for fossil energy, capital and resources (p_R). Additionally, it may consider a carbon tax τ_R:

$$\pi_{F,t} = p_{F,t}\mathbf{E_F}(K_{F,t}, R_t) - r_t K_{F,t} - (p_{R,t} + \tau_{R,t})R_t \quad (5.5)$$

The fossil resource sector

The fossil resource sector extracts resources from an exhaustible stock S using capital K_R. Its objective is to maximize the sum of profits over time, discounted at the (variable) rate $r_t - \delta$:

$$\max_{R_t} \sum_{t=0}^{T} \pi_{R,t} \Pi_{s=0}^{t} \left[1 + (r_s - \delta)\right]^{-1}$$

Resource owners purchase the capital used in the extraction process at the market interest rate. The productivity of capital $\kappa(S)$ decreases with ongoing depletion of the exhaustible resource stock, implying increasing unit extraction costs (Rogner 1997; Nordhaus and Boyer 2000). The resource sector, therefore, has to take into account the following constraints:

$$\pi_{R,t} = p_{R,t}\kappa(S_t)K_{R,t} - r_t K_{R,t} \quad (5.6)$$

$$S_{t+1} = S_t - R_t, \qquad S_t \geq 0, \qquad S_0 \text{ given} \quad (5.7)$$

The renewable energy sector

The renewable energy sector maximizes profit π_L using capital K_L and a fixed amount of land Q. It considers the interest rate and renewable energy prices as given. The optimization problem of the sector reads:

$$\max_{K_{L,t}} \sum_{t=0}^{T} \pi_{L,t} \Pi_{s=0}^{t} \left[1+(r_s-\delta)\right]^{-1}$$

$$\pi_{L,t} = p_{L,t}\mathbf{A_L}(H_t)K_{L,t}^{\nu}Q^{1-\nu} - r_tK_{L,t} \tag{5.8}$$

$$H_{t+1} = H_t + (E_{L,t} - E_{L,t-1}), \qquad H_0 \text{ given} \tag{5.9}$$

We employ Arrows's (1962) learning-by-doing approach for the renewable energy technology: The productivity $\mathbf{A_L}$ grows with cumulative output H, implying $\partial A_L/\partial H > 0$, and converges to $A_{L,max}$ when $H \to \infty$.

The nuclear energy sector

The nuclear energy sector maximizes profit π_N subject to capital input K_N with an AK-technology function:

$$\pi_{N,t} = p_{N,t}A_{N,t}K_{N,t} - r_tK_{N,t} \tag{5.10}$$

5.2.2 The government

In this study, we are interested in optimal first-best and second-best policies and their impact on welfare. We therefore calculate the Stackelberg equilibrium where a welfare-maximizing government selects the optimal trajectory of policy instruments from a pre-defined subset of available policy instruments given the implicit reaction functions of the economic sectors (see for example Dockner et al. (2000, p. 111)).

The first-order conditions (FOCs) of the previously described sectors (that are listed in detail in Chapter 4) define an intertemporal market equilibrium for given policy instruments. The government considers all technology constraints, budget constraints, equations of motion, and first-order and transversality conditions and chooses policy instruments (and not investment and extraction) to maximize welfare. Furthermore, the government balances income and expenditure at every point in time with households' lump-sum tax Γ.

$$\Gamma_t = \tau_{N,t}E_{N,t} - \tau_{L,t}E_{L,t} + \tau_{R,t}R_t \tag{5.11}$$

The mitigation target B is considered by a constraint on cumulative resource extraction:

$$\sum_{t=0}^{T} R_t \leq B \tag{5.12}$$

Considering the amount of cumulative emissions of the next decades is a robust indicator for achieving ambitious temperature targets (Meinshausen et al. 2009). Hence, the government's optimization problem is described by:

$$\max_{\Theta} \quad \sum_{t=0}^{T} (1+\rho)^{-t} L_t \mathbf{U}(C_t/L_t) \tag{5.13}$$
$$\text{subject to Eqs. 5.1–5.12, FOCs}$$

Θ is the set of government policies and comprises all variables the government has direct access to, e.g. carbon taxes τ_R, renewable energy subsidies τ_L and fossil energy taxes τ_F. The description of concrete policies Θ used in this paper follows below (Sec. 5.3).

5.2.3 Calibration and implementation of the model

Model parameters are chosen from Chapter 4. We use a carbon budget of 450 GtC as climate stabilization target for the mitigation scenario. This limits global warming to 2°C above the pre-industrial level with a probability of roughly 50 %.[4] The endogenous fossil energy price starts at 4 ct/kWh in 2010 and increases up to 8 ct/kWh in 2100 (under business as usual) due to increasing extraction costs. The cost of nuclear energy is mostly constant at 15 ct/kWh which is at the upper bound of the IEA's cost estimate (IEA 2010) that ignores external costs of nuclear power, e.g. external costs due to the limited accident liability for operators.[5] For renewable energy we consider a 17% learning rate which leads to generation costs of 9 ct/kWh in 2100. Initially, the generation costs are around 28 ct/kWh. The chosen parameterization implies that renewable energy is the dominating carbon-free technology under an optimal mitigation policy while nuclear energy plays a limited role.[6]

In this paper, we focus on the costs of alternative policies to carbon pricing in the ab-

[4]The chosen carbon budget refers to the entire planning horizon. For $B = 450$, the resulting cumulative emissions for 2010–2050 are 337 GtC. Together with cumulative 2000–2009 emissions of 77 GtC (Boden et al. 2010), 2000–2050 emissions are 414 GtC. Meinshausen et al. (2009) suggest that limiting cumulative emissions for 2000–2049 to 392 GtC yields a 50% probability of not exceeding the two-degree target. This probability increases to 75% if cumulative 2000–2049 emissions are lower than 273 GtC.

[5]Heyes and Heyes (2000) estimate the magnitude of the implicit subsidy to be 0.01–3.58 ct/kWh for nuclear reactor operators in Canada.

[6]If market failures distort the anticipation of future learning benefits in the renewable energy sector, however, nuclear energy becomes temporarily dominant (see Chapter 4, where the same model framework is used).

sence of additional externalities in the renewable energy sector. Hence, we assume perfect anticipation of learning and therefore neglect potential spillover externalities for learning technologies. The optimization problem as defined by (5.13) forms a non-linear program which is solved numerically with GAMS (Brooke et al. 2005).

5.3 Policy instruments and evaluation criteria

In the introduction we mention several arguments why an efficient carbon price – be it a carbon tax or an emissions trading scheme – may be difficult to implement in reality. Hence, policy makers might prefer to use renewable energy subsidies as a practical second-best alternative. In this section, we consider the optimal carbon tax as a benchmark and several second-best policies promoting renewable energy:

- Optimal carbon tax (mitigation benchmark) $\Theta = \{\tau_{R,t}\}$: The optimal carbon tax $\tau^*_{R,t}$ is the first-best instrument as it achieves the mitigation target at least costs and reproduces an economic outcome identical to a social planner economy if no further market failures exist (Chapter 4). The carbon tax increases with the interest rate as it resembles a Hotelling price for the scarcity of the carbon budget.

- Feed-in-tariff (FIT) $\Theta = \{\tau_{F,t}, \varsigma_{F,t}\}$: A tax $\tau_{F,t}$ on fossil and nuclear energy is used to cross-finance a subsidy $\varsigma_{F,t}$ on renewable energy and to limit fossil resource use. The FIT is implemented as income-neutral policy for the government due to $\varsigma_{F,t}E_{L,t} = \tau_{F,t}(E_{F,t} + E_{N,t})$. Hence, the costs of promoting renewable energy are entirely borne by the energy sector. It is calculated to achieve the mitigation target at maximum welfare without an additional carbon price and lump-sum taxes ($\Gamma_t = 0$). [7].

- Carbon trust $\Theta = \{\tau_{R,t}, \tau_{L,t}\}$: For this policy instrument, the revenues of carbon pricing $\tau_{R,t}$ are spent completely to subsidize renewable energy $\tau_{L,t}$, implying $\tau_{L,t}E_{L,t} = \tau_{R,t}R_t$ and $\Gamma_t = 0$.[8] This instrument differs from the FIT only in that not fossil and nuclear energy but fossil resources (i.e. emissions) are taxed.

- Renewable energy subsidy $\Theta = \{\tau_{L,t}\}$: A subsidy $\tau_{L,t}$ on renewable energy is calculated that achieves the climate target at highest welfare. The subsidy is financed by lump-sum taxation Γ_t of the household. No additional carbon price or energy tax is employed.

[7] The FIT is one of the most popular renewable energy policy as at least 45 countries implemented them already (IPCC 2011, ch. 11, p. 14).

[8] This instrument leans on the atmospheric trust proposal by Barnes et al. (2008). It considers an emissions trading scheme where the revenues from auctioning are partly used to promote renewable energy technologies.

- Subsidy with constant carbon tax $\Theta = \{\bar{\tau}_R, \tau_{L,t}\}$: An exogenously given, constant carbon tax $\bar{\tau}_R$ together with a welfare-maximizing subsidy on renewable energy $\tau_{L,t}$ is employed to achieve the climate target. Additional lump-sum transfers Γ_t are allowed. Constant carbon taxes might result from international negotiations where frequent revisions of agreed taxes cause high transaction costs.

- Temporary subsidy policy that is displaced by a carbon price: $\Theta_{t\leq t'} = \{\tau_{L,t}\}$ and $\Theta_{t>t'} = \{\tau_{R,t}\}$. Hence, for $t \leq t'$ there is no carbon price ($\tau_{R,t\leq t'} = 0$) and for $t > t'$ there is no subsidy ($\tau_{L,t>t'} = 0$). This instrument is appropriate if substantial carbon pricing is not politically feasible in the short run or if there is a long regulatory phase-in.[9] In the long run, however, carbon pricing will be implemented and subsidies become obsolete.

- Finally, a business-as-usual (BAU) scenario is considered where the cumulative carbon budget constraint (5.12) is relaxed and government intervention is absent, implying $\Theta = \emptyset$.

These policies are evaluated with respect to their impact on (i) intertemporal welfare, (ii) fossil resource and renewable rents and (iii) energy prices. While the analysis of intertemporal welfare measures the efficiency of instruments to achieve the mitigation budget, the consideration of fossil resource and renewable rents and energy prices indicates possible distributional conflicts provoked by these policies. Usually, we will compare second-best policies with the first-best mitigation policy $\Theta = \{\tau_{R,t}\}$ (carbon pricing). However, it will also be interesting to compare second-best policies with the BAU outcome in order to identify policies making factor owners or energy buyers better off under the mitigation goal.

Intertemporal welfare In order to compare the intertemporal welfare of several policies we use *balanced growth equivalents* (BGE) as introduced by Mirrlees and Stern (1972). As we use a discrete time model, we adopt the modified calculation of Anthoff and Tol (2009). The BGE γ is defined as an exponentially increasing consumption path (with γ as initial consumption level and an exogenously given constant growth rate) that generates the same discounted utility as the original consumption path. Hence, we compare the relative BGE differences for the first-best policy Θ and the second-best policy Θ' according to the

[9] Such a gradual phase-in of regulation can be motivated by distributional concerns (Williams III 2010). Introducing the efficient level of Pigovian taxes immediately devalues past investments into physical and human capital that are related to fossil energy use. These investments had taken place under the prospect of missing Pigovian taxes.

formula:

$$\Delta\gamma = \frac{\gamma(\Theta') - \gamma(\Theta)}{\gamma(\Theta)} = \begin{cases} \left(\frac{W(\Theta')}{W(\Theta)}\right)^{1/(1-\eta)} - 1 & \eta \neq 1 \\ \exp\left(\frac{W(\Theta') - W(\Theta)}{\sum_{t=0}^{T}(1+\rho)^{-\Delta t}}\right) - 1 & \eta = 1 \end{cases} \tag{5.14}$$

where $W(\Theta)$ denotes the resulting intertemporal welfare under policy Θ. By considering the relative difference $\Delta\gamma$ of the two BGEs for Θ and Θ', the growth rate of the exponentially increasing reference consumption path becomes irrelevant (see Anthoff and Tol (2009) for an analytical derivation). In contrast to a discounted consumption measure that uses an exogenously given discount rate, the BGE does not change the welfare ordering of policy outcomes. It translates welfare losses into appropriate consumption losses which occur once and forever. In other words, the BGEs measure the costs of a policy like a (non-recycled) tax levied on consumption.

The welfare difference of a policy compared to the BAU scenario is denoted in the following as *mitigation cost*. The welfare difference of a second-best policy compared to the optimal first-best mitigation policy (carbon pricing) is denoted as *additional second-best cost*.

Rent dynamics Fossil resource rents are simply given by π_R from (5.6). The associated land rent π_Q for renewable resources is calculated by the product of land Q with the scarcity price for land $p_Q = p_L \frac{\partial E_L}{\partial Q}$, thus, $\pi_Q = p_Q Q$.[10]

Energy prices As energy from different sources is imperfectly substitutable, prices for fossil and renewable energy differ. Therefore, we calculate an average energy price $\tilde{p}_{E,t}$ by the fraction of total energy expenditures and total energy consumption E_t:

$$\tilde{p}_{E,t} = \frac{p_{F,t}E_{F,t} + p_{L,t}E_{L,t} + p_{N,t}E_{N,t}}{E_t} \tag{5.15}$$

By comparing this average energy price, we analyze the impact of policies on energy prices.

[10] The intertemporal learning-by-doing technology complicates the rent dynamics in the renewable energy sector. As the renewable energy price entails also the value of future cost reductions, it is lower than the current-period generation costs. Hence, negative profits arise in early decades. By considering the land rent π_Q only, we abstract from the difficult technological rent dynamics and focus on the rent of limited natural resources.

5.4 Renewable energy subsidies in case an optimal carbon tax is not available

In the following we analyze the performance of mitigation policies that focus on renewable energy deployment. First, we study several second-best policies with respect to welfare, rent distribution and energy prices. Next, we consider how important key parameters influence the welfare losses of renewable energy subsidies (Sec. 5.4.2). Finally, we consider small deviations from the optimal second-best subsidy and their impact on welfare and emissions (Sec. 5.4.3).

5.4.1 Ranking of second-best policies

Impact on welfare

Fig. 5.2 shows the welfare losses of the policies described in Sec. 5.3 compared to the business-as-usual scenario without a mitigation target (BAU) and to the optimal first-best mitigation policy (optimal carbon tax). The mitigation costs under an optimal carbon pricing policy are 2.3%. Hence, introducing a carbon budget reduces the consumption level of a balanced-growth path by 2.3%. These costs increase to 3.1% under a FIT and to 2.9% under a carbon trust. The higher mitigation costs occur because taxing fossil energy or fossil resource use always implies a significant subsidy for renewable energy by the cross-financing mechanism. This subsidy, however, is not necessary because further market imperfections (besides the mitigation target) are absent. Hence, the subsidy leads to distortions and reduces welfare – albeit the quantitative effects remain small. The FIT provokes higher welfare losses than the carbon trust because fossil and nuclear energy is taxed instead of fossil resource use and because not all cost-effective re-allocation possibilities in the fossil energy sector are exploited.[11]

A pure subsidy policy, however, increases mitigation costs substantially to 15.4%. If a low constant carbon price is imposed consumption losses remain at high levels. High constant carbon taxes can decrease the additional second-best costs – although, for constant carbon taxes higher than 750 \$/tC, consumption losses begin to increase. Finally, a temporary subsidy which is displaced by a carbon price in the long run provokes higher additional costs the longer carbon pricing is absent. If carbon pricing is implemented after 20 years, additional costs are marginal (0.2%). If, in contrast, carbon pricing is implemented after six decades, additional second-best costs become substantial (3.8%).

[11] In particular, the fossil energy tax fails to decrease carbon intensity in the fossil energy sector by higher capital input. Even without the cross-financing mechanism (i.e. $\varsigma_F = 0$), mitigation costs of an optimal second-best fossil energy tax are 2.6% implying welfare losses of 0.3% relative to the optimal carbon price.

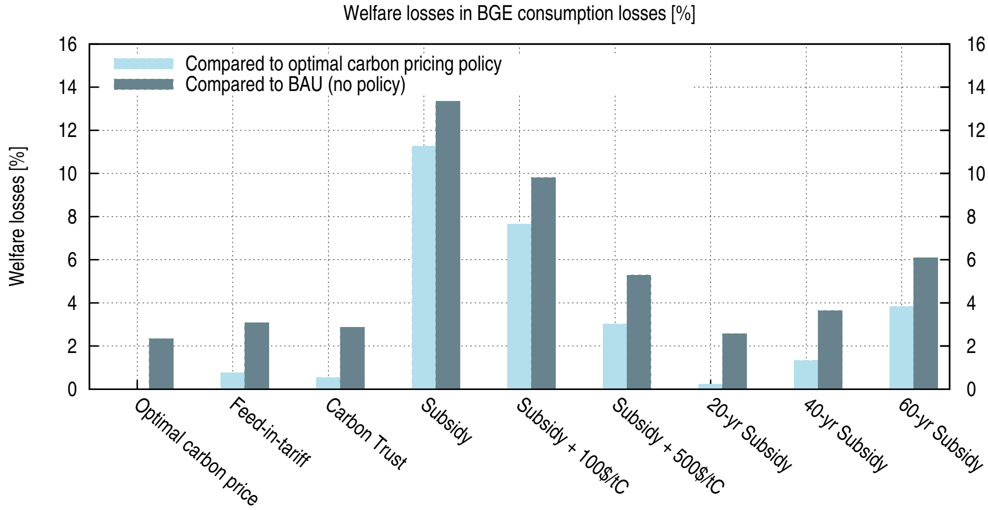


Figure 5.2: Welfare losses (in BGE) for several policies.

Impact on rents

Climate policy does not only affect the welfare of the representative household. It also changes rents and factor prices associated with the consumption of carbon and energy. In particular, mitigation lowers the rent associated with the scarcity of fossil resources because the scarcity of the atmospheric deposit becomes more severe due to ambitious mitigation targets. This can be seen very illustratively in Fig. 5.3,where the net fossil resource price is decomposed into its basic components. In the BAU scenario, the resource rent forms a significant part of the resource price the energy sector has to pay for. This changes under an optimal carbon pricing scheme: In the long run, the carbon price virtually determines the net resource price and, thus, demand for fossil resources. In the first decades – when the carbon price is low –, extraction costs also play an important role. Fossil resource scarcity rents, however, have only a marginal impact on the net resource price.

The mitigation policy decreases the rent per unit of extracted fossil resources as well as the amount of cumulative fossil resource extraction. Under a business-as-usual policy, the scarcity of fossil resources generates rents higher than one percent of GDP for resource owners (Fig. 5.4). In contrast, fossil resource rents shrink dramatically for optimal first-best as well as second-best policies. Interestingly, the revenue-neutral feed-in-tariff and the carbon trust policy lead to higher short-term fossil resource rents than the optimal carbon pricing policy: The cross-financing mechanism of the carbon trust initially leads to lower carbon taxes which imply a higher resource extraction in the early decades. Equally, temporary subsidies that are displaced by a carbon price in the long-term lead to higher short-term rents. The prospect of future high carbon taxes can induce an accelerated resource extrac-

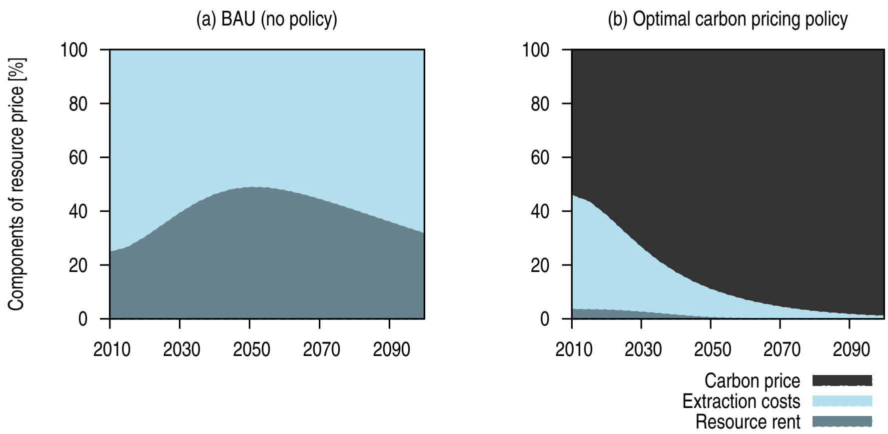


Figure 5.3: Decomposition of the net resource price under (a) business-as-usual and under (b) an optimal carbon pricing policy.

