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Modeling Climate Policy Instruments in a Stackelberg Game with Endogenous Technological Change and Market Imperfections

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[1] Since June 2008 he works at the University of Oldenburg, department of economics and statistics.

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List of Abbreviations

BAU	Business as Usual (scenario)
CBA	Cost-benefit Analysis
CES	Constant Elasticity of Substitution
CliPIDE	Climate Policy Instruments in a Decentralized Economy (the name of the assessment model developed in this thesis)
ETC	Endogenous Technological Change
Eq.	Equation
Fig.	Figure
GDP	Gross Domestic Product
GHG	Greenhouse Gases
IAM	Integrated Assessment Model
IPCC	International Panel on Climate Change
LbD	Learning by Doing
PV	Present-Value
RED	Reduction (scenario)
R&D	Research and Development
Sec.	Section
STPR	Social Time Preference Rate
Tab.	Table
TWA	Tolerable window approach

Formal Conventions

$\dot{x} := \frac{dx}{dt}$	total derivative respect to time
$x'_y := \frac{\partial x}{\partial y}$	partial derivative respect to y
$\hat{x} := \frac{\dot{x}}{x}$	rate of change of x

Executive Summary

The scope of this thesis is to develop a flexible cost-effective integrated assessment model to derive and analyze policy instruments mitigating global warming with regard to several further market failures occurring in climate-related economic markets. Furthermore, this analysis gives important insights into distributional effects of several instruments, which are widely neglected by common assessment and policy models.

I present an open-loop dynamic Stackelberg game with the government as Stackelberg leader (tax paths and R&D expenditures as control variables) and economic sectors – households, final good production, fossil energy, renewable energy and resource extraction sector – as followers. Followers maximize payoff intertemporally according to the maximum principle of dynamic optimization with respect to given taxes, R&D path of the government and (endogenously determined) market prices. The leader's problem is solved with optimization software GAMS. Furthermore, a social planner model neglecting strategical behavior (of followers) serves as benchmark for the regulated market outcome. Analysis is performed analytically as well as numerically based on model runs.

The economic model is set up in the spirit of neoclassical economic theory with the common production functions and a representative household supplying labor and capital. The climate policy target is formulated as constraint for accumulated emissions that are equated with resource extraction from a finite resource stock. Renewable (backstop) energy allows for energy production without the use of fossil resources but under high capital input. Technological change occurs due to capital stock spillovers which augment productivity of labor and energy (not individually controllable) in the production sector and capital productivity in the renewable energy sector. Further on, selective increase of productivity is modeled by public R&D in knowledge stocks (à la Popp and Edenhofer). Market power in the extraction sector is implemented by an (endogenous) estimation of economy's demand function by resource extractors. Therefore, the following market failures are treated: mitigation target, market power and knowledge spillovers.

Three classes of policy instruments are considered to compensate these market failures: quantity restrictions, R&D expenditures and price instruments, e.g. taxes on several factor prices (economy-wide or sectoral). Evaluation is based on efficiency and social optimality criteria as well as on distributional effects on functional income composition – mainly regarding labor and capital income and profits as approximation for important socio-economic groups. In addition to first-best instruments several second-best instrument are evaluated to consider additional political or practical constraints.

Hence, the model allows for some robust qualitative conclusions: The base-model without further market imperfections is always socially optimal. The equivalence between price and quantity instruments with respect to efficiency can be confirmed, but there are important differences with respect to income: While price instruments generate tax revenues, quantity restriction raises the scarcity rent of resource owners even above the case of no political regulation. Efficient taxes to reduce emissions have to be charged on that economic sector which makes an allocation decision on resource use. Thus, a resource tax can achieve optimal outcome, while an energy tax causes considerable welfare losses for realistic elasticities of substitution (which are correctable by an energy-capital subsidy). Combined labor and capital tax is also capable of reaching

the mitigation target, but welfare losses are considerably higher than under second-best energy tax. The latter also indicates that an environmentally aware household can indeed achieve the climate protection goal with climate friendly consumption and investment reduction, but that this option is more expensive than resource or energy taxation. A pure abatement subsidy in terms of capital subsidy to the fossil energy sector augments emissions. Although optimal factor shares and high resource efficiency can be achieved, rebound effects cause higher resource demand. Regarding market structure, monopoly power in resource sector may guarantee the achieving of the mitigation goal without further policy instruments. But this is only possible under welfare losses due to dynamic inefficiency. One single instrument – a resource tax – can correct both distortions due to mitigation and market power, but functional income distribution differs between first-best ad-valorem tax and unit tax instrument. Endogenous technological change augments emissions due to high rebound effects in no-policy scenarios but has an essential impact on the cost reduction of climate protection. Capital income and labor income diverge (in favor of capital income) especially due to spillover caused economic growth. Emerging renewable energies again slightly augment capital income at the expense of labor income. In the presence of endogenous technological change, mitigation charges labor incomes more than capital incomes. Optimal mitigation tax rates depend strongly on technological parameters like elasticities of substitution and on renewable energy production. Thus, a quantity restriction instrument is more robust against technological uncertainties by passing estimation of (future) technological mitigation options on individual enterprises.

The model I developed determines and explains first-best and second-best taxes and other instruments to achieve climate protection. It provides a detailed assessement of a set of prominent climate policies by estimating their distributional effects for the first time.

> “Climate change is a result of the greatest market failure the world has seen. The evidence on the seriousness of the risks from inaction or delayed action is now overwhelming. We risk damages on a scale larger than the two world wars of the last century.” – Stern (2007a)

1 Introduction

1.1 The Problem of Global Warming

The climate is changing – and it always has been changing. 4.5 billion years of Earth’s history are also 4.5 billion years of climate history – of glacial periods with polar ice shields up to equatorial latitudes and heat periods without any ice shields and high sea levels. Climate change – induced by greenhouse gases (GHG), volcanism, photosynthesis and other changes in the global carbon cycle – caused the creation of live, the extinction of mature species as well as the creation of new species including the human being.

But within the last 50 million years climate has not changed as fast as we expect it to change within the past and present century (IPCC, 2007c, p. 465). Furthermore, beside natural impacts on global climate, Earth’s temperature change since 1750 is mostly evoked by human activities: About 90% of the change in radiative forcing is caused by anthropogenic components (IPCC, 2007c, p. 3–4), e.g. industrial activities, transportation and land-use activities (Fig. 1).

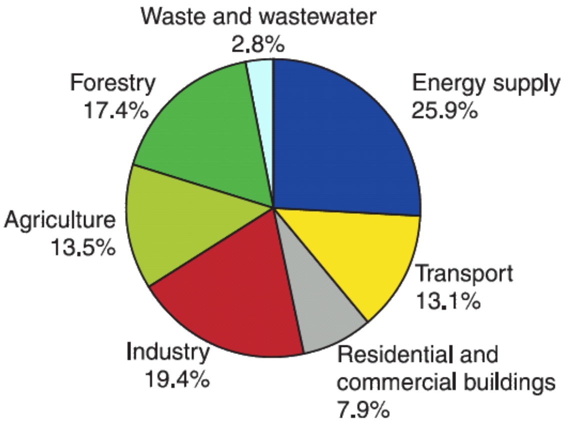

Figure 1: GHG emissions by sector in 2004 (IPCC, 2007b, p. 29)

Although impacts of increased surface temperature will differ by region, global warming will influence virtually all ecological and socio-economic systems worldwide. Temperature change modifies sea levels (due to melting ice shields) and rainfalls (due to higher evaporation) and thus has considerable impacts on agriculture and living spaces. Other impacts concern the health system – such as heatwave deaths and malaria expansion – and both the frequency and intensity of weather extremes like hurricanes (IPCC, 2007a, pp. 35–43). Hence, global warming hits humankind in a very sensitive way and has the potential for catastrophic, unpredictable and irreversible consequences.

1.2 The Economics of Climate Change

The term *economy* comes from the Greek words *ĭkos* (house) and *némo* (to distribute or to manage) and hence, *ikonomía* denotes "one who manages a household". If we (humans) consider the Earth as our household, economics seems to be an appropriate science to deal with the complex issues of climate change. This demands a deep understanding of physical and technical processes as well as aspects of humans' (strategical) behavior. For managing the household, physical and natural goods need to be distributed to all its members, i.e. present and future living species including the human species.

As only human beings seem to do science, also economic science has a somewhat anthropocentric viewpoint of how to manage the big global household.

But since nature provides essential and vital services to everybody, economics – even from such an anthropocentric point of view – is concerned with environmental questions. Humans promoted and still are promoting global warming, but its consequences have the most undesirable consequences effects on mankind. As humans still have the possibility of diminishing these consequences, there is now a great research demand of investigating how to solve this global problem or – in the words of William D. Nordhaus – how to manage the global commons. Thus, the economics of climate change typically deals with the following questions:

1. What are the future (economic) damages of global warming?
2. What are the costs of avoiding dangerous interference to the climate and what are these costs influenced by?
3. What are adequate policy instruments to reach a climate protection target?
4. How can mankind adapt to unavoidable consequences of global warming?