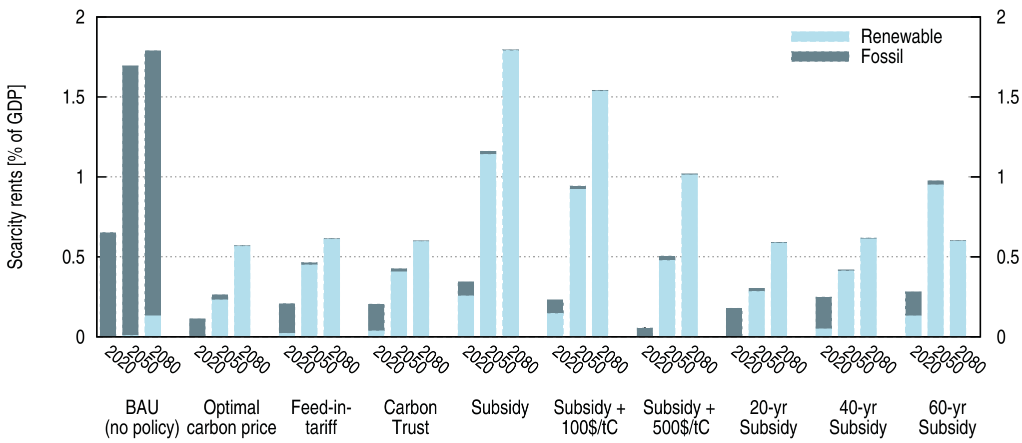


Figure 5.4: Fossil resource and renewable (land) rent for several policies for the years 2020, 2050 and 2080.

tion exceeding even the business-as-usual extraction for the initial period where no carbon price is implemented (cf. Sinn 2008b). The temporary subsidy, however, weakens this effect although the short-term resource extraction is higher than under the optimal carbon pricing policy. In contrast, permanent renewable energy subsidies that are financed by lump-sum taxes reduce fossil resource rents even to a greater extend than an optimal carbon price. Hence, the political economy argument that subsidies provoke less resistance because no firm takes a higher explicit financial burden is flawed. From the resource owners' perspective, a feed-in-tariff, a carbon trust or a temporary subsidy policy is preferable to an optimal carbon pricing policy – and carbon pricing is preferable to a permanent subsidy policy.

While owners of fossil resources lose under all mitigation policies, owners of land used for renewable energy generation profit substantially. Extensive renewable energy subsidies can more than double the land rent associated with renewable energy generation compared to a carbon pricing policy. If subsidies are only temporary, the gains for land owners are moderate and return to the level of the first-best mitigation policy after subsidies have been cut.

Impact on energy prices

As argued in the introduction, distributional concerns are one important reason for the high opposition against carbon prices. Beside resource rents, mitigation policies also change energy prices. First, carbon pricing and fossil energy taxation (FIT) clearly increase fossil energy prices. On the contrary, subsidies on renewable energy decrease fossil energy prices (for an explanation see below). Hence, households and consumers using large amounts of fossil energy face less energy expenditures under a pure renewable energy subsidy policy. Secondly, renewable energy prices decrease for all mitigation policies (partly due to induced learning-by-doing, partly due to paid subsidies).[12] While the cost decrease is smallest for an optimal carbon tax, it is most pronounced under a pure subsidy policy. Finally, the development of average energy prices is shown in Fig. 5.5. The efficient carbon tax leads to high energy prices – almost double as high as in the business-as-usual scenario. The FIT and the carbon trust imply lower energy prices, although higher than in the BAU scenario. Temporary subsidy policies can reduce energy prices near to or below business-as-usual prices as long as subsidies are paid. After replacing the subsidy by a carbon price, energy prices increase sharply up to the energy price under an optimal carbon pricing scheme. Thus, a temporary subsidy effectively delays the cost increase (and the associated distributional conflict). The permanent subsidy policy leads to energy prices that are always lower than without mitigation. Note that in the very long run, energy prices under carbon pricing policies are not substantially higher than in the BAU scenario.[13] Constant carbon taxes increase the short term energy prices until subsidies have expanded to compensate for low carbon prices.

Hence, when firms or households cannot be compensated for higher energy prices resulting from mitigation targets, feed-in-tariffs, a carbon trust or a temporary subsidy policy might be a pragmatic alternative to an optimal carbon pricing policy.

[12] Recall that fossil and renewable energy are good but not perfect substitutes. Prices therefore differ.

[13] First, fossil energy is more expensive in the BAU scenario because extraction costs increase due to high cumulative extraction. Second, learning-by-doing reduces the costs of renewable energy generation.

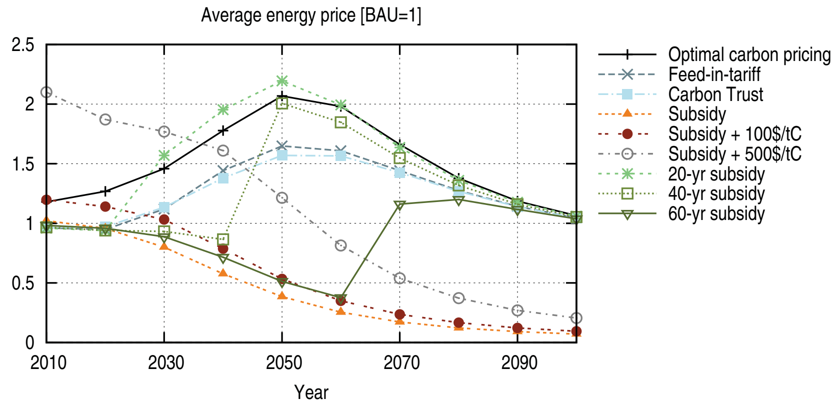


Figure 5.5: Average energy prices according to Eq. (5.15) under different policy regimes relative to BAU prices.

5.4.2 What determines the second-best costs of renewable energy subsidies?

If no tax on carbon or fossil energy is available, renewable energy net prices have to become very low in order to crowd out fossil energy. It is important to note that the subsidy has to be higher than the difference between fossil and renewable energy prices due to the (i) extraction cost dynamics, (ii) the fossil resource rent dynamics and (iii) the imperfect substitutability between energy technologies: The less fossil resources are extracted, the lower are the unit extraction costs as the capital productivity κ of the extraction industry decreases with cumulative extraction. Second, fossil resource owners receive a smaller scarcity rent per unit extracted resources (see Fig. 5.3) because fossil resources become abundant compared to the tight carbon budget under the mitigation policy. Fig. 5.6a indicates how renewable energy subsidies reduce fossil energy prices below BAU prices due to the supply-side dynamics of fossil resources. However, Fig. 5.6a also shows that the subsidy is so high that it pushes the renewable energy price far below the fossil energy price. This is necessary because both energy technologies are good, but not perfect substitutes: It is difficult, for example, to decarbonize the transportation sector by increasing renewable energy subsidies because fossil fuel is not always replaceable by energy from wind, solar or biomass. The fact that the renewable energy price has to be far below the BAU price of fossil energy leads to an enormous energy demand (Fig. 5.6b). As a great part of the GDP is now shifted into the energy sector to generate immense amounts of renewable energy consumption falls dramatically which explains the high welfare losses in Fig. 5.2.

In order to analyze the sensitivity of the consumption losses of a pure renewable energy subsidy, we calculate the mitigation costs for an optimal carbon pricing policy and the additional second-best costs for a variation in several economic parameters. Tab. 5.1 lists the results for parameters describing fossil resource reserves (S_0), substitutability between fos-

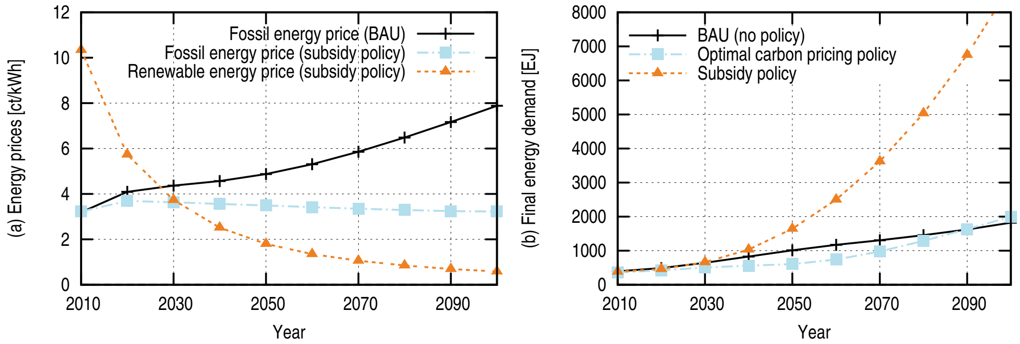


Figure 5.6: Impact of renewable energy subsidies on (a) fossil and renewable energy prices and on (b) fossil and renewable energy generation.

sil and carbon-free energy (σ_3) total energy demand ($A_{L,max}, \sigma_1$), carbon-free energy costs ($A_{L,max}, \nu, A_N$), normative parameters (η, ρ) and the mitigation target (B).

By varying all these parameters we find that the additional second-best costs due to the subsidy are in most cases higher than 5%. A lower fossil reserve size S_0 leads to higher resource extraction costs as resource sites that are difficult to access have to be exploited earlier. Furthermore, resource rents increase due to the higher scarcity. With increasing extraction costs, the subsidy performs better as the fossil energy net price increases in a similar way than under carbon taxes. High fossil energy prices, however, require lower subsidies – which leads to fewer distortions. Additionally, a high substitutability σ_3 between fossil and carbon-free energy reduces the price gradient at which renewable energy crowds out fossil energy. An increase in labor growth productivity $\hat{A}_Y$ implies a higher energy demand in the BAU scenario. This exacerbates the distortions created by the subsidy policy. In the BAU scenario and under the optimal carbon pricing policy a higher substitutability σ_1 between final energy and capital and labor reduces the energy demand as it becomes easier to substitute expensive energy by capital and labor. Large renewable energy subsidies, on the contrary, lead to a higher energy demand for higher σ_1 as labor and capital is substituted by cheap energy. Hence, the second-best costs of renewable energy subsidies increase in σ_1.

If the generation costs of nuclear energy are low (i.e. A_N is high), the technology forms a significant part of an optimal energy mix under an optimal carbon pricing policy. A pure renewable subsidy policy, however, favors renewable energy against both, fossil and nuclear energy. The discrimination against nuclear energy increases the additional second-best costs the cheaper the nuclear energy is. Low generation costs for renewable energy (high $A_{L,max}$ and ν) generally reduce the mitigation costs. As the cost difference for fossil and renewable energy decreases, lower renewable energy subsidies are necessary to achieve the mitigation goal. This implies lower additional second-best costs.

Fossil resource stock [GtC] S_0	5000	4000*	3000	2000	1000	
Mitigation costs [%]	2.55	2.34	2.01	1.47	0.48	
Additional 2nd-best costs [%]	11.68	11.27	10.45	8.56	3.56	
Fossil–carbon-free energy substitutability σ_3	3*	4	5	6		
Mitigation costs [%]	2.34	2.63	2.78	2.85		
Additional 2nd-best costs [%]	11.27	9.19	8.05	7.31		
Initial labor productivity growth rate $\hat{A}_Y$	0.010	0.015	0.020	0.024	0.026*	0.028
Mitigation costs [%]	1.92	2.06	2.2	2.29	2.34	2.38
Additional 2nd-best costs [%]	7.39	8.42	9.54	10.51	11.27	14.27
(KL)–E substitutability σ_1	0.3	0.4	0.5*	0.6	0.7	
Mitigation costs [%]	3.75	2.96	2.34	1.84	1.45	
Additional 2nd-best costs [%]	8.58	9.99	11.27	12.5	13.73	
Nuclear energy productivity A_N	0.15	0.2*	0.25	0.3	0.35	
Mitigation costs [%]	2.37	2.34	2.22	1.99	1.69	
Additional 2nd-best costs [%]	11.18	11.27	11.48	11.79	12.12	
Renewable energy productivity $A_{L,max}$	0.6*	0.7	0.8	0.9	1	
Mitigation costs [%]	2.34	1.87	1.47	1.17	0.93	
Additional 2nd-best costs [%]	11.27	8.36	6.38	4.98	3.95	
Share parameter renewable energy ν	0.85	0.9	0.95*	1		
Mitigation costs [%]	3.46	3.14	2.34	1.56		
Additional 2nd-best costs [%]	41.96	21.47	11.27	6.04		
Pure social time discount rate ρ	0.01	0.02	0.03*	0.04	0.05	
Mitigation costs [%]	3.48	2.94	2.34	1.76	1.27	
Additional 2nd-best costs [%]	18.7	14.68	11.27	8.47	6.29	
Risk (inequaltiy) aversion η	1*	1.5	2	2.5	3	
Mitigation costs [%]	2.34	1.87	1.39	1.02	0.74	
Additional 2nd-best costs [%]	11.27	9.02	6.82	5.36	3.92	
Carbon budget [GtC] B	250	350	450*	550	650	750
Mitigation costs [%]	4.2	3.09	2.34	1.8	1.4	1.09
Additional 2nd-best costs [%]	18.45	14.32	11.27	8.92	7.07	5.6

Table 5.1: Mitigation costs (welfare losses of the optimal carbon pricing policy relative to the BAU scenario) and additional second best costs (welfare losses of the pure subsidy policy relative to the optimal carbon pricing policy) for several parameter variations. The asterisk is assigned to the value used for the standard parameterization.

Normative preferences influence optimal investment and extraction decisions of market agents as well as the policy trajectory and the performance of policies. A higher discount rate reduces mitigation costs because the costs of transforming the energy system are shifted into the far-distant future where they are heavily discounted: Extraction is accelerated and the deployment of learning technologies delayed which increases consumption in early decades at the expense of subsequent decades. This intertemporal re-allocation occurs under an optimal carbon price as well as under the second-best subsidy. As the higher far-distant costs are stronger discounted for higher discount rates, (discounted) welfare losses decrease in ρ. A higher elasticity of the marginal utility of consumption η penalizes an unequal distribution of consumption in time. Within our growth model, consumption grows even under the mitigation target, though growth rates are smaller. Mitigation mainly reduces future consumption (due to higher costs in the energy system) when the society became more productive. Therefore, limiting fossil fuel use reduces the inequality in the consumption trajectory. Hence, a higher η leads to lower welfare losses – both under an optimal carbon pricing as well as under a second-best subsidy policy. Finally, ambitious mitigation targets (implemented by a low carbon budget B) increase the second-best costs of the subsidy as higher renewable energy subsidies are required to crowd out fossil energy use.

Fig. 5.7 compares the (optimal) mitigation costs with the additional second-best costs of the renewable energy subsidy from Tab. 5.1. It becomes apparent that the second-best costs of the subsidy policy correlate positively with the mitigation costs – except for three parameter variations. The positive correlation implies that the costs of the subsidy policy are moderate when climate protection does not place a significant burden on the economy. In this case, carbon pricing has only marginal distributional impacts through increasing energy prices. The rational for choosing renewable energy subsidies instead of the efficient carbon pricing policy becomes obsolete in this case. Only for three parameter variations, higher mitigation costs correlate with lower second-best costs of the subsidy policy. If final energy is to a smaller extent substitutable by labor and capital (low σ_1), if fossil energy and carbon-free energy are very good substitutes (high σ_3), and if nuclear energy generation is expensive (low A_N) the additional second-best costs of the subsidy policy could become small.

5.4.3 The risk of green paradoxes

Motivated by the green paradox of Sinn (2008b) we study the impact of suboptimal subsidies on emissions and consumption. Again, we assume the absence of a carbon price and calculate the optimal subsidy to achieve the 450 GtC mitigation target. Next, we calculate subsidies that deviate slightly from the optimal subsidy by a fixed ratio, e.g. a ratio which is 1% lower than the optimal subsidy at each period in time. The optimal subsidy and the

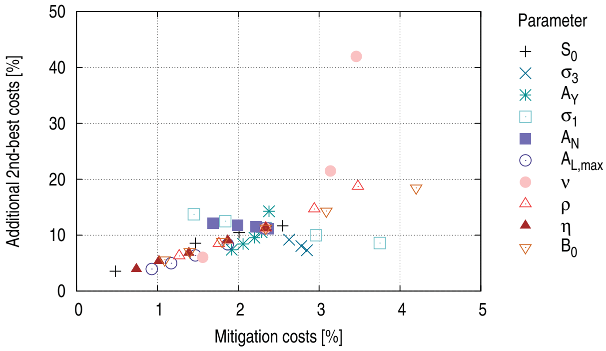


Figure 5.7: Sensitivity analysis for a renewable subsidy policy. The welfare losses of a pure renewable subsidy policy compared to an optimal carbon pricing policy (additional 2nd-best costs) are shown as well as mitigation costs of an optimal carbon pricing policy compared to the BAU scenario. Parameter variations correspond to Tab. 5.1.

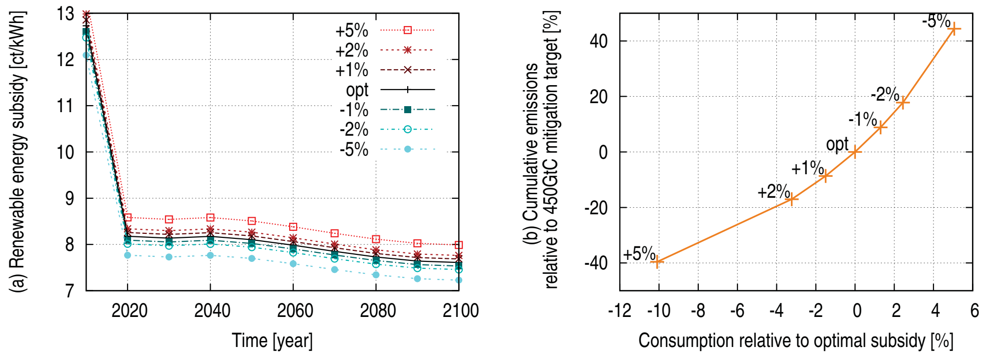


Figure 5.8: (a) Optimal subsidy and perturbations. (b) Impacts of perturbed subsidies on consumption and emissions.

perturbations are shown in Fig. 5.8a. Finally, we impose the perturbed subsidies into the model (still without a carbon price) and compare the impact on cumulative emissions and welfare of these subsidies (Fig. 5.8b).

The numerical calculations show that the economy responds very sensitively on changes of subsidy levels. For a subsidy which is only 2% lower than the optimal subsidy, consumption increases by 2.4% and cumulative emissions even by 17.8% (compared to the 450 GtC carbon budget). In contrast, the implementation of a subsidy which is 2% higher than the optimal one, decreases consumption by 3.2% and cumulative emissions by 17.0%.

Hence, a slightly higher subsidy causes additional consumption losses and a slightly lower subsidy leads to far more emissions. Without any carbon price, the renewable energy subsidy is not only a very expensive instrument. It is also a dangerous instrument because it can provoke unintended side-effects on emissions if the regulator deviates only slightly from the optimal tax.

5.5 Conclusions

Our analysis provides some valuable information for policy makers struggling with introducing high carbon prices. For a wide range of parameters, using permanently renewable energy subsidies instead of carbon prices to achieve mitigation implies disastrous welfare losses: they are multiple times higher than first-best mitigation costs under a carbon price policy.[14] Even if constant carbon prices are feasible, the subsidy cannot correct the suboptimal carbon price at low costs. Although renewable energy becomes cheaper due to subsidies and learning-by-doing, it is difficult to crowd out fossil energy supply. Resource prices decrease due to the supply-side dynamics of fossil resource extraction. And the good – but not perfect – substitutability between energy technologies requires to maintain a high price differential between renewable and fossil energy. Achieving the cost break-through is therefore not sufficient. If the substitutability between fossil and renewable energy is high, the second-best costs decrease substantially. Hence, a sectoral policy approach with renewable energy subsidies in the electricity sector (where technologies are almost perfect substitutes) and carbon taxes in the industry sector may decrease the second best-costs.

A low fossil resource base and low renewable energy generation costs reduce the second-best costs – though the mitigation costs fall dramatically in these cases and a carbon pricing policy only has a marginal impact on the economy. Distributional conflicts due to carbon pricing do not arise for these parameter settings. While renewable energy subsidies indeed lower energy prices even below the business-as-usual prices, the government has to raise taxes on households to finance these subsidies. Furthermore, fossil resource owners lose more rents under a renewable subsidy policy than under a carbon pricing policy. Hence, at a second glance, a subsidy-only policy may provoke even higher resistance of the fossil industry than a carbon tax. Permanent renewable energy subsidies are not only an expensive choice to reduce emissions. They are also a very risky instrument because small deviations from the second-best optimum lead to strong responses in emissions and welfare. If the subsidy was set 2% below its optimal value, emissions would increase by 18%. In contrast, if the subsidy was set 2% above its optimal value, welfare would decrease by an additional 3% due to an over-ambitious emission reduction.

There are some attractive alternatives to a pure carbon pricing policy. The feed-in-tariff

[14]These welfare losses remain almost unaffected if we allow for an additional nuclear energy subsidy promoting the second carbon-free energy technology in our model: In that case, welfare losses of the pure renewable energy subsidy policy decrease only by 0.3 percentage points.

and the carbon trust policy cause only small additional costs. Even if no market failures besides the mitigation target exist, redirecting the revenues of a fossil energy tax (FIT policy) or carbon tax (carbon trust policy) to the renewable sector reduces consumption by 0.8% (FIT) and 0.5% (carbon trust) compared to the optimal carbon pricing policy. In this case, fossil resource rents are higher and energy prices lower than under efficient carbon pricing. If additional market failures in the renewable energy sector exist (like spillover externalities for innovations), the carbon trust may even be welfare-increasing compared to a pure carbon pricing policy. Finally, temporary subsidies delay or ease distributional conflicts provoked by high energy prices and low fossil resource rents due to carbon pricing. A subtle combination of short-term renewable energy subsidies and long-term carbon prices can achieve the mitigation target at moderate costs – although fossil resource owners may slightly accelerate resource extraction in the short term.

Renewable energy subsidies are an efficient policy instrument when they address market failures directly associated with renewable energy technologies or markets. However, if renewable energy subsidies aim to reduce carbon emissions because carbon prices are missing or too low, welfare losses can be substantial. In particular, if mitigation imposes a severe constraint on the economy – i.e. if fossil resources are abundant and cheaply available compared to renewable energy generation – a subsidy policy creates high additional consumption losses. The results of this paper show that without a careful policy analysis, pragmatic policy approaches may turn out to be a fatal aberration for mitigating global warming as costs explode. In order to achieve mitigation targets at low costs, there seems to be no way around direct or indirect carbon pricing – at least in the long run.