All these questions have their own problems to deal with. The first one is about estimating the amplitude of possible damages of climate change and the even more ambitious aim to quantify them. The second issue is about calculating opportunity costs, that is, what welfare losses do we suffer to reach a climate protection target in comparison to a baseline (business as usual) scenario that neglects damages by climate change?

These two crucial questions are often considered jointly in cost-benefit-analysis. The costs of potential climate damages are compared to the benefits of omitted mitigation. This way, an optimal economic development can be obtained. Of course, there exist further important constraints, for example strategical behavior of countries, enterprises and consumers following their own payoff maximizing strategies which may be incompatible with the socially optimal outcome. Thus, the third questions seeks for instruments to arrange private and social interests or national and global interests, respectively.

Research about costs and mitigation of climate change already started in the late 70s (e.g. Nordhaus (1977): Strategies for the Control of Carbon Dioxide) and theory of environmental economics offered since Pigou's work in 1932 a wide palette of policy instruments still valid for today's global warming problem. However, the economics of adaptation on climate change (fourth issue) is still a young area. First experience with global warming (e.g. see level rise) and uncertainty about whether the global mean temperature will increase less then 2°C in the 21st century boosted research activities about adapting on the changing climatic circumstances.[2]

Furthermore, each of these questions concerns important normative aspects of justice (distribution of costs and benefits intra- and intergeneral) and risk management (dealing with lots of uncertainties) as additional dimensions of analysis.

1.3 Scope of this Thesis

The scope of this work is to find appropriate policy instruments avoiding dangerous climate change and analyze these instruments with respect to their distributional effects. This analysis is orientated on three central questions:

- Which policy instruments correct the possibly negative effects of the utility maximizing behavior of the market actors that neglect environmental problems? In particular, what are the differences between resource taxation, energy taxation, abatement subsidy and a restriction of cumulative emissions?
- Which market imperfections – market power and technology spillovers – hinder or help to reach a climate protection goal and how to deal appropriately with them?
- How do several policy instruments benefit or burden capital, labor, tax or profit income recipients?

Existing research about policy instruments usually operates within partial equilibrium analysis and by confining on only market failures only. In contrast, policy models using the more capacious general equilibrium analysis often consider one or two policy instruments – mostly capital and labor taxes. Common integrated assessment models performing a general equilibrium analysis even do not consider policy instruments explicitly as they are social planner models which neglect strategical behavior. Hence, this thesis combines existing approaches to an intergrated policy assessment model which moreover allows for a detailed analysis of distributional effects.

The thesis is structured as follows: Sec. 2 describes the state of the art of climate economic research. First basic methods and concepts used in this thesis are described. Next economic disciplines (including policy instruments considerations) are presented, which are related to the economics of climate change. A differentiated overview over important integrated assessment models (IAM) points out existing shortcomings and hence further research necessities which can partially be considered by this thesis.

Sec. 3 explains the elements of the economic system and their interactions. After detailed introduction to the basic model structure three crucial extensions are developed – endogenous technological change, renewable energy and market power in the resource sector. It follows a calibration of model parameters that

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[2] One could also think of integrating the economics of adaptation into the estimation of costs, as there are several interdependencies between costs and adaptation possibilities.

also gives insight about sensitivity of important parameters. Finally, a short general analysis of the economic system treats considerations about market imperfections, time consistency and economic growth under exhaustible resources.

Sec. 4 focuses on the detailed analysis of policy instruments – the heart of this work. Evaluation is performed along four crucial policy design issues: (1) price vs. quantity policy, (2) input vs. output taxation, (3) competition policy and (4) technology policy.

The conclusion in Sec. 5 highlights the most important results and their relevancies for the climate change debate.

Additional information is located in the appendix: The reformulation of the time-continuous equations for the numerical treatment with computer programs (A), the derivatives of the used functions (B), the detailed Stackelberg-Leader problem formulation (C) and a brief description of the decomposition analysis (D). A list of all variables and parameters with explanations is located at the end of this thesis (E).

Program code of the developed model is available as encrypted ZIP file under:
www.pik-potsdam.de/members/kalkuhl/clipide-model
Password: `policyIAM`

2 Methods and Economic Theory

2.1 Methods

Game Theory In this thesis, the problem of avoiding global warming is treated within game theory. This mathematical theory investigates conflicts and cooperation between rational decision makers (called *players*), often with applications in economics, management and social sciences. Games are classified as cooperative and noncooperative or as static and dynamic. While in static games there is only one decision at one time to make, dynamic game theory generalizes decision making behavior by considering past and (possible) future behavior. Dockner et al. (2000, pp. 21–22) give the following definition:

> "A game is said to be dynamic if at least one player can use a strategy which conditions his single-period action at any instant of time on the actions taken previously in the game. Previous actions are those of the rivals but also a player's own actions."