Bibliography

Anthoff, D. and R. Tol (2009). The impact of climate change on the balanced growth equivalent: An application of FUND. *Environmental and Resource Economics 43*, 351–367.

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

Barnes, P., R. Costanza, P. Hawken, D. Orr, E. Ostrom, A. Umaña, and O. Young (2008). Creating an earth atmospheric trust. *Science 319*(5864), 724b.

Bennear, L. and R. Stavins (2007). Second-best theory and the use of multiple policy instruments. *Environmental and Resource Economics 37*(1), 111–129.

Boden, T., G. Marland, and R. Andres (2010). Global, regional, and national fossil-fuel CO2 emissions. Technical report, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Brooke, A., D. Kendrick, A. Meeraus, R. Raman, and R. E. Rosenthal (2005). *GAMS. A Users Guide*. GAMS Development Corporation.

Burtraw, D., R. Sweeney, and M. Walls (2009). The incidence of u.s. climate policy: Alternative uses of revenues from a cap-and-trade auction. Resources for the Future Discussion Papers dp-09-17-rev.

Dockner, E., S. Jørgensen, N. van Long, and G. Sorger (2000). *Differential Games in Economics and Management Science*. Cambridge: Cambridge University Press.

Farmer, J. D. and J. Trancik (2007). Dynamics of technological development in the energy sector. *The London Accord.*.

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? Resources for the Future Discussion Papers dp-10-19.

Galinato, G. I. and J. K. Yoder (2010). An integrated tax-subsidy policy for carbon emission reduction. *Resource and Energy Economics 32*(3), 310–326.

Grimaud, A., G. Lafforgue, and B. Magne (2011). Climate change mitigation options and directed technical change: A decentralized equilibrium analysis. *Resource and Energy Economics 33*(4), 938–962.

Heyes, A. and C. Heyes (2000). An empirical analysis of the nuclear liability act (1970) in canada. *Resource and Energy Economics 22*(1), 91–101.

IEA (1997). *Renewable Energy Policy in IEA Countries, Volume 1: Overview*. International Energy Agency, Paris, France.

IEA (2010). *Projected Costs of Generating Electricity*. International Energy Agency, Paris, France.

IPCC (2007a). *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

IPCC (2007b). *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

IPCC (2011). *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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.

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.

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.

Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2C. *Nature 458*(7242), 1158–1162.

Metcalf, G. E. (2008). Designing a carbon tax to reduce u.s. greenhouse gas emissions. *Review of Environmental Economics and Policy*.

Mirrlees, J. A. and N. H. Stern (1972). Fairly good plans. *Journal of Economic Theory 4*(2), 268 – 288.

Newell, R., W. Pizer, and J. Zhang (2005). Managing permit markets to stabilize prices. *Environmental and Resource Economics 31*, 133–157.

Nordhaus, W. D. (2009). Designing a friendly space for technological change to slow global warming. *Snowmass Conference on Technologies to Combat Global Warming, Snowmass (CO), August 3-4*.

Nordhaus, W. D. and J. Boyer (2000). *Warming the World. Economic Models of Global Warming*. Cambridge, Massachusetts, London, England: The MIT Press.

Parry, I. W. and R. C. Williams III (2010). What are the costs of meeting distributional objectives for climate policy? NBER Working Papers 16486, National Bureau of Economic Research, Inc.

Parry, I. W. H. (2004). Are emissions permits regressive? *Journal of Environmental Economics and Management 47*(2), 364–387.

Rogner, H.-H. (1997). An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment 22*(1), 217–262.

Sinn, H.-W. (2008a). *Das Grüne Paradoxon: Plädoyer für eine illusionsfreie Klimapolitik*. Berlin: Econ.

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

Sorrell, S. and J. Sijm (2003). Carbon trading in the policy mix. *Oxford Review of Economic Policy 19*(3), 420–437.

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

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy 28*(12), 817–830.

Weitzman, M. L. (2010). GHG targets as insurance against catastrophic climate damages. NBER Working Papers 16136, National Bureau of Economic Research, Inc.

Williams III, R. C. (2010). Setting the initial time-profile of climate policy: The economics of environmental policy phase-ins. NBER Working Papers 16120, National Bureau of Economic Research, Inc.

Chapter 6

The Role of Carbon Capture and Sequestration Policies for Climate Change Mitigation

Abstract: This paper takes the 'policy failure' in establishing a global carbon price for efficient emissions reduction as a starting point and analyzes to what extent technology policies can be a reasonable second-best approach. From a supply-side perspective, carbon capture and storage (CCS) policies differ substantially from renewable energy policies: they increase fossil resource demand and simultaneously lower emissions. We show in a theoretical model that, under idealized conditions, a pure CCS subsidy can be as efficient as a carbon tax. Within a numerical dynamic general equilibrium model, we analyze CCS and renewable energy policies under more realistic parameter settings for imperfect or missing carbon prices. We find that in contrast to renewable energy policies, CCS policies are not always capable of reducing emissions in the long run. If feasible, CCS policies carry often lower social costs compared to renewable energy policies. In case fossil resources are abundant and renewable energy costs low, renewable energy policies perform better. Our results indicate that a pure CCS policy or a pure renewable energy policy carry specific risks of missing the environmental target. A smart combination of both, however, can be a robust and low-cost temporary second-best policy.

6.1 Introduction

While a global carbon price is the economist's textbook advice for reducing emissions efficiently, governments struggle with the introduction of substantial domestic or even global carbon prices. Until now, states could neither agree upon a global emissions trading scheme, nor on a globally harmonized carbon tax. The reasons are numerous: Besides free-rider incentives, carbon pricing policies re-distribute disposable income, rents and wealth through several channels on a domestic as well as a global scale (Fullerton 2011). These redistributions can be regressive, e.g. increased energy prices due to cleaner energy provision reduce the disposable income of low-income households more than for high-income households (e.g. Parry 2004; Parry and Williams III 2010). Climate policy can also have a progressive effect if scarcity rents associated to fossil resource ownership are reduced and revenues from carbon pricing transferred to low-income households.

In any case, the transformation of income and rents creates a bargaining and rent-seeking process about compensation schemes that impedes the implementation of efficient policies: Internationally, negotiating explicit transfers between countries is a difficult task. Every party insists on an advantageous burden sharing rule and fears to be hoodwinked regarding the sharing of costs and benefits. Domestically, compensation policies for higher energy prices may imply high transaction costs, in particular in developing countries with insufficient public institutions.

Despite the difficulties to establish significant carbon prices, many governments euphorically promote renewable energy by targeted technology policies. There are at least 118 countries with explicit renewable energy targets or policies (REN21 2011). Global investments into new renewable energy capacities are higher than into fossil energy capacities in the electricity sector (IPCC 2011, Ch. 11, p. 878). Public support for these measures is high because renewable energy is associated with several local and national benefits, ranging from improved air quality over technological first-mover advantages to greater energy security and higher energy access in remote rural areas (IPCC 2011, Ch. 11.3). [1]

This paper takes the global policy failure in establishing a carbon price as a starting point. It analyzes the extend to which second-best[2] energy policies can replace carbon pricing policies. We provide an extensive discussion for the specific case of renewable energy policies to reduce emissions if carbon prices are missing in Chapter 5: Despite the

[1] This corresponds to the suggestion of Victor (2011) that support for policies is greatest if costs are widely spread or hidden and benefits are concentrated and explicit. By contrast, the benefits of carbon pricing are far more spread out (in fact, across the globe and into the future) and can involve costs that are concentrated on a few sectors and companies that are well-organized.

[2] We use the term second-best as follows: An optimal second-best policy is a policy that maximizes social welfare given that the policy space is constrained.

political appeal, a naive up-scaling of renewable energy deployment is very costly and the resulting emissions are highly sensitive to the level of subsidies undermining environmental effectiveness. This study adds technology policies for carbon capture and sequestration (CCS) as well as portfolios of technology policies.

The underlying supply-side argument providing the basis for our analysis of CCS policies was made by Sinn (2008): Policies reducing the demand for fossil resources can – if ill-designed – accelerate resource extraction and, thus, emissions. This issue has been discussed for suboptimal carbon taxes as well as suboptimal renewable energy subsidies (Sinn 2008; Grafton et al. 2010; Hoel 2010; Edenhofer and Kalkuhl 2011; Gerlagh 2011). In addition to intertemporal re-allocation of carbon extraction, unilateral carbon pricing policies can induce supply-side leakage via reduced (global) fossil resource prices (Eichner and Pethig 2009). CCS differs from other mitigation options (here: energy efficiency increases, renewable energy use) as it allows using fossil resources with low atmospheric emissions. Hence, promoting CCS could increase fossil resource demand and simultaneously reduce carbon emissions. Therefore, we concentrate on the role of CCS policies and their difference to renewable energy policies in particular regarding the supply-side dynamics of fossil resources.

So far, there has been only little research that focuses on the second-best aspect of CCS policies. A number of theoretical papers address the efficient use of CCS under several geological and economic conditions (Amigues et al. 2010; Coulomb and Henriet 2010; Le Kama et al. 2011). Several numerical models have estimated the role of CCS for reducing mitigation costs (e.g. Edenhofer et al. 2005; van der Zwaan and Gerlagh 2009). However, only few papers provide an explicit analysis of policy instruments. Fischer and Salant (2010) find within a Hotelling model framework that mal-adjusted carbon taxes, renewable energy subsidies or energy efficiency improvements can be ineffective or even accelerate extraction and emissions. An obligatory mandate to capture and sequester a certain share of emissions, however, does always reduce emissions and is, thus, the most robust policy. Hoel and Jensen (2010) show in a two-period Hotelling model that reducing the long-term costs for renewable energy can lead to higher emissions while reducing the long-term costs for CCS always reduces emissions.

We start our analysis with a reduced formal analytical model to elaborate the basic dynamic of CCS policies for reducing carbon emissions (Sec. 6.2). We then extend the intertemporal general equilibrium model PRIDE (Chapter 4) by a CCS technology to study the performance of CCS policies in a second-best setting where carbon prices are restricted. To integrate the supply-side dynamics of fossil resource extraction, a general equilibrium model on a global scale is necessary. Although there is no real-world government at a global scale that could implement carbon pricing or technology policies, our model results give an important (least-cost) estimation about the performance of several policies instruments. The model presented in Sec. 6.3 takes a similar approach as the DEMETER model (Gerlagh et al. 2004; Gerlagh and van der Zwaan 2004) or the top-down energy-economic model developed by Grimaud et al. (2011). As DEMETER does not contain an intertemporal fossil resource sector, it cannot capture the supply-side dynamics of fossil fuels. Within a second-best policy analysis in DEMETER, Gerlagh and van der Zwaan (2006) explore the role of renewable energy subsidies and a portfolio standard for CCS for climate change mitigation when innovation spillovers exist. In contrast to DEMETER, the model of Grimaud et al. (2011) contains an intertemporally optimizing fossil resource sector. While Grimaud et al. (2011) focus on carbon pricing and R&D subsidies, no policy analysis is conducted with respect to explicit technology deployment policies under carbon-pricing constraints.

In our general equilibrium model, we consider several second-best settings with respect to the carbon price (Section 6.4). In Section 6.4.1, the implemented carbon price is lower than the carbon price necessary to achieve a certain mitigation target and governments can use low-carbon technology policies to reduce emissions further. This corresponds to a world where governments want to reduce emissions but are reluctant to introduce the efficient carbon prices. Instead, they aim to reduce emissions by promoting low-carbon technologies in form of renewable energy or CCS. Section 6.4.2 assumes that the international community is not able to establish a global carbon price very soon. Instead, governments and firms expect that a carbon price will eventually be introduced in the future and use technology policies for bridging the gap.

We then perform a sensitivity analysis with respect to crucial parameters (Section 6.5.1) and deviations from optimal second-best policies (Section 6.5.2). The latter suggests how sensitively carbon emissions respond to suboptimally chosen policies. Finally, we sum up our main findings and conclude with some further considerations on the design of technology policies for mitigation (Section 6.6).

Our main findings are as follows: In our analytical model, we identify conditions when a pure CCS policy can be an *efficient* policy if carbon prices are missing or too low. The basic intuition behind this finding is that CCS subsidies increase the demand for fossil resources which in turn leads to higher resource prices (scarcity rent markup). If fossil resources are relatively scarce, this scarcity rent markup can be increased to the same level as the carbon price – an efficient outcome is then achieved. This result, however, depends on the restrictive assumptions that leakage is zero, all emissions can be captured and fossil resources are scarce relative to underground storage.

In the numerical model, we consider more realistic geological assumptions about CCS.

We find that CCS policies can achieve a mitigation target in many cases at lower costs than renewable energy policies, in particular, when fossil resources are scarce. By increasing the fossil resource prices, renewable energy deployment is also accelerated. However, CCS policies are only feasible under favorable geological conditions, while renewable energy subsidies are always capable to achieve the mitigation target but costs may be large. When reducing the time span during which carbon prices are missing, CCS policies become more likely to be a feasible second-best policy and costs decrease further. Hence, CCS policies can be an attractive short-term option to buy time until optimal carbon prices have been established. As the delay of carbon pricing stretches out, renewable energy subsidies become more and more important as long-term second-best policy. A smart combination of CCS and renewable energy policies can therefore simultaneously reduce mitigation costs and the risk of exceeding the mitigation target.

6.2 Analytical model: The fundamental dynamics of CCS policies

This part of the paper focuses on a partial equilibrium model that highlights the fundamental dynamics of CCS policies within a cost-effectiveness analysis. The model extends a standard Hotelling (1931) model by a constraint on cumulative fossil resource extraction to represent government policy, and by an option to capture emissions and store them underground. This basic model provides some important insights for our subsequent analysis within a numerical general equilibrium model.

6.2.1 The social planner economy

In the social planner economy, fossil resources R are used to generate output $f(R)$.[3] The fossil resources can be used in conventional plants to generate energy but also emissions which are released into the atmosphere. We denote these resources as R_N. Alternatively, fossil resources R_C can be converted to energy in CCS plants, whereby a share $\theta \leq 1$ of carbon is captured and only the corresponding share $1-\theta$ is released into the atmosphere.[4] As capturing requires additional energy, we introduce an energy penalty parameter $\tilde{\alpha} \leq 1$. This parameter indicates how much additional fossil resources is used to generate the same amount of energy as with the conventional technology, i.e. $R_N = R_C/(1+\tilde{\alpha})$. Since the evolving temperature increase can be approximated by the amount of cumulative emissions

[3] To improve the readibility of this article, we will usually omit the time indicies for most variables.

[4] The capture rate depends on the chosen capture method (post-combustion, pre-combustion, oxyfuel combustion) and separation technology (i.e. physical or chemical solvents) (IPCC 2005, Ch. 3).

(Meinshausen et al. 2009), we simply consider the mitigation target as cumulative constraint on emissions. We also denote this constraint B_0 the carbon budget.

The initial fossil resource stock S_0 under ground limits cumulative total extraction by $\int_0^\infty R\,dt \leq S_0$. Storage capacity X for captured carbon is assumed to be finite and decreases with the captured carbon. However, stored carbon may also leak out of the storage into the atmosphere at the rate $\delta_X \geq 0$. The remaining carbon budget B decreases by non-captured resources R_N and $(1-\theta)R_C$ as well as leaked carbon $\delta_X(X_0 - X)$. Unit extraction costs $g(S)$ depend on the remaining stock size S, and capture and storage costs $h(X)$ depend on the remaining storage capacity X. Hence, we define the social planner's problem of finding a cost-effective extraction and capture path as:

$$\max_{R_N,R_C} \int_0^\infty [f(R_N + \alpha R_C) - g(S)R - \theta h(X)R_C]\, e^{-rt}\, dt$$

subject to:

$$\dot{S} = -R = -(R_C + R_N) \tag{6.1}$$

$$\dot{B} = -(R_N + (1-\theta)R_C + \delta_X(X_0 - X)) \tag{6.2}$$

$$\dot{X} = -\theta R_C + \delta_X(X_0 - X) \tag{6.3}$$

where $R_C, R_N, B, S, X \geq 0$, $\alpha := 1/(1+\tilde{\alpha})$ and r is the discount rate. The corresponding Hamiltonian is $H = f(R_N + \alpha R_C) - g(S)R - \theta h(X)R_C - \lambda R - \mu(R_N + (1-\theta)R_C + \delta_X(X_0 - X)) - \psi(\theta R_C - \delta_X(X_0 - X))$ where λ, μ and ψ are the shadow variables associated with the fossil resource base S, the atmospheric carbon budget B and the underground storage for carbon dioxide X, respectively. With $f'(\cdot)$ denoting the first derivative (i.e. $f'(R) := \partial f(R)/\partial R$), the first-order conditions including the equations of motion and terminal conditions are:

$$\alpha f'(R_N + \alpha R_C) - g(S) - \theta h(X) - \lambda - (1-\theta)\mu - \theta\psi \leq 0 \qquad (= 0 \text{ if } R_C > 0) \tag{6.4}$$

$$f'(R) - g(S) - \lambda - \mu \leq 0 \qquad (= 0 \text{ if } R_N > 0) \tag{6.5}$$

$$\dot{\lambda} = r\lambda + g'(S)R \tag{6.6}$$

$$\dot{\mu} = r\mu \tag{6.7}$$

$$\dot{\psi} = r\psi + \theta h'(X)R_C - \delta_X(\mu - \psi) \tag{6.8}$$

$$0 = \lim_{t\to\infty} S(t)\lambda(t)e^{-rt} \tag{6.9}$$

$$0 = \lim_{t\to\infty} B(t)\mu(t)e^{-rt} \tag{6.10}$$

$$0 = \lim_{t\to\infty} X(t)\psi(t)e^{-rt} \tag{6.11}$$

The system of (differential) equations (6.4–6.11) implicitly describes the optimal solution in the social planner economy. This solution serves as benchmark for the decentralized market equilibrium that is discussed subsequently.

6.2.2 The decentralized economy

The resource sector maximizes discounted profit for given resource prices p and increasing extraction and capturing costs similar to the social planner above. Additionally, the resource sector has to consider an emission tax τ on non-captured and leaked carbon as well as a subsidy σ for captured carbon. As the atmospheric carbon deposit is an open-access resource, the resource sector does not take the carbon budget B into account. The optimization problem reads:

$$\begin{aligned}\max_{R_N,R_C} \int_0^\infty & [p(R_N+\alpha R_C) - g(S)R - \theta h(X)R_C \\ & - \tau(R_N+(1-\theta)R_C+\delta_X(X_0-X)) + \sigma R_C]e^{-rt}\,dt\end{aligned}$$

subject to:

$$\dot{S} = -R = -(R_C+R_N) \tag{6.12}$$

$$\dot{X} = -\theta R_C + \delta_X(X_0-X) \tag{6.13}$$

where $R_C, R_N, S, X \geq 0$. Eqs. (6.12–6.13) are the same as in the social planner problem (6.1–6.3), except for the missing equation for the carbon budget. The corresponding Hamiltonian is $H = p(R_N+\alpha R_C) - g(S)R - \theta h(X)R_C - \lambda R - \tau(R_N+(1-\theta)R_C+\delta_X(X_0-X)) + \sigma R_C - \psi(\theta R_C - \delta_X(X_0-X))$ The first-order conditions describing the market equilibrium are:

$$\alpha p - g(S) - \theta h(X) - \lambda - (1-\theta)\tau + \sigma - \psi \leq 0 \qquad (= 0 \text{ if } R_C > 0) \tag{6.14}$$

$$p - g(S) - \lambda - \tau \leq 0 \qquad (= 0 \text{ if } R_N > 0) \tag{6.15}$$

$$\dot{\lambda} = r\lambda + g'(S)R \tag{6.16}$$

$$\dot{\psi} = r\psi + \theta h'(X)R_C - \delta_X(\tau-\psi) \tag{6.17}$$

$$0 = \lim_{t\to\infty} S(t)\lambda(t)e^{-rt} \tag{6.18}$$

$$0 = \lim_{t \to \infty} X(t)\psi(t)e^{-rt} \tag{6.19}$$

6.2.3 Efficient policies

By comparing the first-order conditions of the social planner problem and the decentralized economy, we can identify cost-efficient policies. As intuition suggests, a carbon tax τ on emissions which equals the shadow price of the carbon budget μ in the social planner economy will reduce emissions at lowest costs and reproduce the socially optimal outcome:

Proposition 6.1. *Let $\mu^*(t) = \mu_0^* e^{rt}$ denote the shadow price of the carbon budget from the optimal social planner solution given by (6.4–6.11). If the regulator implements carbon tax τ with $\tau(t) = \mu^*(t)$, an optimal allocation is achieved.*

Proof. Simply set $\tau = \mu^*$ in Eqs. (6.14–6.17). The first-order and terminal conditions in the market model (for $\sigma = 0$) equal the corresponding conditions in the social planner model. □

As argued in the Introduction, carbon prices are difficult to implement in reality. Under specific conditions, however, it is possible to achieve efficient carbon reduction without any carbon pricing by merely subsidizing CCS:

Proposition 6.2. *Assume that the following conditions hold: (i) In the social planner model, the optimal solution yields $\lim_{t\to\infty} S(t) = 0$, i.e. all fossil resources are used under the carbon budget, (ii) the carbon budget is a binding constraint (i.e. $\mu_0^* > 0$), (iii) leakage is zero ($\delta_x = 0$) and (iv) the capture rate is 100 percent ($\theta = 1$). Then, a combined tax-subsidy policy with $\tau = \beta\mu^*$ and $\sigma = (1-\beta)\mu^*$ for any $\beta \in \mathbb{R}$ reproduces the (optimal) social planner outcome (with $\mu^* = \mu_0^* e^{rt}$ equal to Proposition 6.1 the shadow price of the carbon budget from the social planner model).*

Proof. See Appendix 6.A. □

Proposition 6.2 says that if fossil resources are scarce under a carbon budget, if there is no leakage and if there is perfect capture, a carbon price instrument – which reflects the scarcity of the atmospheric budget – can be replaced by CCS subsidies (set $\beta = 0$) or any combination of carbon taxes and CCS subsidies without sacrificing efficiency. As the subsidies on CCS increase the demand for fossil resources, they increase the associated scarcity rent λ. With an appropriate choice of the subsidy the resulting scarcity rent $\tilde{\lambda}$ can be equalised with the sum of the socially optimal shadow price for resources, λ^*, and the carbon price μ^* (see the proof in Appendix 6.A for details). In other words, the CCS subsidies create an implicit carbon price through the scarcity price of fossil resources which reduces resource demand to the socially optimal level.