The dynamics of decision making can be treated by differential equations describing the time-continuous development of state variables (differential game) or time-discrete difference equations (difference game) which are often used for numerical computations.

An important question subject to game theoretic analysis concerns the players' choice of strategies and hence the possible outcome of the game. The Nash equilibrium describes such a possible outcome by denoting a situation (i.e. strategy set) where no individual player has an incentive to deviate from his strategy given the strategy of the other players (see for formal definition Fudenberg and Tirole, 1991, pp. 11-14). Although the Nash equilibrium provides a plausible outcome consistent with typical assumptions of rationality of players, it is not necessarily a good prediction of outcome nor a "good" outcome. The first is the case if players do not play rationally or do not have essential informations for their decision-making. The latter is the case, if there is a strategy set unequal the Nash equilibrium that gives at least one player a higher payoff without reducing of other players' payoff. Such an improvement is also called *Pareto improving.* If no Pareto improving change is possible, the outcome is called *Pareto efficient* or *Pareto optimal.* A famous example of a Nash equilibrium which is not Pareto optimal is the prisoner's dilemma with defecting strategies as Nash equilibrium and cooperative strategies as Pareto efficient outcome that benefits both players respectively to the Nash equilibrium (Fudenberg and Tirole, 1991, pp. 9-10).

The application of the concept of Nash equilibrium as optimal strategy of each player given the (optimal) strategies of other players to dynamic games requires solving an intertemporal optimization problem of each player (Dockner et al., 2000, ch. 4.1)

If there are no asymmetries in information and strategic power, multiplayer games are usually modeled by simultaneous decision making with the Nash equilibrium as outcome. However, Stackelberg games assume a hierarchical asymmetry between players in the form that one player (called *Stackelberg leader*) makes her decision before the other players (*Stackelberg followers*) by considering secured information about the reaction of the followers after her move. Alternatively, the leader can commit herself to a public announced strategy which is considered by the followers in the same way as if the leader had made her move before them (Dockner et al., 2000, p. 109, and Fudenberg and Tirole, 1991, p. 75). Asymmetric power is typically considered in the investigation of market structures (e.g. monopoly or oligopoly power) or by a government that knows about the reaction of the economy to tax paths and that is not directly influenceable by economic players.

Intertemporal Optimization As main assumption of noncooperative game theroy every player maximizes his payoff (e.g. utility or profits) given the strategy of the other players. Players have to maximize their payoff over the entire (finite or infinite) time interval. The maximum principle of dynamic optimization developed by Pontryagin et al. (1962) supplies a formalism to devolve intertemporally optimal behavior (in terms of necessary and sufficient conditions) by reducing the intertemporal problem to a static maximizing problem of the Hamiltonian with additional equations of motion and transversality conditions for shadow variables (for detailed information see Chiang, 1999, part 3).

Numerical Optimization Software While the strategy of Stackelberg followers is determined analytically by applying the maximum principle of dynamic optimization, the intertemporal optimization problem of the Stackelberg leader is solved by a numerical optimization software because analytical treatment would be too elaborate. Within the *General Algebra Modeling System* (GAMS, version 22.3; see Brooke et al. (2005) for further documentation) the solver CONOPT3 is used to solve the non-linear optimization problem (NLP). Because GAMS can only treat static problems, the time-continuous optimization model has to be transformed in a time-discrete (static) one. CONOPT3 works with a generalized reduced gradient method (Abadie and Carpentier, 1969): After finding a feasible solution, derivatives of the Jacobian of the constraints are computed and evaluated. If an improvement of the objective is possible, the next iteration closer to the local optimum starts and the procedure is repeated.

2.2 Approaches to Valuating and Decision Making

Cost-benefit Analysis A common practice in environmental economics is to evaluate an environmental program or political measure by comparing its costs with its benefits. Furthermore, such a cost-benefit analysis (CBA) often seeks to find the optimal environmental program by comparing several possibilities and its outcomes. With regard to climate change it is often difficult to quantify the benefits – i.e. avoided damages – of environmental policy, because they touch huge time scales and concern future preferences of future generations as well as many ecological systems which are not primarily subject to economic consideration (Dowlatabadi, 1999). In developing an alternative approach of valuating damages, Manne et al. (1995) point out the problem of common methods of quantifying damages, in which "[...] economists count what they can count, and not necessarily what counts". Morgan et al. (1999) criticize common simplifications made for cost-benefit analysis – e.g. widely neglected differing distribution of costs and benefits or unrealistic simplification about Earth's systems response to human impacts – which result in problematic policy recommendations of underprotection of the environment.