In case of leakage or an imperfect capture rate the subsidy policy cannot be efficient as an additional carbon tax (for the emitted carbon) would be necessary. When the fossil resource base is so large that it is not exhausted in infinite time, the shadow price λ cannot be increased sufficiently to achieve an optimal extraction and capture path. In particular, for an undersized underground storage,[5] cumulative extraction has also to be lowered and $\lim_{t\to\infty} S(t) > 0$. In that case, CCS subsidies cannot replace a carbon tax.

Proposition 6.2 shows that infinitely many efficient tax-subsidy combinations are possible. Note that the CCS subsidy σ always increases exponentially in time at the discount rate r. Although these policies do not affect extraction and prices, it is easy to see that they influence discounted profits in the resource sector:

Corollary 6.1. *Under the assumptions of Proposition 6.2, the net present value of the resource rent is:*

$$\Pi = \int_0^\infty \Psi e^{-rt}\, dt + \mu_0^*(S_0 - B_0) - \beta \mu_0^* S_0 \tag{6.20}$$

with $\Psi := p(R_N + \alpha R_C) - g(S)R - \theta h(X) R_C$ *and* μ_0^* *the initial shadow price of the carbon budget from the social planner model.*

Proof. Setting $\theta = 1$ and $\delta_X = 0$ and substituting $\tau = \beta\mu_0^* e^{rt}$ and $\sigma = (1-\beta)\mu_0^* e^{rt}$ into the discounted profit (objective) function, we obtain $\int_0^\infty [\Psi e^{-rt} - \beta\mu_0^* R_N + (1-\beta)\mu_0^* R_C]\, dt$. Using $\lim_{t\to\infty} S(t) = 0$ together with (6.1–6.2), we obtain $\int_0^\infty R_C\, dt = S_0 - \int_0^\infty R_N\, dt = S_0 - (B_0 - \lim_{t\to\infty} B(t))$. As the carbon budget is binding and $\mu_0^* > 0$, it follows from (6.10) that $\lim_{t\to\infty} B(t) = 0$ which leads to (6.20). □

Therefore, without influencing efficiency, the rent of resource owners is affected by the policy choice β, i.e. to what extend carbon taxes and CCS subsidies are used. The lower β, the higher are the profits in the resource and sequestration sectors. In particular, a pure carbon tax policy ($\beta = 1$) gives lower discounted profits than a pure CCS subsidy policy ($\beta = 0$). Resource owners can thus receive an arbitrarily high non-distortionary lump-sum transfer.

The analysis above indicates that CCS subsidies can – under restrictive assumptions – be a first-best alternative to carbon pricing. However, such a CCS policy does only work if there is no leakage and storage capacities are high relative to the fossil resource base. Leakage or scarce storage capacities inhibit the existence of an efficient CCS policy. In

[5]This is the case if $X_0 < S_0 - B_0$ which follows directly from (6.1–6.3) if $\theta = 1$ and $\delta_X = 0$.

order to study the performance of CCS subsidies for less restrictive conditions, we use in the following a numerical general equilibrium model. We focus on the question whether well-designed CCS subsidies can reduce emissions at low efficiency costs if carbon taxes are not available or imperfect.

6.3 Numerical model: Analysis in PRIDE

The model PRIDE (Policy and Regulatory Instruments in a Decentralized Economy) is an intertemporal general equilibrium model with a generic top-down representation of different energy technologies. Its formulation as non-linear program and its implementation in GAMS (General Algebra Modeling System, Brooke et al. 2005) allows calculating welfare maximizing policies subject to environmental constraints (i.e. a mitigation target) or political constraints (i.e. restriction on carbon prices).

For the following numerical analysis we extend the PRIDE model described in Chapter 4 by an additional fossil energy sector that sequesters emissions from fossil fuel combustion, and a storage sector that transports and stores carbon underground. In contrast to the analytical model of the previous section, PRIDE allows to consider general equilibrium effects on the energy market and imperfect substitutability between different energy technologies. We model the government as Stackelberg leader that anticipates the reaction of the market economy on its policies. With this top-level optimization of the government, the welfare-maximizing potential of a variety of policy instruments ranging from carbon taxes to subsidies for renewable energy and CCS are studied. In particular, we will focus on cases where the conditions of Proposition 6.2 are violated due to leakage, imperfect carbon capture, imperfect substitutability between energy technologies, or due to an abundance of fossil resources.

6.3.1 The technological structure of PRIDE

The basic model equations are presented in Chapter 4; here, we restrict the explanation to a general description of the economic sectors and focus in more detail on the sectors affected by CCS. If not stated otherwise, the first-order conditions can be found in Chapter 4.B.

Final output sector

Fig. 6.1 gives an overview of the technological structure of the economy. Economic output Y is generated by energy E and a composite Z of capital K_Y and labor L. Energy is composed of conventional fossil energy E_F causing carbon emissions, carbon-neutral renewable energy

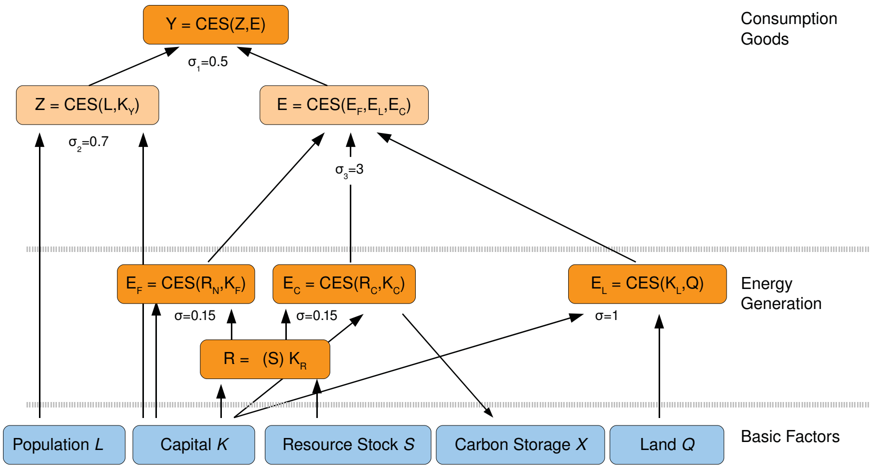


Figure 6.1: Production technology.

E_L, which exhibits learning-by-doing effects, and a CCS fossil energy technology E_C which sequesters carbon emissions. The constant-elasticity-to-scale (CES) production technology is described by:

$$Y(Z,E) = \left(a_1 Z^{\frac{\sigma_1 - 1}{\sigma_1}} + (1-a_1) E^{\frac{\sigma_1 - 1}{\sigma_1}} \right)^{\frac{\sigma_1}{\sigma_1 - 1}} \tag{6.21}$$

$$Z(K_Y,L) = \left(a_2 K_Y^{\frac{\sigma_2 - 1}{\sigma_2}} + (1-a_2)(A_Y L)^{\frac{\sigma_2 - 1}{\sigma_2}} \right)^{\frac{\sigma_2}{\sigma_2 - 1}} \tag{6.22}$$

$$E(E_F,E_L,E_C) = \left(a_3 E_F^{\frac{\sigma_3 - 1}{\sigma_3}} + b_3 E_L^{\frac{\sigma_3 - 1}{\sigma_3}} + c_3 E_C^{\frac{\sigma_3 - 1}{\sigma_3}} \right)^{\frac{\sigma_3}{\sigma_3 - 1}} \tag{6.23}$$

where σ are the respective elasticities of substitution, a_1,a_2,a_3,b_3,c_3 are share parameters and A_Y is an exogenously growing labor productivity factor. Population L grows exogenously. Due to the high aggregation level, we do not distinguish between different technologies within one of the three generic energy types. We also abstract from different uses of energy ranging from electricity generation, transportation, heating/cooling or industry processes. However, integrating the different energy technologies within one CES nest allows to study a wide range of substitution possibilities that captures to some extend the different properties in energy generation and usage (see Chapter 4 for a discussion on substitutability between energy technologies).

Firms in the production sector sell output, pay wages w for labor input, interest rates r for capital input and energy prices p_F, p_C, p_L for conventional fossil, CCS fossil and renewable energy, respectively. Additionally, subsidies for renewable energy τ_L and CCS fossil τ_C energy can be imposed by the government. By deriving the profit function $\pi_Y = Y(K_Y, L, E_F, E_L, E_C) - rK_Y - p_F E_F - (p_L - \tau_L)E_L - (p_C - \tau_C)E_C$ with respect to the inputs, we obtain the usual first-order conditions.

Conventional fossil energy sector

The conventional fossil energy sector uses capital K_F and fossil resources R_F for energy generation according to:

$$E_F(K_F, R_F) = \left(a_F K_F^{\frac{\sigma-1}{\sigma}} + (1-a_F) R_F^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{6.24}$$

Firms sell energy at the price p_F, rent capital at the interest rate r and purchase fossil resources at the price p_R. Additionally, the government may levy a carbon tax τ_R for fossil resources R_F that directly translate into carbon emissions. The profit function reads $\pi_F = p_F E_F(K_F, R) - rK_F - (p_R + \tau_R)R_F$.

CCS fossil energy sector

The basic fossil energy production technology (6.24) remains unchanged when capturing of carbon emissions for sequestration is added. However, due to the energy panelty and the need to install additional equipment (capital costs), productivity $A_C \leq 1$ is lowered and the relative factor inputs may change due to a_C:

$$E_C(K_C, R_C) = A_C \left(a_C K_C^{\frac{\sigma-1}{\sigma}} + (1-a_C) R_C^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{6.25}$$

In contrast to the conventional fossil energy sector, the CCS energy sector has to pay the transportation and storage price p_X per unit of captured carbon R_X. We assume that a fixed share $\theta \leq 1$ of carbon emissions is captured, i.e. $R_X = \theta R_C$. Thus, a carbon tax on non-captured emissions $(1-\theta)R_C$ applies. With the corresponding profit function $\pi_C = p_C E_C(K_C, R_C) - rK_C - p_R R_C - p_X \theta R_C - \tau_{R,t}(1-\theta)R_C$ the usual static first-order conditions result.

Fossil resource sector

Fossil resources $R = R_F + R_C$ that are used in both fossil energy sectors are extracted from a finite resource stock S with capital input K_R according to $R(S, K_R) = \kappa(S)K_R$. With ongoing depletion of S, more capital is needed to extract one unit of resources. We use a typical extraction cost curve (Rogner 1997; Nordhaus and Boyer 2000; Edenhofer et al. 2005) to describe the decrease of capital productivity $\kappa(S)$, implying increasing extraction costs $\kappa(S) = \chi_1 / \left(\chi_1 + \chi_2 \left(\frac{S_0 - S}{S_0}\right)^{\chi_3}\right)$. The profit function in the extraction sector reads $\pi_R = p_R R(S, K_R) - rK_R$ where additionally the depletion dynamics $S_{t+1} = S_t - R_t$ have to be considered.

Sequestration sector

The sequestration sector transports captured carbon R_X from the plant and stores it underground in storage X. As storage is limited, storage becomes essentially an exhaustible resource. Leakage R_L at the rate $\delta_X \geq 0$, however, increases the storage capacity and is taxed with the carbon price τ_R.[6] Similar to the fossil resource sector, storage costs $h(X)$ depend on the size of the remaining storage and decrease in X: Usually easily accessible storage sites are used first while sites with difficult access and monitoring or a long-distant location from the plant are used later. With the instantaneous profit function $\pi_X = (p_X - h(X))R_X - \tau_R R_L$, the intertemporal optimization problem reads:

$$\max_{R_{X,t}} \sum_{t=0}^{T} \pi_{X,t} \Pi_{s=0}^{t} \left[1 + (r_s - \delta)\right]^{-1}$$

subject to:

$$X_{t+1} = X_t - (R_{X,t} - R_{L,t}), \qquad X_t \geq 0, \qquad X_0 \text{ given} \tag{6.26}$$

$$R_{L,t} = \delta_X (X_0 - X_t) \tag{6.27}$$

$$h(X_t) = c_1 + c_2 \left(\frac{X_0 - X_t}{X_0}\right)^{c_3} \tag{6.28}$$

where X_0 is the (initial) size of the storage and δ denotes the capital depreciation rate which is subtracted from the marginal rate of capital productivity r to obtain the net discount rate. The first-order conditions are stated in Appendix 6.B.

Renewable energy sector

Renewable energy is generated from capital K_L and land Q; its generation costs decrease in cumulative output H. This learning-by-doing effect is modeled as a productivity increase $A_L(H)$, which is perfectly anticipated by the market economy (e.g. as if innovation spillovers were already internalized through a technology policy). In Chapter 4, we analyze how

[6] We consider the simplifying case of exponential leakage. A possible alternative is found in van der Zwaan and Gerlagh (2009), who develop a two-layer leakage model where leakage rates are non-constant.

spillovers or risk-premiums can lead to costly lock-ins into intertemporally inefficient low-carbon technologies. In order to concentrate on the efficiency cost of second-best policies for imperfect carbon pricing, we abstract from these additional market failures in the renewable energy sector.

By selling renewable energy at price p_L and renting capital at the interest rate r, the instantaneous profit function reads $\pi_L = p_L E_L(A_L(H), K_L, Q) - rK_L$. The production technology is Cobb-Douglas $E_L(A_L, K_L, Q) = A_L K_L^{\nu} Q^{\nu-1}$ with $A_L = \frac{A_{L,max}}{1+\left(\frac{\Omega}{H}\right)^{\gamma}}$ and $H_{t+1} = H_t + (E_{L,t} - E_{L,t-1})$. $A_{L,max}$ and Ω are scaling factors, γ is the learning exponent.

Household sector

The representative household maximizes intertemporal utilitarian social welfare $\sum_{t=0}^{T}(1+\rho)^{-t} L_t U\left(C_t/L_t\right)$ with the discount rate ρ and the CES-utility function in per-capita consumption $U(C/L) = (C/L)^{1-\eta}/(1-\eta)$. The household receives wages, capital income, the firms' profits $\pi = \sum_j \pi_j$ and (positive or negative) lump-sum government transfers Γ. It invests I in the aggregate capital stock $K = \sum K_j$. Thus, consumption is $C = wL + rK + \pi + \Gamma - I$ and the capital stock evolves at $K_{t+1} = (1-\delta)K_t + I_t$ with δ the depreciation rate. The government balances tax incomes and subsidy expenditures with the household's lump-sum tax according to $\Gamma = \tau_R(R_F + (1-\theta)R_C + R_L) - \tau_L E_L - \tau_C E_C$.

6.3.2 Atmospheric carbon emissions and the carbon budget

Emissions occur at several points in the economy: Conventional fossil energy firms emit R_F; in the CCS fossil energy sector, the non-captured share of fossil resources $(1-\theta)R_C$ is released into the atmosphere; and finally, carbon R_L leaks from the CCS storage. Total emissions amount to $Em = R_F + (1-\theta)R_C + R_L$. The government's mitigation target is formulated as cumulative constraint on emissions with $B_{t+1} = B_t - Em_t$ where $B_t \geq 0$ and $B(0) = B_0$ is the size of the carbon budget.

6.3.3 Implementation and policy assessment

We consider three types of equilibria: (i) the *social planner optimum* is obtained by maximizing the households utility subject to the technological constraints; (ii) the *laissez-faire market equilibrium* is defined as the solution of the system of equations describing technology, profits, budgets and the first-order conditions where all policies are set to zero (i.e. $\tau_R = \tau_L = \tau_C = 0$); (iii) the *optimal policy market equilibrium* is calculated from (ii) by additionally maximizing the household's utility over the policy variables (τ_R, τ_L, τ_C).[7]

Without a mitigation target (i.e. if $B_0 \geq S_0$) the laissez-faire economy equals the social optimum because there are no further market failures in the economy. Since no emissions are reduced, we also denote this case as the *business-as-usual* (BAU) scenario. When the mitigation target is considered and the government has all policy instruments available, the optimal policy market equilibrium equals the social optimum.[8]

We will focus on optimal second-best policies for fossil-CCS and renewable energy when the carbon tax variable τ_R is constrained. τ_L and τ_C are calculated to achieve the carbon budget at least costs. We evaluate the policies with respect to the laissez-faire (BAU) economy (without mitigation) and the social planner optimum under a mitigation target. Policies are evaluated according to their welfare change measured in balanced-growth equivalences (BGE) (Mirrlees and Stern 1972).

6.3.4 Calibration of the model

The parameters for the economy without CCS equal those in Chapter 4. We employ a moderate mitigation target by limiting cumulative emissions to 450 GtC. This corresponds roughly to a 50% probability of achieving the two-degree target. For the CCS technology added in this study, we reproduce typical estimations of costs and factor inputs available for CCS.

IPCC (2005, Tab. TS.3) estimates 11–40% more energy use to generate electricity under the CCS technology. If we set the share and productivity parameter to $a_C = 0.95$ and $A_C = 0.65$, we obtain a 20% higher fossil resource input for one unit of energy than for non-captured fossil energy ("energy penalty") and costs for fossil energy with carbon capture increase by roughly 2 ct/kWh. This lies in the range of the IPCC (2005, Tab. TS.3) estimation of 1.2–3.4 ct/kWh cost increase. We set $\theta = 0.9$ in our basic parameterization in line with the current ability of technologies to capture 85–95% of the emissions (IEA 2010, Tab. 10.2).

There is high uncertainty regarding the costs of carbon storage and transportation. In IPCC (2005, p. 260), costs for storage in depleted oil and gas fields as well as in saline formations range between 1 and 111 \$/tC. IEA (2010, p. 184) estimates transportation costs of 7–22 \$/tC per 100 km pipeline, IPCC (2005, p. 42) only 1–12 \$/tC per 100 km pipeline or shipping. We parameterize the CCS cost curve (Eq. 6.28) such that initial transportation

[7] This is done in GAMS (Brooke et al. 2005) as a non-linear program (NLP) using the CONOPT solver with the intertemporal first-order conditions as additional constraints.

[8] In this paper, there are no additional market failures beyond the mitigation target. Therefore, it is in line with Proposition 6.1 sufficient for the government to appropriately choose τ_R. No additional technology policies are needed.

and storage costs are 50 $/tC; they increase to 65 $/tC in 2100 when 710 GtC are stored in the social planner optimum. IPCC (2005, p. 197) estimates the size of geological storage in oil and gas fields between 184 GtC and 245 GtC, in unminable coal seems between 1 and 55 GtC, and in deep saline formations between 273 and 2,730 GtC.[9] In our basic parameterization, we chose a very large storage capacity of 3,500 GtC in order to avoid a hard constraint for CCS. Costs increase sharply if X approaches zero and in most of our model runs stored carbon does not exceed 1,500 GtC in 2100. Within geological formations IPCC (2005) finds it very likely that $\geq 99\%$ of stored carbon remains underground within 100 years (i.e. $\delta_X \leq 10^{-4}$) and likely that $\geq 99\%$ remains underground within 1,000 years (i.e. $\delta_X \leq 10^{-5}$). We assume a leakage rate of 0.01%. In the sensitivity analysis we vary this value as well as the storage capacity and the capture rate.

6.4 CCS policies if carbon pricing is imperfect

In the following we analyze the performance of second-best technology policies for CCS and renewable energy if carbon prices are imperfect. The basic idea of using second-best technology policies is to increase the relative price of emission-intensive technologies compared to low-carbon technologies. While carbon pricing provides a direct measure for this objective, subsidizing low-carbon technologies has an indirect effect on the relative price between low-carbon and carbon-intensive technologies: if energy from low-carbon technology becomes sufficiently cheap through subsidies, energy consumers will switch to the latter and, hence, cause less emissions.

In the first subsection, we consider the case when carbon prices are too low to achieve the mitigation target. This is motivated by the observation that international or domestic compensation for the distributional effects of high carbon taxes is difficult to implement. The international community therefore may only agree on suboptimally low harmonized carbon taxes and a financing mechanism for additional technology policies. In the second subsection, we assume that the introduction of carbon prices is delayed substantially because no agreement can be achieved in the near future. Once scientific knowledge or social perception about climate damages may change, first impacts of global warming become visible or global coordination between nation states has been improved, the optimal tax can be implemented in the future. We therefore analyze how far technology policies can substi-

[9]Besides geological storage, there is also the possibility to store carbon in the oceans or in solid carbonates after accelerated mineral carbonation. The storage capacity of the oceans is practically unlimited. However, there are high uncertainties about the impacts for marine ecosystems and the permanency of storage. Mineral carbonation offers also a practically infinity large sink. However, both costs and land consumption from mining and disposal are high (IPCC 2005, Ch. 6–7).

tute temporarily missing carbon prices. Although our main focus lies on CCS subsidies, we will also discuss their performance relative to renewable energy subsidies being a popular second-best policy option (Chapter 5).