Tolerable Window Approach An alternative to the CBA constitutes the tolerable window approach (TWA) developed by Petschel-Held et al. (1999)

who define physical, ecological, social and economic constraints (also called *guardrails*) which form a tolerable window for potential economic and political solutions.[3] Yohe (1999) considers it an important strength of this approach that quantification of all damages is not required and important sensible thresholds of the Earth system can be regarded whose exceeding might have catastrophic implications beyond meaningful economically valuable damages. However, defining these constraints requires again evaluation and valuation (but not quantification) of impacts and is subject to difficult scientific, political and public consideration.

Cost-effectiveness Analysis Regardless of whether the political (environmental) target is economic efficient or not, cost-effectiveness analysis seeks to find options to achieve this aim with the lowest costs possible (Helfand et al., 2003, p. 270). This approach considers political reality of existing constraints or targets to deal with. However, if the target already is an efficient one, cost-effectiveness analysis yields to the same outcome as optimal CBA.

Nevertheless, even supporters of CBA admit that it is only one benchmark of evaluation beside others like distributional criteria (Portney and Weyant, 1999; Bradford, 1999). This yields in principle for the cost-effectiveness analysis, which also usually does not consider distributional effects if they are not already covered implicitly or explicitly in the political target formulation. Furthermore, the TWA can be combined with a cost-benefit or cost-effectiveness analysis to highlight economic and technological possibilities that provide maximal welfare within the tolerable window.

With respect to climate economic integrated assessment models, the cost-effectiveness approach often assumes a given political guardrail of maximal global temperature change within a certain time interval. Such a mitigation target is the 2°C–constraint[4] formulated by the WBGU (1995), while in contrast cost-benefit approaches determine the optimal temperature change endogenously by using a damage function.

2.3 Economic Theory and Policy Instruments

Economics of climate change has to deal with broad and interdisciplinary research questions. Starting from physical insights about the link between CO2 emissions, global warming and differing spatial impacts, main emission sources and its mitigation options are examined. Formulating a climate protection goal requires a detailed estimation of future damages and its valuation. Hence, ethical issues are touched, e.g. how to quantify ecological damages or how to deal with unequally distributed damages. Furthermore, achieving such climate protection demands for a good understanding of technological options for a sustainable economic development. The International Panel on Climate Change (IPCC) is a scientific body, which collects and prepares research to the physical science basis (working group I), to impacts and adaptation (working group II) and to mitigation of climate change (working group III). Assessment reports

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[3] Such constraints may touch for example temperature changes, minimal consumption levels for every human being, limitation of distributional differences in incomes, biodiversity considerations etc.

[4] I.e. 2°C of temperature change within the 21st century.

(e.g. IPCC, 2007b) highlight fields of certain scientific knowledge (of consensus) and of further research necessity (in controversial areas).

Other important economic tools are integrated assessment models (IAMs). They try to find an optimal economic development by considering estimated damages (cost-benefit approach) or to a achieve a given climate policy target (cost-effectiveness approach).

Game theoretic analysis is used for analyzing the interplay of crucial world regions and their (existing, missing or differing) climate protection targets. Important research questions concern the stability and time consistency of mitigation coalition and incentives to join, to leave from or to free-ride in such a coalition. Another application of game theoretic modeling regards the strategical behavior of economic actors. Economic theory of market failures uses (sometimes implicitly) game theoretic approaches when derivating incentive based instruments to align Nash equilibrium with Pareto optimum.

Valuation of normative questions cannot be made by scientists (alone), but requires a broad debate of global society. Nevertheless, scientists can point out mechanisms and consequences of economizing that are subject to normative evaluation. A big challenge for economic science lies in a clear and exact distinction between descriptive scientific analysis and normative assumptions.

In the following I introduce some important economic subdisciplines that form the scientific base of climate economic research with focus on mitigation.

2.3.1 Microeconomic and Macroeconomic Theory

This thesis lies in the intersection of micro- and macroeconomics. It considers the interplay of entire sectors in a closed economy and the payoff-maximizing behavior of individual enterprises and households (c.f. Linde, 1992). This allows for the use of important microeconomic theorems like the existence of market clearing (and efficient) equilibrium prices (c.f. Mas-Colell et al., 1995, ch. 16–17). A common approach to combine micro- and macroeconomic analysis is the abstract model of representative households and firms, but which provides a good model of reality only under very restrictive assumptions (c.f. Morgan et al., 1999). However, Lengwiler (2005) shows the considerable difference between the representative household with “representative” discount rate and heterogenous households with differing discount rates.

Another important classification going across micro- and macroeconomic analysis concerns the anticipation of endogenously determined market equilibria by the economic model. Partial equilibrium analysis assumes at least some exogenously given markets (e.g. demand or supply curves) that are independent of feedback effects. In contrast, general equilibrium analysis regards a preferably complete economic system with all market equilibria endogenously determined (Mas-Colell et al., 1995, p. 538). An exact graduation is not always possible, as there are smooth transitions from partial to general equilibrium with respect to the importance of neglected feedback effects.[5]

2.3.2 Welfare Economics

Considering a whole society instead of a single household raises the question of the aggregation of individual preferences into collective and social preferences.

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[5] The “perfect” general equilibrium analysis is doubtlessly an ideal of concerning the whole universe in one model with all possible feedback effects.

Although Arrow (1950) shows that in general individual preferences cannot be converted to a social preference order which is consistent with individual preferences, a missing definition of society's utility (or welfare) is hardly imagineable for evaluating policies. Such a social welfare serves as measure for society's well-being. Hence, a socially optimal outcome (of economic or political activity) is one that maximizes social welfare. However, almost all climate economic models use a CES utility function (or logarithmic utility function as special case of the CES function) which implies well-being as a consequence of higher consumption. Even this concept is subject to critique by the economy of happiness (e.g. Layard, 2006) which considers more determinants of human well-being.

2.3.3 Economics of Taxation

Usually the problem of charging taxes arises to finance public expenditures for public goods like education, infrastructure, administration etc. To collect revenues a government can impose taxes on factors (unit tax) or on factor prices (ad-valorem tax). Differences between both approaches concern mainly the levels of taxincome if either prices or quantities of factors are more uncertain and hardly predictable. Although a tax can be charged on the purchase or on the selling side, allocation effects remain the same and only elasticities of demand and supply decide who has to pay which part of the tax burden (Salanie, 2002, pp. 16-22).[6]

Every tax on an economic activity like producing, selling, buying or investing distorts the allocation of the market outcome as it influences economic decisions linked to the taxed activities. Thus, if markets are already efficient, such taxes reduce overall efficiency. Then, the only possibility is to charge a tax which is not linked to any economic activity, a so-called lump-sum tax, which – following the second welfare theorem – allows redistribution without welfare losses (Salanie, 2002, part II).[7]

2.3.4 Environmental Economics

Environmental economics explains the occurrence and the overcome of excessive environmental pollution by external effects (Cropper and Oates, 1992). Hence, a main reason for market failures concerning environmental quality is the non-appropriability of many environmental resources (Starrett, 2003, pp. 104-106). If property rights for an environmental resource (e.g. clean air) are not well defined or cannot be enforced with adequate effort, such a resource becomes a public good accessible and depletable to everybody. This leads in general to an overuse of resources as the produced externality – degrading the public good – is not considered by the real price of degradation.[8]

To classify solutions of this problem, Cropper and Oates (1992) distinguish between economic incentive based instruments like effluent taxes, abatement subsidies, permits or negotiations (à la Coase) and command-and-control instruments like (technology) standards and regulations. Incentive based instruments give individual firms more freedom how to solve the environmental problem and allow for (market based) cooperation to achieve a certain mitigation target by using firms' differing abatement costs (e.g. via marketable permits). In contrast

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[6] Hence, the more inelastic side – i.e. the party who can not react with the greater flexibility in quantity reducing due to modified net prices – has to bear the greater part of the tax burden.

[7] In reality such a tax could be a poll tax equal for every person.

[8] In the language of game theory, the Nash equilibrium is not the Pareto optimum.

by setting (inflexible) standards equal for all enterprises, command-and-control instruments often cannot capture adequately the large differentials in abatement costs across polluters and therefore fail to achieve the optimal economic outcome (Goulder and Parry, 2008).[9]

Bargaining (Coase Theorem) If property rights of polluting are well defined and can be enforced – either in the way that the polluter has the right to his polluting activity or the consumer has the right to a clean environment – both parties will begin a bargaining process of paying abatement costs or compensation for damages, respectively, resulting in a Pareto optimal level of pollution, if transaction costs are neglected (Coase, 1960). For this outcome distribution of property rights to polluter or consumer is irrelevant although distribution of wealth will differ in favor of the party who has the property right (Mas-Colell et al., 1995, pp. 356–357). Within the class of incentive based instruments, the Coase solution of negotiations is also considered not to be feasible in practice because of the immense effort of negotiations of millions of affected consumers by environmental damages and thousands of polluting firms. Furthermore, the Coase allocation considers compensation for the victims of pollution and thus it sets negative incentives in individual defensive activities against environmental damages (Cropper and Oates, 1992). Another important critique of the Coase theorem mentions that the bargaining outcome indeed depends on assigning the rights as such an allocation influences the income of both parties and hence may influence level of compensation request or abatement payments (cf. Starrett, 2003, p. 113).