6.4.1 Second-best policies for suboptimally low carbon prices

In our first analysis, we calculate optimal second-best policies if carbon taxes τ_R are set to a fixed fraction $0 \leq \vartheta < 1$ of the socially optimal carbon tax τ_R^*. This tax is obtained from the shadow price of the social planner optimum or directly from the optimal policy market equilibrium when τ_R is unconstrained. The optimal carbon tax τ_R^* limits cumulative emissions efficiently to the carbon budget constraint. Subsidies on CCS or renewable energy are not needed in this case. However, if a suboptimal tax $\tau_R = \vartheta\tau_R^*$ is implemented, the carbon budget is violated – unless further instruments are used to reduce emissions. For this case, we consider three second-best policies:

`CCS` a pure CCS technology policy τ_C that limits emissions by subsidizing CCS; renewable energy subsidies τ_L are set to zero. Thus, the policy space is constrained to $\{\tau_R = \vartheta\tau_R^*, \tau_L = 0, \tau_C \in \mathbb{R}\}$

`REN` a pure renewable energy policy that limits emissions by subsidizing renewable energy; CCS subsidies are zero and the policy space is $\{\tau_R = \vartheta\tau_R^*, \tau_L \in \mathbb{R}, \tau_C = 0\}$

`CCS+REN` a hybrid CCS and renewable energy policy that limits emissions by subsidizing CCS and renewable energy, i.e. $\{\tau_R = \vartheta\tau_R^*, \tau_L \in \mathbb{R}, \tau_C \in \mathbb{R}\}$

The optimal time paths of the policies are calculated for several values of ϑ and evaluated with respect to their welfare losses compared to the optimal carbon pricing policy ($\vartheta = 1$) and the business-as-usual (no mitigation) case.

The effect of technology policies on welfare and emissions Fig. 6.2a shows the performance of the second best policies compared to the optimal carbon pricing policy. Where data points are missing, no feasible solution was found.[10] The lower ϑ, the higher are the welfare losses of the technology policies because it becomes more and more difficult to reduce emissions at low carbon prices. In particular, for $\vartheta < 0.5$ costs become substantial. If the carbon price is lower than 20% of the optimal carbon price, the pure CCS policy is

[10] In principle, this may just be a failure of the numerical solver and a solution (although difficult to find) may exist nevertheless. Due to our stepwise reduction of ϑ in 0.01 intervalls and the use of successful solutions as starting point for the next calculation, we judge it very unlikely that a feasible solution, particularly one that is similar to the last successful solution, exists.

even infeasible, due to the imperfect capture rate $\theta = 0.9$. While the 'pure' policies begin to become prohibitively expensive or infeasible for carbon prices below 20% of the optimal level, a hybrid technology policy achieves the mitigation target at an additional welfare costs of only 3% even if carbon prices are missing.

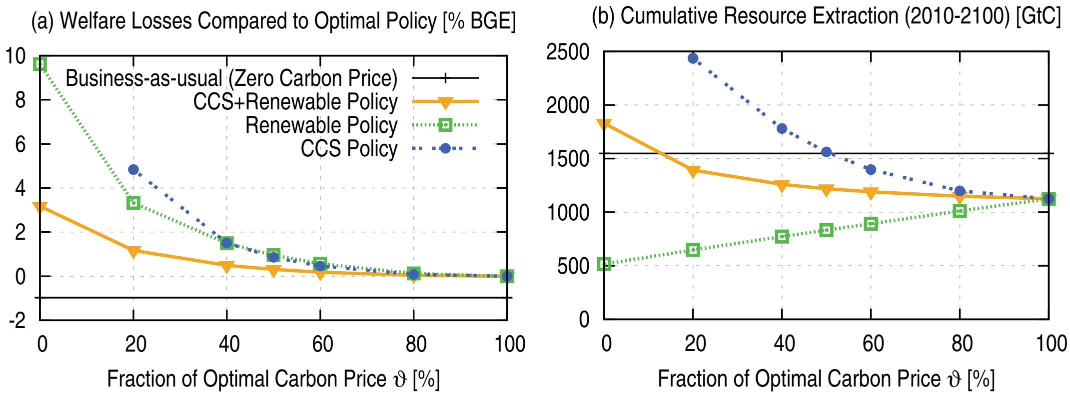


Figure 6.2: (a) Welfare losses (in balanced-growth equivalents) of optimal second-best policies compared to the social optimum ($\vartheta = 100\%$) under a carbon budget. The negative welfare losses of the laissez-faire (business-as-usual) economy indicate the mitigation costs due to the carbon budget constraint. (b) Impact on cumulative fossil resource extraction within the time span 2010–2100.

Although a pure CCS policy and a pure renewable energy policy provoke similar welfare losses for $\vartheta \geq 0.4$, they lead to completely different fossil resource extraction (Fig. 6.2b): The renewable energy policy increases the relative price of all fossil-resource based technologies compared to the price of renewable energy technologies and therefore reduces fossil resource demand. In contrast, the pure CCS policy induces a relative price advantage for CCS energy compared to conventional fossil and renewable energy. Consequently, CCS is scaled up enormously and fossil resource extraction increases with lower ϑ. If carbon prices fall below 50% of the optimal carbon price, fossil resource extraction exceeds the business-as-usual scenario extraction.

The supply-side dynamics of technology policies Proposition 6.2 relied on the fact that subsidies on CCS can increase the demand for fossil resources, which produces a scarcity rent and thereby creates an implicit carbon price that reduces emissions. This policy was even an efficient first-best policy under restrictive conditions. By displaying the components of the resource price, Fig. 6.3a confirms that CCS subsidies have a similar effect in a second-best setting: At the optimal carbon tax ($\vartheta = 1$), the tax dominates the net resource price. As the tax is reduced, CCS subsidies cause more extraction. Extraction costs and scarcity rents increase and almost compensate the decreasing carbon tax. Hence, increasing scarcity rents and extraction costs constitute an implicit carbon price for conventional fossil energy firms. Contrary, a pure renewable energy subsidy decreases the scarcity component of the resource price (Fig. 6.3b). As cheap renewable energy forces the fossil resource price to decrease, increasingly high subsidies are needed to maintain a large price differential between conventional fossil and renewable energy (see Chapter 5 for a detailed discussion on this aspect of renewable energy subsidies).

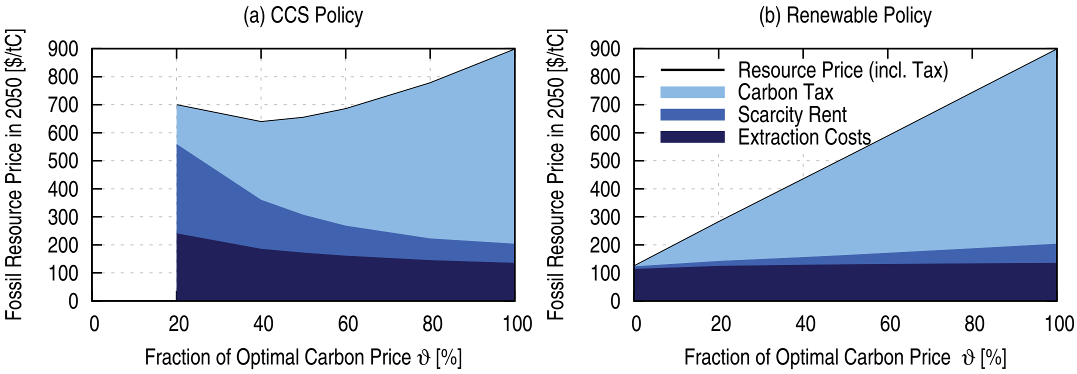


Figure 6.3: Snapshot of fossil resource prices and their components in 2050 for imperfect carbon prices under (a) a pure CCS policy and (b) a pure renewable energy policy.

The different supply-side dynamics translate directly to the level of the fossil resource rent: As CCS policies increase fossil resource demand, fossil resource rents increase drastically for lower ϑ (Fig. 6.4a). The introduction of the optimal carbon price reduces fossil resource rents by roughly one third compared to the business-as-usual economy. This impact on the fossil resource rent may constitute one important obstacle for implementing a globally harmonized carbon price. However, if carbon taxes are reduced sufficiently and complemented by CCS subsidies, fossil resource rents can even be higher than in the business-as-usual economy. While this also applies for the hybrid CCS and renewable energy policy with zero carbon prices, a pure renewable energy subsidy policy decreases fossil rents even further. The reason is that renewable energy subsidies do not only decrease conventional fossil energy deployment but also fossil energy with CCS, implying less fossil resource extraction as in the social optimum (see also Fig. 6.2b). This contrasts our previous findings in a model without CCS technology, where a pure renewable energy policy hardly affected fossil resource rents as cumulative extraction is of the same magnitude as under the optimal carbon pricing policy (Chapter 5).

With respect to renewable energy generation, Fig. 6.4b indicates that all policies lead to higher renewable energy deployment than in the BAU economy. Except for the pure CCS policy under low carbon prices ($\vartheta < 0.4$), pure CCS policies lead to even higher renewable energy deployment than under an optimal carbon price. The reason is once more the supply-

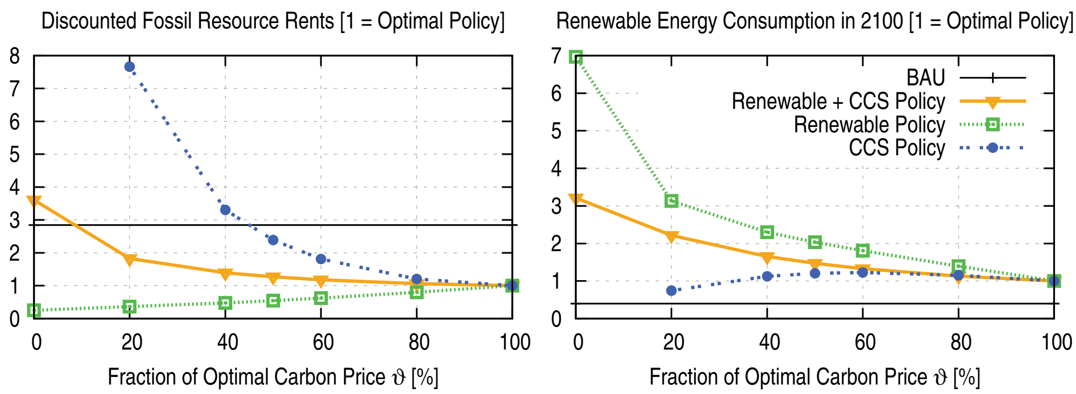


Figure 6.4: Impact of technology policies on (a) discounted fossil resource rents and (b) renewable energy production in 2100. For the optimal carbon pricing policy, discounted fossil resource rents amount to 0.34% of GDP.

side dynamics: As CCS subsidies increase fossil resource prices they also decrease the relative price of renewable energy compared to fossil energy.

The time-path of technology policies How do second-best technology policies evolve over time? Fig. 6.5 shows the trajectory of optimal CCS and renewable energy policies for $\vartheta \in \{0, 0.2, 0.4\}$. While the efficient CCS subsidy in Proposition 6.2 in the analytical model increases exponentially, the second-best CCS subsidies are inverted U-shaped: After an initial increase for several decades, subsidies decline and even turn into taxes in the long run to prevent high leakage. Although CCS is taxed in the long-run, extraction costs and fossil resource prices have become so high due to the early extraction boom that conventional fossil energy generation remains sufficiently low. The taxes on CCS provide now an additional price advantage for renewable energy deployment.

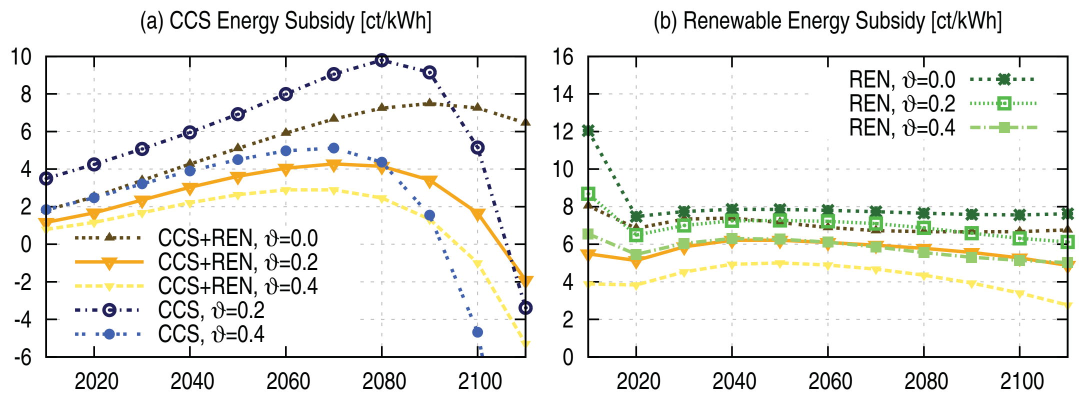


Figure 6.5: (a) Optimal CCS subsidy and (b) optimal renewable energy subsidy for selected policy scenarios.

In contrast to the CCS subsidies, renewable energy subsidies remain on a more or less stable level after an initially high support phase to exploit the learning-by-doing effect. Both figures show that in the hybrid policy case, the subsidy level for each technology is lower than under a pure CCS or renewable energy policy.

Impact on energy prices Besides reducing fossil resource rents, carbon taxes also increase energy prices and thereby induce further pressure of voters and energy-intensive industries on regulators. Fig. 6.6 shows how different policies change the energy price relative to the business-as-usual economy. Energy from different technologies are good but imperfect substitutes; we calculate an average energy price by: $\tilde{p}_E = (p_F E_F + (p_L - \tau_L)E_L + (p_C - \tau_C)E_C)/E$. As all second-best policies subsidize energy, they lead to substantially lower energy prices by 2050. Although initially lower, the pure CCS policy leads to higher energy prices in the very long run because fossil resources become more expensive due to their early exploitation.

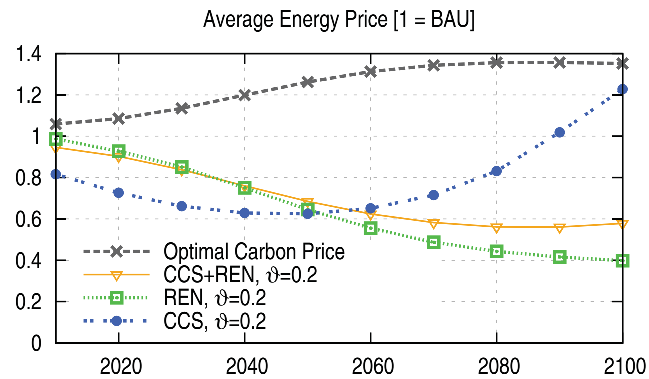


Figure 6.6: Impact of the optimal carbon prices and second-best policies with 20% of the optimal carbon price on energy prices.

6.4.2 Second-best policies for delayed carbon pricing

So far we analyzed the capability of technology policies to reduce emissions if carbon prices are permanently low or missing. In this section, we relax this permanence condition and focus on a delayed-carbon pricing scenario.

For the policy analysis, we set carbon taxes τ_R to zero for $t < T^*$. For $t > T^*$, the government sets an optimal carbon tax. Fig. 6.7 shows the welfare costs of delaying the introduction of carbon pricing to the year $T^* \in [2010, 2160]$ for several policy scenarios. First, a no CCS/renewable energy policy scenario is considered that is only feasible up to a delay until 2050. Without the use of further instruments, delaying the introduction of carbon

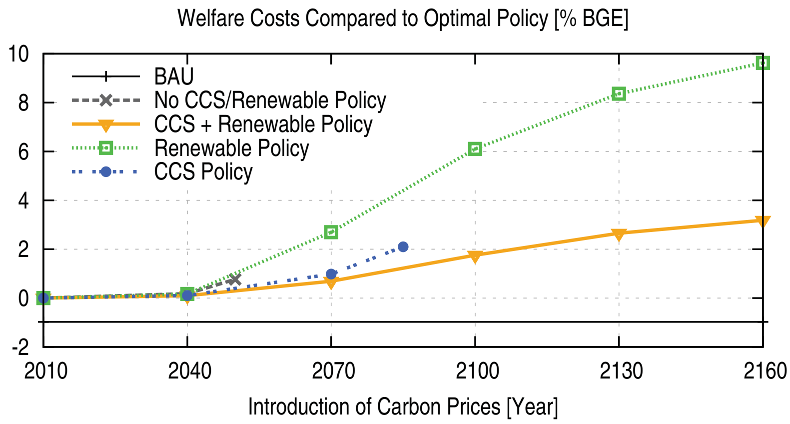


Figure 6.7: Welfare losses of delayed carbon pricing policies. The right-sided end of trajectories corresponds to the feasibility frontier with respect to delaying carbon pricing. Note that the x-axis denotes the year when a carbon price is introduced.

prices beyond 2050 leads to a violation of the carbon budget. Second, if CCS subsidies are available before the introduction of carbon prices, the critical value of T^* can be postponed until 2085. In this case, additional welfare costs due to the delayed carbon price increase up to 2%. Third, if renewable energy subsidies are available, the carbon pricing can be delayed arbitrarily. The pure renewable energy subsidy causes approximately twice the welfare losses of the CCS policy. If carbon prices are introduced before 2070, adding renewable energy subsidies to the pure CCS policy brings only marginal welfare gains. If carbon pricing is introduced far later than 2070, a combination of CCS and renewable energy subsidies is clearly the cheapest second-best policy.

6.5 Sensitivity analysis

6.5.1 Sensitivity of key parameters

Many uncertainties exist with respect to our chosen parameterization: CCS is still a relatively new technology with little experience, and capture rates θ, leakage rates δ_X and underground storage capacity X_0 are uncertain. The substitutability σ_3 between the three generic energy technologies is also difficult to measure directly and might change with further innovations and the invention of new technologies. Further, the stringency of the mitigation target B_0 is difficult to predict because there are scientific uncertainties regarding the climate system and the magnitude of climate damages as well as political uncertainties regarding the international negotiations for a harmonized mitigation policy. Finally, the size of exploitable fossil resources S_0 in the ground is speculative: BGR (2010) quantifies the size of proven oil, gas and coal reserves with 856 GtC (both, conventional and unconventional). There are further 2,064 GtC oil and gas and 12,417 GtC coal resources estimated where technical feasibility, extraction costs and the magnitude of extractable carbon is speculative.[11]

We vary the parameters θ, δ_X, X_0, σ_3, B_0 and S_0 and calculate the mitigation costs (welfare losses of the optimal carbon pricing policy) as well as the pure and combined CCS and renewable energy policies. As the pure CCS policy is already infeasible in our standard parameter setting, we also consider a delayed carbon pricing policy with $T^* = 2070$. Hence, we compare the CCS policy (CCS_60) with the renewable energy policy (REN_60) if carbon pricing is delayed by six decades. We summarize the main insights of the parameter sensitivity analysis and focus in more detail on the size of fossil resources in the ground (Tab. 6.1). The results for the other parameter variations are listed in Tab. 6.3 in Appendix 6.D.

Before discussing the relative performance of instruments, we examine the mere feasibility of CCS policies for achieving the mitigation target. The sensitivity analysis indicates that pure long-term CCS policies are feasible if the capture rate θ is sufficiently high, the carbon budget B_0 not too ambitious or fossil resources sufficiently scarce (Tab. 6.1 and Tab. 6.3). The temporary CCS policy is always feasible except for the case of high leakage rates. In contrast to CCS policies, renewable energy policies are always feasible.

Regarding the costs of second-best policies, we find that CCS policies – where feasible – are in most cases cheaper than renewable energy policies. An exception is when the storage capacity is low, or when fossil resources are abundant and renewable energy generation costs is low. Complementing the pure renewable energy subsidy by a CCS policy leads to substantial welfare gains. Only when leakage is very high, an additional CCS policy hardly improves the renewable energy policy. Finally, while the pure renewable energy policy is fairly insensitive to the capture rate and the underground storage capacity, CCS policies perform best for high capture rates, low leakage rates and high storage capacity. A higher resource base and a more ambitious carbon budget increase the second-best costs of both CCS and renewable energy policies remarkably.

With respect to the resource base S_0 (Tab. 6.1), our calculations suggest a somewhat paradoxical conclusion: When (cheap) fossil resources are scarce, subsidizing CCS is, assuming normal renewable energy costs, a far cheaper second-best policy than subsidizing renewable energy. Although the economy's fossil resource use peaks within the 21st cen-

[11] The uncertainties about CCS storage costs and fossil resource extraction costs are already reflected in the parameter variations of X_0 and S_0, respectively. Due to the functional form of (6.28) and the extraction cost curve, reductions of X_0 and S_0 imply stronger costs increases if X and S decrease.

Resource Base S_0 [GtC]	2,000	3,000	4,000*	6,000	10,000	15,000
Normal renewable energy costs (9 ct/kWh after learning; $A_{L,max} = 0.60$*)*						
Mitigation costs [%]	0.48	0.77	0.97	1.21	1.44	1.56
2nd-best costs (CCS+REN) [%]	0.40	1.25	3.18	4.77	6.56	7.37
2nd-best costs (CCS_60) [%]	0.34	0.69	0.98	1.42	1.91	2.16
2nd-best costs (REN_60) [%]	1.07	2.12	2.69	3.20	3.51	3.61
2nd-best costs (CCS) [%]	0.40	1.26				
2nd-best costs (REN) [%]	6.03	8.47	9.62	10.57	11.11	11.29
Low renewable energy costs (6 ct/kWh after learning; $A_{L,max} = 0.85$*)*						
Mitigation costs [%]	0.26	0.47	0.61	0.80	0.98	1.07
2nd-best costs (CCS+REN) [%]	0.36	1.10	2.07	3.01	3.90	4.24
2nd-best costs (CCS_60) [%]	0.21	0.52	0.80	1.20	1.63	1.86
2nd-best costs (REN_60) [%]	0.35	0.85	1.15	1.43	1.59	1.65
2nd-best costs (CCS) [%]	0.36	1.10				
2nd-best costs (REN) [%]	2.83	4.20	4.86	5.42	5.74	5.84

Table 6.1: Mitigation costs (welfare losses of the optimal carbon pricing policy relative to the BAU scenario) and additional second best costs (welfare losses relative to the optimal carbon pricing policy) for different fossil resource bases in balanced-growth equivalents. The asterisk is assigned to the value used for the standard parameterization. Blank entries denote infeasibilities, i.e. the policy instrument cannot achieve the mitigation target. CCS_60 denotes the CCS policy if carbon pricing is delayed by 60 years; REN_60 the corresponding renewable energy policy, if carbon pricing is introduced in 2070.

tury in the laissez-faire (BAU) economy and renewable energy dominates in the 22nd century, subsidizing renewable energy instead of CCS causes substantial welfare losses. The explanation for this outcome is again rooted in the supply-side dynamics: A pure renewable energy subsidy has to be very high to reduce fossil resource extraction. In contrast, a moderate CCS subsidy does not only encourage capturing of carbon emissions, it also encourages fossil resource exploitation. This accelerated depletion increases extraction costs and scarcity rents, making renewable energy attractive without renewable energy subsidies. Hence, a CCS policy can be a cheaper way to accelerate the energy transition to renewable energy.

For our standard parameterization of renewable energy costs, the CCS_60 policy outperforms the REN_60 policy even if the resource base is very large. In this case, the CCS policy cannot provoke a substantial increase in fossil resource prices through a stimulated demand. Whether the CCS or renewable energy policy is cheaper, depends then on the technological costs of energy generation: If future costs of renewable energy generation are low, they can replace temporary missing carbon prices at lower costs (Tab. 6.1).

Fig. 6.8a addresses the fossil resource rents as an indicator for political feasibility. As suggested by Corollary 6.1, it shows that temporary CCS policies can diminish rent losses without increasing total mitigation costs substantially. However, a pure CCS policy – if

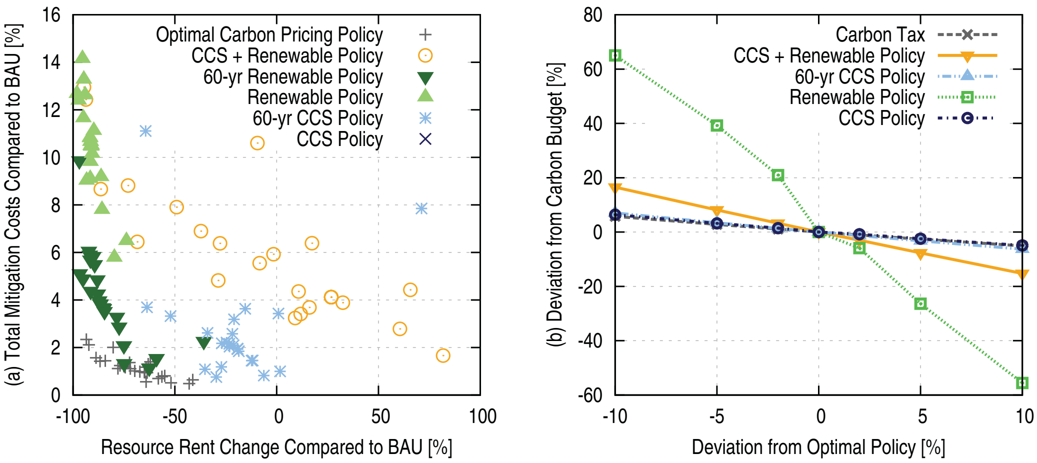


Figure 6.8: (a) Correlation between resource rent change and mitigation costs under all parameter variations shown in Tab. 6.1 and Tab. 6.3. The data points for the pure CCS subsidy policy are excluded as they lie far outside the other data points. (b) Change in emissions if the policy instrument is changed around its optimal value. As the pure CCS subsidy is not feasible under the standard parameterization, we set the resource base at $S_0 = 3000$ for the CCS subsidy analysis.

feasible – overcompensates fossil resource owners by increasing rents by a multitude (data points beyond the range of Fig. 6.8a). In contrast, most renewable energy policies decrease fossil resource rents below the optimal carbon pricing policy at high welfare losses.

6.5.2 Sensitivity of policies

So far, we studied how different parameter changes influence the performance of policies. In the following, we focus on the sensitivity of policy instruments with respect to emission reductions and welfare. Policy-makers do not have perfect information about all economic parameters and technologies and the political implementation process is an outcome of a complex interplay of interests. Thus, taxes or subsidies will likely deviate from the optimal value.

For Fig. 6.8b, we first changed each of the labeled policy instrument by 2, 5 and 10 percent (in each time step) compared to the respective optimal value. We then implemented these policies in the laissez-faire economy and displayed the change in cumulative emissions. As intuition suggests, lower carbon taxes and lower subsidies for low-carbon technologies lead to higher emissions. However, in line with our findings in Chapter 5, cumulative emissions react highly sensitive to a pure renewable energy policy: If subsidies are only two percent lower than their optimal value, carbon emissions increase by 18 percent. In contrast to renewable energy policies, the sensitivity of carbon pricing and CCS policies is very low and hardly distinguishable. The high sensitivity for renewable energy subsidies is due to the learning-by-doing dynamics: if subsidies are too low, learning-by-doing is slowed down, which leads to additionally cost increases for renewable energy (and *vice versa* if subsidies are too high). Hence, the impact on the energy mix is amplified in both directions.

6.6 Conclusions

It is questionable whether the world's governments will agree on a substantial global price on carbon in the next decades. As a response to this global policy failure, second-best technology policies for reducing carbon emissions become an important alternative. Our model analysis suggests that short-term policies promoting carbon capture and storage could play a key role for transforming the energy system. Due to the supply-side dynamics of fossil resource extraction, subsidies for CCS can accelerate the transformation to a carbon-free economy at lower cost than renewable energy policies – assuming favorable geological and technical conditions. As CCS subsidies increase the demand for fossil resources they lead to higher fossil resource prices. Thus, an implicit price on carbon is created that co-benefits renewable energy deployment. As a result, renewable energy deployment can be even higher than under an (efficient) first-best carbon pricing policy. In contrast, a pure renewable energy policy decreases fossil resource prices by reducing the demand. Consequently, they act as an implicit small subsidy on carbon, making high renewable energy subsidies necessary to crowd out fossil energy.

An at first glance paradoxical conclusion is that the comparative cost advantage of CCS policies over renewable energy policies is greater the scarcer fossil resources are. Although the future belongs to the 'renewables' and renewable energy might be a cheaper *technology* than CCS, a temporary CCS subsidy could be the cheaper *policy* to transform the energy sector when carbon prices are missing. In particular, if fossil resources are sufficiently scarce and leakage is low, a permanent CCS policy can achieve the mitigation target without any additional carbon price or renewable energy subsidy. Furthermore, second-best costs of CCS policies are lower (i) the better carbon can be captured in power plants, (ii) the lower carbon leakage is, and (iii) the higher the underground storage capacity is. For the limiting case of zero leakage and 100% carbon capture of carbon emitting sources, a permanent CCS policy can even be as efficient as a carbon pricing policy (Proposition 6.2). If, in contrast, fossil resources are abundant and renewable energy costs low, renewable energy subsidies outperform CCS subsidies.

While renewable energy policies are always a feasible (but often more expensive) second-best policy in case of missing carbon prices, CCS policies cannot always guarantee to achieve ambitious mitigation targets: underground storage capacity, capture rates and the politically targeted carbon budget have to be sufficiently high and carbon leakage sufficiently low. If the introduction of carbon is delayed, CCS subsidies can replace carbon pricing for a certain time span, but become more difficult and even infeasible for very long time horizons. CCS policies are therefore an attractive short-term option to buy time until the international community agreed on a carbon price. Due to the feasibility constraints, a long-term CCS policy, however, may also be a risky policy.

CCS and renewable energy subsidies differ in their impact on fossil resource rents: As CCS policies increase fossil resource extraction and, thus, fossil resource prices, they lead to higher energy prices in the long run. In contrast, renewable energy subsidies decrease energy prices substantially below the business-as-usual price. This benefits energy-intensive industries and possibly also low-income-households which could increase the political support for this policy. With respect to fossil resource rents, CCS policies mitigate the rent losses associated with climate policy and can even over-compensate fossil resource owners at moderate additional costs.

Although there is no global government to implement these policies, international negotiations about emission reductions could use these insights when focusing on technology protocols and technology financing mechanisms. The cost mark-ups for CCS in developing countries could be paid by OECD countries. This establishes a no-regret option for developing countries, allowing them to extend their energy system in an almost business-as-usual way without substantial additional costs. If a critical mass of countries adopts CCS policies, the increasing fossil resource prices could also lead to lower emissions in countries not participating.

There are, of course, several limitations of our model that raise further important questions. First, we do not explicitly differentiate between coal, gas and oil, the latter being practically not suitable for CCS. The imperfect substitutability between conventional fossil energy and CCS fossil energy as well as the imperfect carbon capture rate consider this to a certain extent. Nevertheless, there might be additional second-best policies required for the transportation sector if carbon pricing is not implemented. Secondly, increasing fossil resource prices due to CCS policies could increase exploration activities leading *ceteris paribus* to lower scarcity rent increases. This effect could be integrated in a modified formulation of the extraction cost curve (by including exploration costs) and the initial resource base (by including estimations about fossil resources). We paid tribute to this consideration partly in our sensitivity analysis with respect to the resource base. Fossil resource price increases might also have adverse effects on deforestation and food prices due to the expansion of energy crop cultivation. Thirdly, (temporary) CCS policies conserve or even strengthen the existing fossil-fuel based industrial metabolism. While this eases political implementation in the short-term, it could impede the delayed transformation to renewable energy. In particular, if fossil resources turn out not to be scarce (and the implicit carbon tax effect of CCS subsidies is low), there is low economic pressure to invest into renewable energy. As underground carbon storage fills up and fossil resource prices are continuously low, additional political measures are necessary to decarbonize the energy system. However, when large investments into fossil capital have been already undertaken, introducing carbon prices or renewable energy subsidies might become even more difficult. Finally, there has to be a proper management of CCS storage sites, including an effective monitoring system which detects leakage as well as an appropriate design regarding the long-term liability for leakage and the sharing of environmental risks between firms and the public (Held and Edenhofer 2009; IPCC 2005). Underground storage is a further scarce exhaustible resource requiring well-defined and secure property rights for an efficient intertemporal allocation. This could, in particular, become crucial if scarce storage has to be used for capturing emissions from combustion of biomass. As this technology can create negative net emissions, the remaining storage capacity might become highly valuable in the future. Our model calculations suggest that CCS policies could increase the scarcity rent associated with limited storage capacity up to 0.5% of the total GDP. If there are no auctions or fees for use concessions of underground storage, this scarcity rent is transferred implicitly to CCS operators.

Beside these limitations, our findings suggest an important conclusion: Pure CCS as well as pure renewable energy policies aiming to replace a permanently missing carbon price are not a pragmatic policy approach. Both, CCS and renewable energy policies carry specific risks of failure: CCS policies rely on favorable physical and technological conditions; renewable energy policies are costly and lead to a highly sensitive outcome in emissions that undermines environmental effectiveness. A smart combination of both policies, however, might be a robust second-best strategy. Such a hybrid policy would initially push CCS to increase fossil resource prices in a sustained way. With ongoing depletion, extraction costs and scarcity rents increase. This makes lower CCS subsidies necessary and even turns the optimal CCS subsidy into a tax in the long run. As fossil resource prices continue to increase, renewable energy – permanently backed by moderate subsidies – becomes more and more the dominant low-carbon technology. The second best-costs of this hybrid policy approach and its risks decrease further in case carbon pricing can be introduced eventually in the future.

6.A Proof of Proposition 6.2

With the policy $\tau = \beta\mu^*$ and $\sigma = (1-\beta)\mu^*$, the first-order conditions (6.14–6.15) read:

$$\alpha p - g(S) - \theta h(X) - \lambda - (1-\theta)\beta\mu^* + (1-\beta)\mu^* - \theta\psi \leq 0 \qquad (= 0 \text{ if } R_C > 0)$$
$$p - g(S) - \lambda - \beta\mu^* \leq 0 \qquad (= 0 \text{ if } R_N > 0)$$

Using the transformation $\tilde{\lambda} := \lambda - (1-\beta)\mu^*$ we can rewrite the first-order conditions to:

$$\alpha p - g(S) - \theta h(X) - \tilde{\lambda} - (1-\theta)\beta\mu^* - \theta\psi \leq 0 \;\; (= 0 \text{ if } R_C > 0) \tag{6.29}$$
$$p - g(S) - \tilde{\lambda} - \mu^* \leq 0 \;\; (= 0 \text{ if } R_N > 0) \tag{6.30}$$

Furthermore, substiting the transformation for $\tilde{\lambda}$ and $\dot{\lambda} = \dot{\tilde{\lambda}} + (1-\beta)\dot{\mu}^*$ into (6.16) and using the fact that $\dot{\mu}^* = r\mu^*$ from (6.7), we obtain:

$$\dot{\tilde{\lambda}} = r\tilde{\lambda} + g'(S)R \tag{6.31}$$

Finally, the transversality condition for λ reads:

$$0 = \lim_{t\to\infty} S(t)\lambda(t)e^{-rt} = \lim_{t\to\infty} S(t)(\tilde{\lambda}(t) + (1-\beta)\mu^*(t))e^{-rt} \tag{6.32}$$
$$= \lim_{t\to\infty} S(t)\tilde{\lambda}(t)e^{-rt} + \lim_{t\to\infty}(1-\beta)\mu_0^* S(t) \tag{6.33}$$

The first-order conditions (6.30) and (6.31) now equal those of the social planner system (6.5–6.6). The equation of motion for ψ (6.17) is only equal to the corresponding social-planner condition (6.8) if $\delta_X = 0$. It becomes apparent that the first-order condition (6.29) of the decentralized economy equals that of the social planner system (6.5) if $(1-\theta)\beta = (1-\theta)$. The latter condition implies that either $\theta = 1$ (and $\beta \in \mathbb{R}$) or that $\beta = 1$ if $\theta \neq 1$. Finally, the transversality condition (6.33) equals the social planner condition (6.9) if $\lim_{t\to\infty} S(t) = 0$. If $\lim_{t\to\infty} S(t) > 0$, the transversality condition of the decentralized resource sector and the social planner differ and the policy cannot achieve the social optimum (as $\mu_0^* > 0$). □

6.B First-order conditions of the CCS sector

Maximizing the associated Lagrangian with λ_X as co-state variable for X, we obtain as dynamic first-order conditions:

$$\lambda_{X,t} = p_{X,t} - h(X_t) \tag{6.34}$$

$$\lambda_{X,t-1}(1+(r_t-\delta)) - \lambda_{X,t} = -\left(\frac{\partial h(X_t)}{\partial X_t} R_{X,t} + \delta_X \tau_R\right) \tag{6.35}$$

$$\lambda_{X,t} X_{t+1} = 0 \tag{6.36}$$

6.C Parameters

Symbol	Parameter	Value
ρ	pure time preference rate of household	0.03
η	elasticity of intertemporal substitution	1
δ	capital depreciation rate	0.03
L_{max}	population maximum (bill. people)	9.5
f	population growth parameter	0.04
a_1	share parameter in final good production	0.95
σ_1	elasticity of substitution energy–intermediate	0.5
b_2	share parameter in intermediate production	0.7
σ_2	elasticity of substitution labor–capital	0.7
a_3, b_3, c_3	share parameter (energy usage)	1
σ_3	elasticity of substitution energy types	3
a_F	share parameter in fossil energy generation	0.8
σ	elasticity of substitution fuel–capital	0.15
a_C	share parameter in fossil energy generation	0.95
A_C	productivity factor	0.65
θ	capture rate	0.9
χ_1	scaling parameter	20
χ_2	scaling parameter	700
χ_3	slope of extraction curve	2
c_1	scaling parameter (10^4\$/tC)	0.05
c_2	scaling parameter (10^4\$/tC)	0.45
c_3	slope of storage and transportation cost curve	2
δ_X	leakage rate	10^{-4}
ν	share parameter learning carbon-free energy generation	0.95
$A_{L,max}$	maximum productivity learning carbon-free energy	0.6
Ω	scaling parameter	200
γ	learning exponent	0.27
Q	land	1
K_0	Initial total capital stock (trill. US$)	165
S_0	Initial stock of fossil resources (GtC)	4000
S_0	Underground carbon storage capacity (GtC)	3500
B_0	Carbon budget (GtC)	450
H_0	Initial experience stock renewable energy	0.2
L_0	Initial population (bill. people)	6.5
$A_{Y,0}$	Initial productivity level	6
T	time horizon (in years)	150

Table 6.2: Parameters used for the numerical model.

Population L grows exogenously from L_0 to L_{max} according to $L_t = L_0(1-q_t) + q_t L^{max}$ with $q_t = 1 - \exp(-ft)$. Labor productivity A_Y grows exogenously at the variable rate $[1 - g_0 \exp(-\zeta t)]^{-1} - 1$ implying for $g_0 = 0.026$ and $\zeta = 0.006$ an initial growth rate of 2.7% which decreases to 1.5% in 2100.

6.D Sensitivity analysis

Capture rate θ	0.8	0.85	0.9*	0.95	1
Mitigation costs [%]	1.24	1.11	0.97	0.81	0.64
2nd-best costs (CCS+REN) [%]	5.73	4.49	3.18	1.99	1.03
2nd-best costs (CCS_60) [%]	2.42	1.48	0.98	0.65	0.36
2nd-best costs (REN_60) [%]	2.77	2.75	2.69	2.50	1.64
2nd-best costs (CCS) [%]					2.18
2nd-best costs (REN) [%]	9.72	9.66	9.62	9.75	9.58
Leakage rate δ_X	0	0.01*	0.1	1	2
Mitigation costs [%]	0.94	0.97	1.16	2.11	2.34
2nd-best costs (CCS+REN) [%]	2.97	3.18	5.28	10.54	10.87
2nd-best costs (CCS_60) [%]	0.91	0.98	2.04		
2nd-best costs (REN_60) [%]	2.60	2.69	3.13	3.65	3.65
2nd-best costs (CCS) [%]					
2nd-best costs (REN) [%]	9.60	9.62	9.76	10.73	11.20
Elasticity of Substitution σ_3	2	3*	4	5	6
Mitigation costs [%]	0.56	0.97	1.17	1.30	1.40
2nd-best costs (CCS+REN) [%]	3.89	3.18	2.54	2.14	1.87
2nd-best costs (CCS_60) [%]	0.53	0.98	0.94	0.87	0.82
2nd-best costs (REN_60) [%]	0.78	2.69	3.73	4.25	4.51
2nd-best costs (CCS) [%]					
2nd-best costs (REN) [%]	10.62	9.62	8.75	7.83	7.82
Storage Capacity X_0 [GtC]	200	500	1000	1500	3500*
Mitigation costs [%]	1.43	1.12	1.01	0.99	0.97
2nd-best costs (CCS+REN) [%]	7.34	5.39	3.85	3.40	3.18
2nd-best costs (CCS_60) [%]		10.11	1.17	1.06	0.98
2nd-best costs (REN_60) [%]	2.46	2.60	2.66	2.68	2.69
2nd-best costs (CCS) [%]					
2nd-best costs (REN) [%]	9.37	9.51	9.58	9.60	9.62
Carbon Budget B_0 [GtC]	250	350	450*	550	650
Mitigation costs [%]	2.00	1.36	0.97	0.70	0.51
2nd-best costs (CCS+REN) [%]	8.77	5.10	3.18	1.65	1.01
2nd-best costs (CCS_60) [%]	5.96	2.09	0.98	0.49	0.25
2nd-best costs (REN_60) [%]	8.02	4.76	2.69	1.40	0.64
2nd-best costs (CCS) [%]				1.65	1.01
2nd-best costs (REN) [%]	17.62	12.96	9.62	7.15	5.30

Table 6.3: Mitigation costs (welfare losses of the optimal carbon pricing policy relative to the BAU scenario) and additional second best costs (welfare losses relative to the optimal carbon pricing policy) for several parameter variations in balanced-growth equivalents. The asterisk is assigned to the value used for the standard parametrization. Blank entries denote infeasibilities, i.e. the policy instrument cannot achieve the mitigation target. CCS_60 denotes the CCS policy if carbon pricing is delayed by 60 years; REN_60 the correxponeding renewable energy policy, if carbon pricing is introduced in 2070.

Bibliography

Amigues, J., G. Lafforgue, and M. Moreaux (2010). Optimal capture and sequestration from the carbon emission flow and from the atmospheric carbon stock with heterogeneous energy consuming sectors. *IDEI Working Papers*.