Effluent Taxes The idea of an effluent tax is to drop demand (here for emission causing fossil resource extraction) due to a rising price. The environmental tax can be charged on several places and products (Goulder and Parry, 2008): on emissions causing the environmental damage, on the input factors that cause the later emissions (e.g. fossil resource tax) or on the output of a production process with emissions as by-product (e.g. fossil energy or final consumption goods). A special and popular case of effluent tax is the Pigovian tax (Pigou, 1932) that is attached directly to the polluting activity on exactly that level such that marginal benefits from reduced pollution equal marginal abatements costs (Cropper and Oates, 1992). While this approach requires a quantification of damages and benefits (cost-benefit approach), a modified emission tax could be used by defining an environmental target (of concentration) that must not be exceeded (cost-effectiveness approach). From a massbalance point of view, Vatn (1998) shows that input taxation is equivalent to emission taxation if emissions are homogenous and transaction costs of monitoring and enforcing are zero. Schmutzler and Goulder (1997) state that under high monitoring costs, emission tax may be suboptimal and output tax (or combination) may be a more efficient second-best option. They show that output tax is more appropriate, (i) the higher monitoring costs are, (ii) the lower the abatement options for emissions are (i.e. the lower the carbon substitutability is), and (iii) the better the substitutability of output is. Thus, several demand decreasing (output) taxes are able to achieve an emission reduction but efficiency may be lower than that

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[9] However, in idealized world of perfect information for the regulator and no transaction costs of information gathering and policy measures, the government could set a certain standard perfectly adapted on individual circumstances of each firm.

of an emission or input tax. Further modifications of the level of environmental or Pigovian tax are necessary if multiple externalities are considered like market power or positive technology spillovers and no other taxes are applicable (Goulder and Parry, 2008). Then, such a tax would have to correct more than one market failure that are usually involved in environmental problems.

An important feature of tax instruments are their revenue collecting properties. Thus, by collecting further income, the government can reduce existing taxes with negative distortions for the economic system (e.g. payroll taxes) and increase overall welfare due to the so-called double-dividend effect (Goulder, 1995).

Abatement Subsidies Although subsidies on abatement can set the same incentive for abatement on the enterprise level like an emission tax, they might also give incentives to increase overall production due to decreased production costs and thus augment overall emissions (Cropper and Oates, 1992; Goulder and Parry, 2008).

Quantity Instruments An alternative way to achieve an efficient pollution level is to calculate the optimal emission level within the cost-benefit approach and then distribute emission permits of that amount. While in principle this results in the same outcome as the Pigovian tax, there are differences respect to many institutional aspects (Cropper and Oates, 1992). An important discrepancy of quantity and price (tax) instruments was stated by Weitzman (1974) regarding uncertainties concerning marginal costs and benefits (of abatement): If the marginal benefits curve has a greater absolute slope than the marginal costs curve, quantity restriction guarantees not to exceed critical pollution levels with disastrous consequences (if the Pigovian tax was not calculated correctly). In contrast, if the marginal costs curve has a greater absolute slope than the marginal benefits curve, a price instrument avoids excessive mitigation costs (if the permission quantity was not calculated correctly). Pizer (2001) transfers these insights to the global warming problem and highlights important aspects of the nature of global warming for economic considerations. Because GHG concentration increases due to GHG emissions over several decades and the optimal level GHG concentrations is not obvious, he argues for a price policy that might be extended by a long-term quantity mechanism to avoid crossing a certain threshold of potential catastrophic consequences. Furthermore, he emphasizes not to restrict annual emissions but accumulated emissions (as they determine the concentration level) and hence provide more flexibility of the time path of abatement.

In the discussion about price and quantity instruments the question of distributional effects could attract only little attention. If the government imposes a quantity restriction, this would be the same as a free allocation of tradeable permits. Helfand et al. (2003, pp. 280–281) state that restricting the level of output, regulation acts like a government-imposed cartel with even higher possible profits than in baseline scenario. Maloney and McCormick (1982) give some empirical evidence of rising profits at the example of cotton-dust regulation in the U.S., but there exists only little research about profit raise of quantity restriction. Hence, in this work I examine this point of great actual relevance in climate policy debates.[10]

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[10] The largely free allocation of pollution permits by the EU emission trading scheme or

If auctioned, pollution permits can achieve the same double-dividend effect as taxes since they collect revenues for the government. Although in theory the permit price has to equal the Pigovian tax, uncertainties cause a crucial asymmetry within price and quantity instruments: While tax income is more predictable due to experiences in historical emission levels (and emission reduction due to tax is afflicted with uncertainties), the revenues due to permission auction as well as the later certificate price are difficult to forecast. A combination of price and quantity instruments may overcome the weakness of each of the single approach regarding the differing outcome under uncertainties (Cropper and Oates, 1992; Edenhofer et al., 2007).