BGR (2010). Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen. Technical report, Bundesamt für Geowissenschaften und Rohstoffe, Hannover, Germany.

Brooke, A., D. Kendrick, A. Meeraus, R. Raman, and R. E. Rosenthal (2005). *GAMS. A Users Guide*. GAMS Development Corporation.

Coulomb, R. and F. Henriet (2010). Carbon price and optimal extraction of a polluting fossil fuel with restricted carbon capture. *HAL-PSE Working Papers*.

Edenhofer, O., N. Bauer, and E. Kriegler (2005). The impact of technological change on climate protection and welfare: Insights from the model mind. *Ecological Economics 54*(2-3), 277–292.

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 (2009). Carbon leakage, the green paradox and perfect future markets. *CESifo Working Paper* (2542).

Fischer, C. and S. Salant (2010). On hotelling, emissions leakage, and climate policy alternatives. *Resources for the Future, Discussion Paper*.

Fullerton, D. (2011). Six distributional effects of environmental policy. *Risk Analysis 31*(6), 923–929.

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

Gerlagh, R. and B. van der Zwaan (2004). A sensitivity analysis of timing and costs of greenhouse gas emission reductions. *Climatic Change 65*, 39–71.

Gerlagh, R. and B. van der Zwaan (2006). Options and instruments for a deep cut in co2 emissions: Carbon dioxide capture or renewables, taxes or subsidies? *The Energy Journal 27*(3), 25–48.

Gerlagh, R., B. van der Zwaan, M. Hofkes, and G. Klaassen (2004). Impacts of CO2-taxes in an economy with niche markets and learning-by-doing. *Environmental and Resource Economics 28*, 367–394.

Grafton, R., T. Kompas, and N. Van Long (2010). Biofuels subsidies and the green paradox. *CESifo Working Paper* (2960).

Grimaud, A., G. Lafforgue, and B. Magne (2011). Climate change mitigation options and directed technical change: A decentralized equilibrium analysis. *Resource and Energy Economics 33*(4), 938–962.

Held, H. and O. Edenhofer (2009). Ccs-bonds as a superior instrument to incentivize secure carbon sequestration. *Energy Procedia 1*(1), 4559–4566.

Hoel, M. (2010). Is there a green paradox. *CESifo Working Paper* (3168).

Hoel, M. and S. Jensen (2010). Cutting costs of catching carbon: intertemporal effects under imperfect climate policy.

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

IEA (2010). *Projected Costs of Generating Electricity*. International Energy Agency, Paris, France.

IPCC (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

IPCC (2011). *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Le Kama, A., M. Fodha, and G. Lafforgue (2011). Optimal carbon capture and storage policies. *LERNA Working Paper* (11.13.347).

Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature 458*(7242), 1158–1162.

Mirrlees, J. A. and N. H. Stern (1972). Fairly good plans. *Journal of Economic Theory 4*(2), 268 – 288.

Nordhaus, W. D. and J. Boyer (2000). *Warming the World. Economic Models of Global Warming*. Cambridge, Massachusetts, London, England: The MIT Press.

Parry, I. and R. Williams III (2010). What are the costs of meeting distributional objectives for climate policy? *The BE Journal of Economic Analysis & Policy 10*(2), 9.

Parry, I. W. H. (2004). Are emissions permits regressive? *Journal of Environmental Economics and Management 47*(2), 364–387.

REN21 (2011). *Renewables 2011. Global Status Report*. Paris: REN21 Secretariat.

Rogner, H.-H. (1997). An assessment of world hydrocarbon resources. *Annual Review of Energy and the Environment 22*(1), 217–262.

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

van der Zwaan, B. and R. Gerlagh (2009). Economics of geological co 2 storage and leakage. *Climatic change 93*(3), 285–309.

Victor, D. (2011). *Global Warming Gridlock: Creating More Effective Strategies for Protecting the Planet*. Cambridge University Press.

Chapter 7

Synthesis and outlook

This section summarizes the main findings of the thesis and discusses its relevance and implications for climate policy. It takes up several prominent economic debates and examines different proposals to reduce emissions and foster the development of low-carbon technologies. The insights gained in the previous chapters rely on specific mathematical models that are highly aggregated and stylized and therefore neglect important aspects of the reality (see below for suggestions regarding further model improvements). Hence, the reported numbers should not be taken too literally. Nevertheless, the analytical partial equilibrium models as well as the numerical policy assessment model PRIDE reveal important mechanisms describing the development and transformation of economies: How do policies influence intertemporal arbitrage decisions of fossil resource owners? How do different policy instruments trigger technological innovation and specific substitution possibilities? How does climate change and its mitigation transform rents and how does it change energy prices?

In contrast to existing integrated assessment models like DICE (Nordhaus 2008), MERGE (Manne and Richels 2005), REMIND (Leimbach et al. 2010), WITCH (Bosetti et al. 2006) and others, the intertemporal general equilibrium PRIDE considers explicitly a welfare maximizing government to examine the general performance of different policy instruments. A general equilibrium analysis that aims to capture the supply side of fossil resource extraction necessarily has to be a global model. Although no global real-word government exists that implements the policies considered in PRIDE, exploring the (rather generic) policy space illustrates the options policy makers have. This may not only guide national governments (considering the applicability of their policies on a global scale) but also the international negotiations about implementations of mitigation measures.

7.1 Technology policies in the energy sector

7.1.1 The risk of technology lock-ins

As emphasized in the Introduction, one important contemporary debate between economists centers around to the question of whether technology policies in the energy sector play an outstanding role (compared to other sectors of the economy). Chapter 4 argued that the energy sector indeed differs from many other sectors due to the high substitutability of the product – energy or electricity – for consuming firms or households. While in many other sectors product differentiation creates a sufficiently large niche demand that triggers further innovation through ongoing production, high substitutability in the energy sector exacerbates ‘small’ market failures and causes technological lock-ins. A perfect emissions trading scheme can prevent the lock-in into fossil energy technologies, but not into dynamically inefficient low-carbon technologies. Due to the high share of energy on GDP, the latter can cause considerable carbon price increases and consumption losses.

Many economists claimed that policies to promote renewable energy should be technology-neutral to incentivize renewable energy deployment at least costs. Chapter 4 demonstrated that policy instruments need a certain degree of technology discrimination depending on the learning potential in order to avoid lock-ins. A temporary technology stimulus will be sufficient to exploit the scale-effects. Income-neutral policies like feed-in-tariffs or quotas are more robust but slightly less efficient than an optimal and lump-sum financed subsidy policy. Although it will be difficult for real-world governments to determine the optimal promotion policy for each technology, costs of a suboptimal policy could be lower than under the complete absence of policies.

7.1.2 Pure technology subsidies

Chapter 4 highlighted that additionally to carbon pricing, policies that promote innovative low-carbon technologies can be welfare-improving. In reality, however, many governments struggle with the implementation of carbon prices. The current global average carbon price is around 5 $/tCO_2$ (Nordhaus 2010) as only few countries have established an explicit carbon tax or an emissions trading scheme. Contrary, technology policies are far more popular and widely implemented: More than 110 countries have explicit renewable energy targets or policies (REN21 2011) and investments into new renewable energy capacities are higher than into fossil energy capacities in the electricity sector (IPCC 2011, Ch. 11, p. 878).[1]

[1] The reasons why carbon pricing faces often higher resistance than technology policies are discussed in Section 1.1.3 and 6.1.

The popularity of technology policies raises the question whether emission reductions are possible with policies that do not rely on carbon pricing. Chapter 5 and 6 showed that renewable energy subsidies can always reduce carbon emissions to the desired level and subsidies for CCS can achieve this under favorable conditions. The costs for these policies, however, are in most cases prohibitively high because subsidies lead to lower energy prices, which in turn increase energy demand. This rebound effect requires a large amount of subsidies and blows up the energy sector.

There are parameter constellations where pure technology subsidies provoke only moderate welfare losses, e.g. when fossil resources are scarce, the learning potential for renewable energy is high or the geological storage for carbon dioxide is large. In these cases, however, mitigation costs of a pure carbon pricing policy are in most cases very low and high resistance against carbon pricing is therefore not likely. There is only one exception from this pattern: If energy demand is inelastic (i.e. when energy can hardly be substituted by capital and labor), the rebound effect of technology subsidies is very small. In this specific case, technology policies perform better although mitigation costs increase (as energy efficiency improvements cannot be used as mitigation option). Regarding environmental effectiveness, renewable energy subsidies are highly problematic as the learning-by-doing dynamic exacerbates small deviations from the optimum and leads to high response in emissions. Despite their political appeal, pure technology subsidies may not be a pragmatic second-best alternative to carbon pricing. The numerical results call for high caution when such policies are to be implemented.

7.1.3 Hybrid policies: Combining carbon pricing and technology policies

Although support for technology policies is high, such policies hardly consist of pure lump-sum financed subsidies. Rather, clean technologies are often supported by some kind of cross-financing mechanism at the expense of fossil energy technologies (see IPCC 2011, Ch. 11.5, for an overview). A feed-in-tariff, for example, subsidizes renewable energy technologies but finances this subsidy simultaneously by a levy on fossil and nuclear energy generation. A renewable energy portfolio standard works along the same lines. Priority grid access for renewable energy providers is effectively a subsidy for renewable energy and a tax for non-renewable energy generators (who have to pay for the fluctuations of renewable energy supply).

Additionally to renewable energy policies, governments have imposed taxes on the use of final energy (including electricity, gasoline, diesel, gas) to raise income for government spending, reduce traffic volume or increase energy savings.[2] Although these taxes are not always directly related to the released emissions, they also encourage mitigation and retard possible rebound effects. An important result of the Chapters 4–6 is that such hybrid approaches are – if well-designed – capable to reduce emissions at low efficiency losses (compared to the optimal carbon pricing policy). Suboptimally low carbon prices can be combined with technology policies to achieve a certain mitigation target. Income-neutral technology policies (like feed-in-tariffs) can also achieve a mitigation target at low additional costs. A precondition for the success of these technology policies is that they are framed to induce a big energy transformation rather than a marginal increase in renewable energy deployment.

Permanent subsidies for renewable energy or CCS are an expensive and, in the latter case, not always feasible alternative to carbon pricing. They can, however, serve as transitional instrument to bridge the gap until a global carbon tax or emissions trading scheme has been established (Chapter 5 and 6). Without technology policies a given carbon budget can only be achieved if carbon pricing is implemented rather soon. Technology policies that promote renewable energy or CCS allow to 'buy time' until carbon pricing is adopted. Given the current deadlock in the international negotiations about binding emission reductions or harmonized global carbon taxes, it can be reasonable to start already with the transformation of the energy system.

7.1.4 Renewable energy vs. carbon capture and sequestration

Technology policies play an important role to reduce lock-ins and compensate for missing or imperfect carbon prices. There are several low-carbon technologies; which of these should be promoted specifically? Chapter 4 suggested that learning technologies need special support. This would favor learning renewable energy technologies (i.e. PV solar, biomass use) but also to a certain extent CCS technologies (as they are relatively immature). The learning potential of CCS is, however, limited due to increasing scarcities for (cheap) fossil resources and storage capacities.

Besides the learning and innovation potential, Chapter 6 highlighted the different supply-side effects of renewable energy and CCS policies. Even if renewable energy is the cheaper long-term *technology*, CCS subsidies may be the cheaper *policy*, in particular if (easily accessible) fossil resources are scarce. In contrast to renewable energy subsidies, CCS policies increase the demand for fossil energy leading to an implicit carbon price. This also bene-

[2] Despite taxes on energy, global subsidies on fossil energy in 2010 amounted to 409 billion US$ (IEA 2011). In most cases, these subsidies aim to reduce energy costs in particular for low-income households and are often implemented in countries that export fossil resources.

fits renewable energy. Such an implicit carbon price effect does not only reduce the costs of the second-best policy, but also influences leakage in a world lacking harmonized policies. As CCS policies increase fossil resource prices for countries without technology or carbon pricing policies, they also reduce emissions abroad ('negative leakage'). Renewable energy subsidies reduce fossil resource prices abroad and provoke the contrary – although learning-by-doing will also spill-over and reduce the opportunity costs of fossil resource use.

Chapter 6 emphasized that a smart mix of renewable energy and CCS policy is not only the cheapest but also the most robust second-best option regarding uncertainties in future innovations and geological storage conditions as well as in the response of the economy to technology policies. Internationally, a technology protocol accelerating knowledge transfer and adoption of low-carbon technologies can play a significant role in reducing emissions if it considers renewable energy as well as CCS. High-income countries might perceive such a technology policy as an opportunity to increase exports and to reduce emissions abroad without using problematic lump-sum transfers (as it would be the case under a global ETS or carbon tax with compensation payments). Developing countries can choose low-carbon technologies as no-regret option if industrialized economies pay the necessary cost markup. Hence, such a technology protocol could be a valuable intermediate policy to establish a global carbon price.

There are some precautionary considerations with respect to CCS that are worthwhile to consider. First, CCS policies have to be designed to discourage the use of leaky reservoirs, i.e. by an appropriate monitoring and liability scheme. Even if CCS is subsidized as second-best policy, the liability for leakage should not be removed. Although such removal results effectively in an additional subsidy on CCS, it would incentivize negligence and the use of leaky reservoirs if they are less expensive. Hence, if firms argue liability rules are too strict to use CCS even under a given subsidy, it is better to increase the CCS subsidy than to relax the liability. Second, CCS subsidies encourage the technological business-as-usual paradigm of using fossil resources for energy generation. In case fossil resources are scarce, this would accelerate the transition to renewable energy at low economic and political costs due to increasing fossil resource prices. In contrast, if fossil resources are abundant, a transformation of a further growing carbon-intensive capital stock into a clean one could become politically even more difficult. It is therefore important to avoid such a lock-in by designing a robust exit-strategy right from the start and by up-scaling simultaneously renewable energy with CCS.

7.2 Price vs. quantity policies revisited

7.2.1 The supply-side dynamics

Another controversy among economists focuses on the choice of a tax or emissions trading scheme to establish a price on carbon and internalize external costs. The 'green paradox' of Sinn (2008) suggests that considering the supply-side of fossil resource extraction favors quantity over price instruments: an accelerated extraction due to suboptimal taxes can be ruled out. Chapter 2 demonstrated how the green paradox arises in case of a low initial tax level *and* a high tax growth rate. Although existing carbon tax proposals are unlikely to cause an accelerated resource extraction, an imperfect political implementation process may change this.[3] Sinn's robustness argument that quantity instruments are preferable as they never induce an accelerated extraction, however, falls short, because he compares a *suboptimal* price instrument with an *optimal* quantity instrument. But is there a specific reason why a regulator is more likely to implement a suboptimal tax than a suboptimal quantity instrument? Chapter 3 established an explanation why policy makers could implement such a suboptimal carbon tax which results in a green paradox: If damages are convex and the regulator permanently adjusts the carbon tax to the experienced marginal climate damages, resource extraction is accelerated. Each resource owner seeks to extract resources as long as taxes (and marginal damages) are low.

Resource owners' response to carbon taxes is rather complex and depends on the expected future tax rates, the security of property rights and the existence of complete futures markets. Although a perfectly informed regulator can consider these issues and implement appropriate taxes, an emissions trading scheme will always enforce the optimal extraction path automatically – as long as the cap was set optimally (Chapter 3). The quantity instrument may therefore be more robust than the price instrument as it requires less information on the (effective) discount rate of resource owners and less credibility of the announced future policy path. Nevertheless, Chapter 6 showed that the economy's response to suboptimal carbon taxes is less sensitive than to quantities: Even if the carbon tax was set 10% lower than its optimal value that is consistent with the carbon budget, resulting cumulative emissions increase only by 6%. If the cap was likewise relaxed by 10%, cumulative emissions would increase by 10%.

[3] In order to reduce the risk of a green paradox, governments relying on carbon taxes should implement an initially high tax with a moderate increase in time.

7.2.2 Intertemporal management issues

Besides the question of how much carbon to emit (and how to incentivize this amount), the stock-pollutant nature of climate change also creates an intertemporal decision problem regarding the timing of emission reductions: How does an additional unit of carbon in the atmosphere at time t compare to an additional unit at time $t^* > t$? Can agents decide when to release emissions into the atmosphere according to their preferences or available technologies? Chapter 3 discussed to what extend these intertemporal allocation decisions can be carried out by individual agents on a free market. The first important result was that the intertemporal allocation decision can hardly be 'decentralized' and, hence, a regulatory institution has to manage the intertemporal allocation. Only if the regulator suppresses the climate damage function (and the optimal intertemporal distribution of damages) and employs a cost-effectiveness approach, a decentralization is possible under general conditions. In the case of a cumulative carbon budget as mitigation goal, emissions trading with free banking and borrowing achieves the mitigation target at least costs and equal to the social planner outcome. This result implicitly assumes perfect commitment of the regulator to the budget and the existence of complete futures markets for very long time horizons – both being problematic conditions in reality.

An important conclusion of these findings is that climate policy needs to a certain extent a 'central planning' institution which cares about the intertemporal allocation of emissions. Avoiding such strong government intervention is only possible under the carbon budget approach where the intertemporal allocation of damages is neglected.

7.2.3 Additionality of multiple policies

Recalling the political constraints on imposing an optimal carbon price, Chapter 6 showed that a suboptimally low carbon price can be complemented by subsidies on low-carbon technologies to achieve a certain mitigation target. When designing such a second-best policy *ex-ante*, the suboptimal carbon price $\tilde{p}$ can equally be implemented via a tax $\tau = \tilde{p}$ or an emissions trading scheme. In the latter case, the yearly emission caps have to be set such that the allowance price resulting from the technology policy equals the original suboptimal carbon price $\tilde{p}$. Hence, price and quantity instruments are *ex-ante* equivalent. After having established an emissions trading scheme, however, one could drop the second-best technology policy and end up with the optimal carbon price that achieves the mitigation target in an efficient manner. Indeed, the climate and energy policy of the European Union is criticized for its inconsistent policy mix (Fankhauser et al. 2010): Under the emissions trading scheme, additional technology policies do not reduce emissions but only carbon prices which causes inefficient allocations and, thus, additional consumption losses. How to resolve these contradicting policy appraisals? Whether an additional technology policy is consistent with a cap and trade system or a carbon tax depends on the political decision process which renders the constraints for policy makers. With q^* the mitigation target and p^* the optimal carbon price consistent with that target, one can imagine three constraints for policy makers

(i) an emissions cap q may not be lower than a value $\tilde{q}$, i.e. $q = \tilde{q} > q^*$

(ii) a carbon tax τ may not exceed a value $\tilde{\tau}$, i.e. $\tau = \tilde{\tau} < p^*$

(iii) a combination of (i) and (ii)

Rational and perfectly informed firms and voters will opt for position (iii): If they claimed (i), the regulator would simply implement the carbon tax τ^* (rather than an ETS) which results in $q^* < \tilde{q}$ emissions. Likewise, if they persisted on (ii) only, the regulator could implement an ETS with the optimal cap (leading to an allowance price $p^* > \tilde{p}$). However, firms and voters may not behave perfectly rational. First, there is no representative agent. Firms and voters differ with respect to their interest in using fossil resources, paying taxes, and having the capability and the information to evaluate the implications of such policies. Some voters have a pronounced aversion against high taxes as they fear that firms turn-over taxes to consumers and that low-income households ultimately have to pay for climate policy. Others sense the threat of reduced fossil resource rents and capital income through the explicit and immutable number of maximum emissions allowed under an ETS. In any case, political acceptability relies on the attitude towards rather symbolic elements that are associated with certain measures. In case the policy maker faces constraint (iii), he could implement a carbon tax $\tilde{\tau}$ which – as standalone policy – exceeds the environmental target q^*: By adding successively several technology policies, however, she can reduce emissions to q^*.

Considering political constraints, the symmetry between price and quantity instruments breaks: A suboptimal tax can always be complemented by a technology policy to achieve q^*. This type of hybrid policy will, if well designed, cause only moderate efficiency losses (Chapter 6). A suboptimal cap, however, cannot be complemented by a technology policy to reduce the emissions – except when the technology policy is so 'strong' that allowance prices fall to zero and the cap becomes ineffective. In the latter case, efficiency losses equal a pure technology policy approach and are, thus, rather high (Chapter 5 and 6).

While the effects of carbon taxes and technology policies on mitigation roughly sum up, technology policies under a non-ambitious ETS lead to a bang-bang outcome. Either the technology policy is to weak and achieves no emission reductions (but efficiency losses), or the technology policy is strong enough making the ETS completely obsolete. One way out of this dilemma could be to complement the ETS by a price floor at the politically feasible level $\tilde{\tau}$. This has the advantage, that emissions will never exceed $\tilde{q}$ and regulators may still reduce emissions below $\tilde{q}$ by using technology policies or by increasing the floor price.[4]

7.3 Rent distribution aspects

Climate policy is about establishing property rights on the environment and therefore necessarily involves rent re-distribution associated with these property rights. It devalues fossil resource rents as fossil resources become abundant compared to the (small) atmospheric carbon deposit. Simultaneously, it creates a new explicit rent associated with the atmospheric deposit, the *climate rent*, which is directly visible via the carbon price. Although many government policies that internalize externalities change the rent distribution pattern, there is no comparable case to climate policy due to its outstanding dimension: One single policy destroys rents of the magnitude of the one-year gross world product and generates a new rent of a similar dimension. Fig. 7.1 shows how the value of fossil resources in the ground relates to climate policy, given different technological or political conditions. More ambitious climate targets increase the climate rent and reduce fossil resource rents drastically. The availability of low carbon technologies like renewable energy and CCS reduces the climate rent, but only the existence of the CCS technology has a positive impact on fossil resource rents (as extensively discussed in Chapter 6).

In contrast to typical cases of government intervention, the rent transformation is explicit and visible as both commodities – fossil resources and emission allowances – are traded on markets. Property of fossil resources is concentrated in few hands – governments, monarchs, state-owned or private firms – that receive and control this rent. Furthermore, climate policy explicitly raises the question of how to distribute the scarcity rent of the global commons. This is something exceptional because humankind has not been confronted with this issue so far. Although philosophers thought about the ownership and the 'just' initial acquisition of natural resources, in practice natural resource ownership was often claimed by those who discovered or used resources first or by potentates exercising force (or threaten the use of it). The latter includes governments that claim natural resources belong to them (rather than to the global human community) even if they redistribute the associated rents to their

[4]Considerations above refer to a static framework but are directly transferable to a dynamics setting. Note that floor prices have to increase at the interest rate to be dynamically consistent. See also Murray et al. (2009) and Burtraw et al. (2010) for further discussions on price floors and caps.

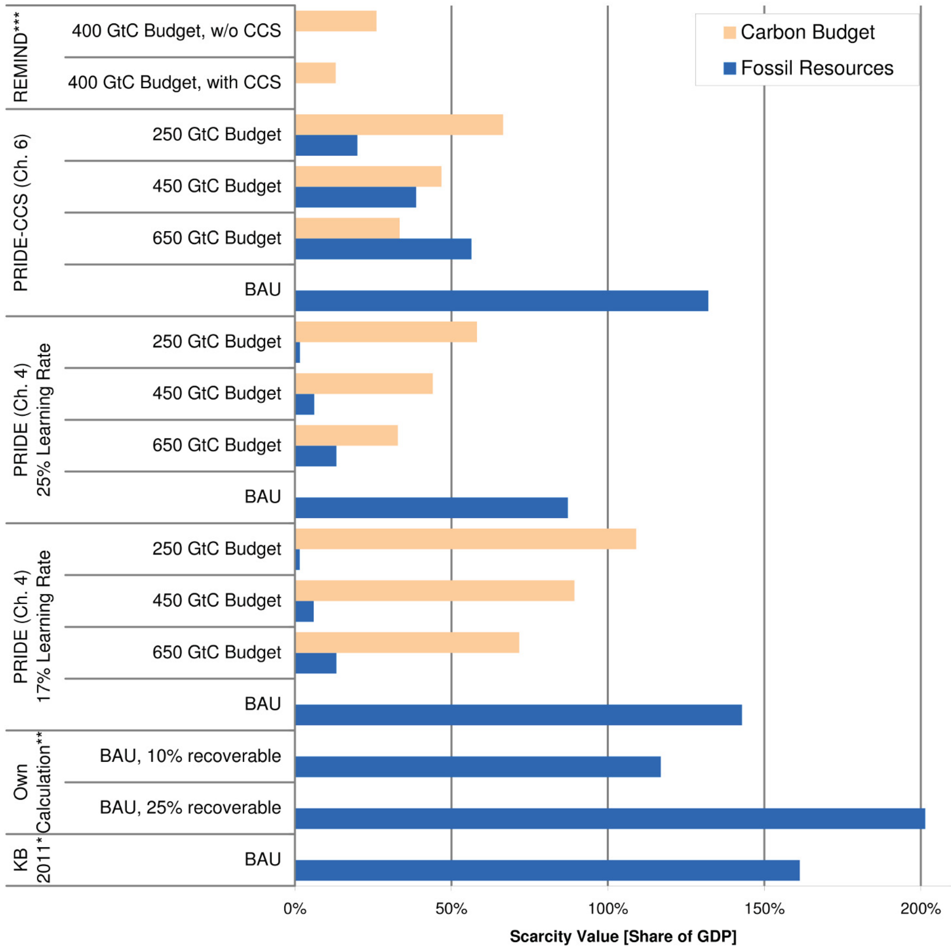


Figure 7.1: Value of fossil resource stocks and the climate budget relative to current GDP. The value of both stocks is determined by multiplying the effective stock size (i.e. the cumulative consumption) with the initial scarcity value (i.e. price minus extraction costs for fossil resources and allowance price for carbon, respectively). *KB 2011 refers to Kalkuhl and Brecha (2011). **Numbers denoted as 'own calculation' are a rough estimation obtained from BGR (2010) data as follows: Scarcity values of oil, gas, and coal are set to 20 $/bbl, 1 $/GJ and 10 $/tce. These are multiplied with the fossil resource stock, which consists of the sum of proven conventional reserves and remaining resources. As the latter are speculative, they are down-sized by a recovery factor of 0.25 and 0.1, respectively. ***Results from the integrated assessment model REMIND are adopted from Lüken et al. (2011) where no fossil resource rents are reported.

citizens.[5] For most resources, property rights have already been established: Land usually belongs to people who purchased or inherited it or own it due to some customary law; ultimately, however, it belongs to the sovereign nation state who may regulate the use of this

[5]This is, for example, done by the Alaska Permanent Fund for the rent income of Alaska's oil extraction (O'Brien and Olson 1990).

land, raise taxes on it or defend it against foreign aggressors. If new natural resources are discovered, they belong to the national government of that territory (or to the land owners if national law permits this). In contrast, the scientific 'discovery' of anthropogenic global warming included the discovery of a new natural resource: the limited atmospheric deposit for greenhouse gases which is expressed by a carbon budget, a concentration target or by the increasing climate damages. The discovery of the value of the atmosphere raises the question of the property of a formerly unowned resource.[6] In what follows, one proposal that aims to give each person an equal share on that property is discussed in more detail.

7.4 The Carbon Trust proposal and its implementation in PRIDE

There are several proposals how to distribute the climate rent. Under an emissions trading scheme, the rent is distributed through the allocation of allowances. Industrial countries often claim an allocation according to their current emissions or GDP, as their economies 'need' more emissions than poorer economies. In contrast, some developing countries demanded to allocate emissions reversely to historic emissions, because the heavy polluting countries have already used the atmosphere for a long time and became rich by its use. Both approaches are controversial: The first one entails a first-come first-serve attitude regarding the initial acquisition of natural resources; the latter one insinuates that industrial countries had always known for sure that the atmospheric deposit is limited (and can therefore be held responsible for their past actions). An alternative appealing approach is to give each human an equal right on the use of the atmosphere, independently whether he is rich or poor or his ancestors polluted much or less.

Chapter 3 highlighted the importance of an institution that manages the atmosphere intertemporally. Barnes et al. (2008) propose an independent 'Earth Atmospheric Trust' that sets the emission caps, auctions emission allowances and tightens the cap to stabilize emissions below 450 ppm CO_2-eq. The revenues from this trust are used as follows: one part is lump-sum transferred to each individual (reflecting the equal-ownership of the atmosphere), the remaining share is re-invested into low-carbon infrastructure, renewable energy technologies or ecosystem conservation. The equal-per-person lump-sum transfer of rents primarily benefits poor households because their income would increase by a considerable

[6] If one believes that the distributional conflict about the rent transformation is unresolvable, a combination of low carbon taxes and technology policies for CCS and renewable energy (as explored in Sec. 6) might become an attractive alternative: Low carbon taxes do not raise the international climate rent distribution question as they remain at the national government. Renewable energy and CCS policies ensure that the climate target is achieved, the latter also reduces the rent losses of fossil resource owners.

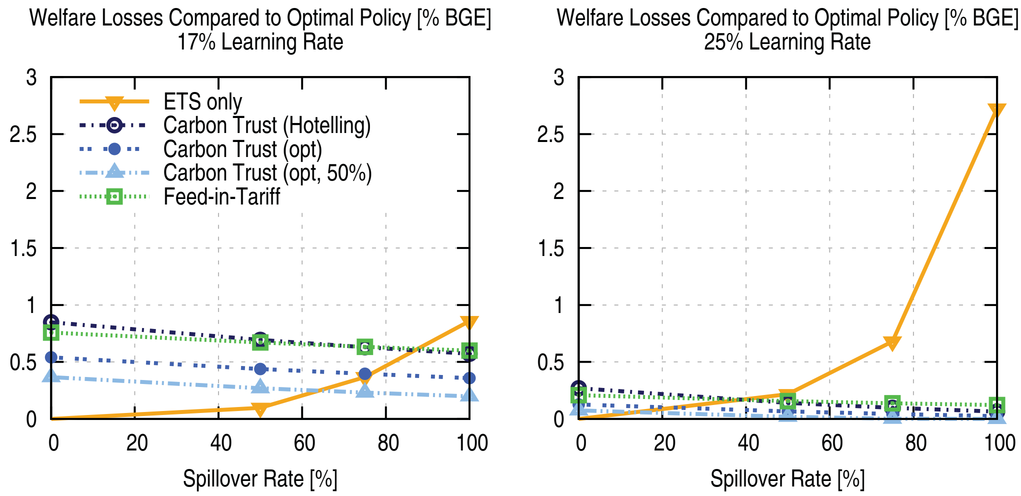


Figure 7.2: The performance of carbon pricing and technology policies in balanced-growth equivalents relative to the social optimum for a medium (17%) and high (25%) learning scenario. The following policies are considered: A pure emissions trading scheme (ETS) with lump-sum recycling of revenues and without any technology policy; a Carbon Trust policy where the carbon price develops according to the Hotelling rule and revenues are completely spent for subsidizing renewable energy; a Carbon Trust policy where the carbon price grows optimally and revenues are completely spent for subsidizing renewable energy; a Carbon Trust policy where the carbon price grows optimally and 50% of the revenues are spent for subsidizing renewable energy (and the remaining revenues are lump-sum transferred to households); and, finally, a Feed-in-Tariff policy where no carbon price exists but fossil and nuclear energy are taxed and revenues completely spent for subsidizing renewable energy. The performance of the policies is evaluated according to different spillover rates that capture the size of the innovation market failure. The elasticity of substitution between learning and non-learning energy is $\sigma_3 = 12$ and the risk premium in the learning energy technology sector is set to zero. All remaining parameters are chosen according to Chapter 4.

amount.[7] As argued in Chapter 4, investments into renewable energy can be welfare increasing if targeted at additional market failures.

Fig. 7.2 shows the performance of such an Atmospheric Trust (also called Carbon Trust because it effectively controls the carbon flows) under different conditions in the PRIDE model. The first important insight is that the intertemporal allocation matters: If the trust issues permits with free banking and borrowing, a Hotelling price path evolves. While this would be optimal if revenues were not transferred to renewable energy, a deviation of the Hotelling rule leads to clearly higher welfare. This strengthens the role of the Carbon Trust for the intertemporal management as a free market cannot find this optimal path. Secondly, although a global feed-in-tariff performs quite well, changing the levy from fossil energy to fossil resources (or emissions) brings similar improvements as adjusting the intertemporal allocation from the case before. Thirdly, if not all revenues are invested into technologies, but 50% are lump-sum transferred to households, welfare increases further. The reason is

[7] Barnes et al. (2008) estimate 71–285 $ per capita and year if half of the rent was redistributed to individuals.

that the Carbon Trust collects more revenues than necessary to treat the market failure in the renewable energy sector. Finally, the Carbon Trust outperforms a pure carbon pricing policy if the market failure in the renewable energy sector is large (i.e. high spillovers or risk premiums) or the learning potential of renewable energy is high. The lower the innovation market failure, the fewer revenues should be re-invested and the more should be lump-sum transferred.

7.5 Some suggestions for future research

The PRIDE model developed in this thesis is a first step for a comprehensive integrated policy assessment for climate change mitigation. One important strength of the model is to study general equilibrium effects and thereby the 'indirect' effects of policy measures on linked markets. Another advantage of the hierarchical optimization approach is to calculate *optimal* second-best policies to obtain a comparable reference point when assessing different second-best policies. The second-best policies were motivated by exogenous political constraints that seemed plausible but remain to a certain extent ad-hoc. The model could therefore be refined to endogenize these constraints by considering them in specifications of preferences or technologies: The (distributional) concerns regarding high energy prices could be captured by households with different productivity and income; the political pressure of fossil resource owners that are afraid of their rents could be reflected in the objective function of the government; considerations regarding positive or negative leakage, international competitiveness and relocation of industries under unilateral policies requires a multi-region extension.

Likewise, further externalities (such as positional externalities of (status) consumption, local air pollution, energy security issues but also biodiversity and food security aspects of increased energy-crop cultivation) should be considered as they could alter the performance of policy instruments. A probably severe market failure consists in the missing futures markets for resources and commodities (whose demand determines fossil resource demand) and in the imperfect commitment of governments to announced future policies. Finally, damages due to climate emissions should be captured to motivate the choice of a specific carbon budget and to analyze how non-climate related market failures relate to climate damages and their mitigation.[8]

[8]One particular strength of PRIDE is to combine a decentralized (descriptive) model with a normative welfare optimization approach. This allows to consider a wide range of normative parameters in a real-world setting of profit-maximizing agents. The main dispute about the appropriate discount rate arises from the fact that the social planner model reproduces a decentralized economy only for certain normative parameters. If one seeks to calculate the costs of mitigation and the level of carbon prices within an existing market economy, the social

Besides the extension of the model to capture and endogenize further important features, uncertainties and imperfect information could be addressed more intensively. Within a dynamic model over many decades, uncertainty about costs, fossil resources, underground storage, leakage from geological formations etc. should resolve. Anticipating this learning about uncertainty, the regulator's optimization problem and its numerical implementation would become quite complex. Nevertheless, incorporating uncertainty and learning would be valuable to understand the performance of policies and to calculate, for example, tax rates or subsidies or a policy shift from price to quantity instruments that maximize expected welfare under uncertainty.

Bibliography

Barnes, P., R. Costanza, P. Hawken, D. Orr, E. Ostrom, A. Umaña, and O. Young (2008). Creating an earth atmospheric trust. *Science 319*(5864), 724b.

BGR (2010). Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen. Technical report, Bundesamt für Geowissenschaften und Rohstoffe, Hannover, Germany.

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti, and M. Tavoni (2006). WITCH: A world induced technical change hybrid model. *The Energy Journal 27*(1), 13–38.

Burtraw, D., K. Palmer, and D. Kahn (2010). A symmetric safety valve. *Energy Policy 38*(9), 4921–4932.

Fankhauser, S., C. Hepburn, and J. Park (2010). Combining multiple climate policy instruments: How not to do it. *Climate Change Economics 1*(03), 209–225.

IEA (2011). *World Energy Outlook*. International Energy Agency, Paris, France.

IPCC (2011). *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kalkuhl, M. and R. Brecha (2011). The carbon rent economics of climate policy. *Working Paper. Potsdam Institute for Climate Impact Research*.

Leimbach, M., N. Bauer, L. Baumstark, and O. Edenhofer (2010). Mitigation costs in a globalized world: Climate policy analysis with REMIND-R. *Environmental Modeling and Assessment 15*, 155–173.

planner model (and its normative parameters) have to be chosen to be consistent with the market data.

Lüken, M., O. Edenhofer, B. Knopf, M. Leimbach, G. Luderer, and N. Bauer (2011). The role of technological availability for the distributive impacts of climate change mitigation policy. *Energy Policy 39*(10), 6030–6039.

Manne, A. and R. Richels (2005). MERGE: An integrated assessment model for global climate change. In R. Loulou, J.-P. Waaub, and G. Zaccour (Eds.), *Energy and Environment*, Chapter 7, pp. 175–189. Springer.

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

Nordhaus, W. (2008). *A Question of Balance. Weighing the Options on Global Warming Policies.* New Haven, USA: Yale University Press.

Nordhaus, W. (2010). Economic aspects of global warming in a post-copenhagen environment. *Proceedings of the National Academy of Sciences 107*(26), 11721.

O'Brien, J. and D. Olson (1990). The alaska permanent fund and dividend distribution program. *Public Finance Review 18*(2), 139–156.

REN21 (2011). *Renewables 2011. Global Status Report*. Paris: REN21 Secretariat.

Statement of Contribution

Chapter 2 to 6 are written by the author of this thesis in collaboration with his advisers Prof. Dr. Ottmar Edenhofer and Dr. Kai Lessmann. The author of the thesis has made significant contributions to all chapters from conceptual design, to technical development, numerical implementation and writing. A detailed list regarding the contribution to specific chapters follows below.

Chapter 2 The author of this thesis was responsible for the basic model set-up, for the analytical results and the numerical calculations as well as the writing of the paper. Ottmar Edenhofer provided support for framing the research question (in the introduction part) and the discussion of policy implications (in the conclusion). He strongly motivated to focus on the supply-side dynamics of climate policy.

Chapter 3 The author developed the model set-up and the analytical results and wrote the paper. Ottmar Edenhofer provided support for framing the research question and the discussion of policy instruments, in particular with respect to their intertemporal dimension. He enriched the manuscript with references and considerations regarding the role of futures markets, uncertainty and tipping-points for the cost-benefit analysis.

Chapter 4 Ottmar Edenhofer suggested a hierarchical game-theoretic model framework to analyze the performance of different policy instruments in a setting of intertemporally optimizing agents. The integrated policy assessment model PRIDE was jointly developed by the author of the thesis and the co-authors of this chapter, Ottmar Edenhofer and Kai Lessmann. Implementation and technical development of the model, data collection and visualization of results was solely performed by the author of the thesis. The author of the thesis wrote most parts of the Chapter 4 with minor contributions of the co-authors. Ottmar Edenhofer helped to shape the research question and the relation to current economic debates. Kai Lessmann emphasized the distinction of different equilibria (Sec. 4.2.2), contributed to the literature review and assisted in a consistent formal and verbal description of the model.

The following two Chapters consider the role of technology policies for climate change mitigation. Ottmar Edenhofer promoted and encouraged strongly this analysis in order to understand whether technology policies are substitutes or complements of carbon pricing policies.

Chapter 5 The chapter was written by the author of this thesis after joint discussions with Ottmar Edenhofer and Kai Lessmann regarding the relevance and implementation of second-best policies. The author of the thesis implemented the second-best policies, and evaluated and visualized them.

Chapter 6 The analytical model of this chapter was developed by the author of the thesis. He also extended the PRIDE model by a CCS sector and performed the various model runs and their visualization. Ottmar Edenhofer encouraged to consider second-best CCS policies and to extend the PRIDE model. Kai Lessmann helped to improve the manuscript. Both co-authors assisted through fruitful discussions on the model development, the interpretation of results and the selection of policy scenarios for the final paper.

Acknowledgments

This thesis in its final form would not have been possible without the support and help of my supervisors, colleagues, friends and my family. I would like to thank my supervisor Ottmar Edenhofer for his encouraging comments and discussions to this work. He helped to improve my economic understanding of the intertemporal dynamics and the normative dimension of economic policy analysis. Due to his excellent management of the Research Domain III of the Potsdam Institute for Climate Impact Research, he created an inspiring working environment. I am also grateful for the help of my second adviser Kai Lessmann, who had always time to discuss modeling and programming issues. Kai gave me helpful hints for preparing the articles and carefully read many parts of this thesis. I would further like to acknowledge Klaus Eisenack's support in the early stage of the model development.

I would not have enjoyed the years working on my PhD thesis without my colleagues at Research Domain III of the Potsdam Institute for Climate Impact Research. I am grateful for the cooperative working spirit and the animating and critical discussions, in particular with Nico Bauer, Steffen Brunner, Christian Flachsland, Michael Jakob, Brigitte Knopf, Robert Marschinski, Michael Pahle, Robert Pietzcker and Jan Steckel. I would like to thank Elmar Kriegler for giving PRIDE its name; the administration of Research Domain III – Jutta Neuhaus, Dorothe Ilskens, Kristiyana Neumann and Nicole Reinhard – for assisting in formalities; and the numerous colleagues for their comments on my research presentations at the PhD seminar.

I am grateful for Sarah's untiringly and patiently proof-reading of the manuscript, for her discussions and overall support. I thank Jonas for his friendship, for proof-reading parts of this thesis and challenging the economists (including me) with insisting on improving the well-being of the poor first. I would also like to thank Anja, David, Elisabeth, Judith, Matt and Moritz for having shared so much time together.

Last but not least, I want to say thanks to my family: My parents Monika and Andreas who have supported me my entire life, and my brother Stephan for his open-minded and generous spirit.

Tools and Resources

Wide parts of this dissertation rely on numerical modeling. The PRIDE model is written in the General Algebraic Modeling System (GAMS), version 22.8.1 (Brooke et al. 2005) and solved with the CONOPT3 solver, version 3.14S, for non-linear programs (Drud 1994). The model output was processed by using GNU R, version 2.8.1 (R Development Core Team 2010) and visualized by Gnuplot, version 4.2, (Williams and Kelley 2007). Fig. 1.1 and Fig. 7.1 were created with Microsoft Excel 2003. The final document was prepared with LaTeX2$_\varepsilon$ (Lamport 1994).

Bibliography

Brooke, A., D. Kendrick, A. Meeraus, R. Raman, and R. E. Rosenthal (2005). *GAMS. A Users Guide*. GAMS Development Corporation.

Drud, A. (1994). CONOPT – a large-scale GRG code. *ORSA Journal on Computing 6*(2), 207–216.

Lamport, L. (1994). *LaTeX: A Document Preparation System User's Guide and Reference Manual*. Amsterdam: Addison-Wesley Longman.

R Development Core Team (2010). *R: A language and environment for statistical computing*. Vienna, Austria: R foundation for statistical computing.

Williams, T. and C. Kelley (2007). *Gnuplot: An Interactive Plotting Program.*