Information Instruments Well-functioning markets depend usually on informed consumers and producers. Thus, information programs like product labeling and reporting requirements may help to reduce environmental burden (Stavins, 2003, pp. 411–414). However, this option is not considered very much by environmental economists,[11] possibly because the impact of such programs is seen as very small (IPCC, 2007b, pp. 764–765).

What insights can be transferred from environmental economics to the problem of climate change? In the context of global warming, a stable climate can be seen as the (global) public good that is damaged by individual GHG emissions. Although environmental economics can offer a palette of adequate policy instruments to internalize harmful impacts of emissions, there is a problem of a missing global institution that could enforce all polluters to consider these externalities (IPCC, 2001, p. 607–609). Even international contracts like the Kyoto protocol cannot make countries commit their mitigation efforts as there exist incentives of free-riding for every single country. Hence, an important political challenge is to overcome this dilemma. Other issues that make climate change problem inherently different from textbook environmental economic problems (e.g. pollution) concern the determination of optimal GHG concentrations in the atmosphere due to high uncertainties, potentially irreversible consequences and the long time horizon of at least one century which has to be considered (IPCC, 2001, p. 606–609).

2.3.5 Economics of Exhaustible Resources

Exhaustible resources are important for the economics of climate change, because more than half of the global GHGs result from burning fossil resources.[12] Emissions of carbon dioxide are closely linked to the extracted amount of fossil resources. Understanding the rate of resource extraction crucially determines future emission paths and policy instruments to decrease emissions by decreasing resource extraction. It can be questioned whether the real size of deposit

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demands for a moratorium of coal-fired power plants fall also in the class of quantity restriction instruments with possibly raising profits for enterprises as consequence.

[11] If at all mentioned in textbooks or survey articles to environmental economics, information programs are treated only very briefly by mention some empiric examples and their consequences.

[12] In 2004, CO2 from burning fossil fuels formed 56,6 % of anthropogenic greenhouse gas emissions (measured with respect to the 100 year global warming potential to convert non-CO2 emissions). Other important GHG sources were deforestation (17,3 %), methane emissions (14,3 %) and nitrous oxide (7,9 %) (IPCC, 2007b, p. 103).

of fossil resources and their decreasing extraction due to scarcity will lead to a sufficient reduction of emissions.

Fundamental research about exhausting of a finite resource stock was performed by Hotelling (1931). The rule for efficient resource extraction postulates that marginal productivity of capital equals the relative change of marginal product of resources, if extraction costs are neglected:

$$y'_K = \frac{\dot{y}'_R}{y'_R}, \tag{1}$$

where y denotes production of final goods, K capital and R resources.[13] The intuition behind this rule is that the value of the resource stock has to increase with the interest rate as otherwise extracting more resources and investing that money would bring more present-value benefits. In the case of (constant or changing) extraction costs modified formulas of this rule hold (Hanley et al., 1997, Sec. 9.3)

The oil crisis in the 70s boosted investigations about the influence of taxation and market structure on resource depletion (c.f. Dasgupta et al., 1981) and gave reason to the question whether economic long-term growth is possible if resources are finite (e.g. Stiglitz, 1974b,a; Hartwick, 1977; Ströbele, 1984). I will discuss this issue briefly in Sec. 3.4.3 although the final answer of this question is still open.

Realistic models of resource depletion take extraction costs into account that are often given exogenously by estimated constant marginal extraction costs. To specify extraction costs the state of depletion and the accessability of remaining reserves play an important role (Rogner, 1997). Usually low-cost resource deposits will be extracted first while more expensive deposits will be depleted later. This increasing cost-effect interferes with cost-decreasing technological development but which usually cannot dominate the rise of the extraction costs with proceeding stock depletion (cf. Edenhofer et al., 2005; Nordhaus and Boyer, 2000, p. 54).

Sinn (2007b,a) considered these insights to analyze policy instruments against climate change. His policy recommendations (like an increasing resource subsidy) partially differ considerably from common advices. In particular, he shows that an exponentially increasing resource tax would even worsen the problem of global warming.[14]

2.3.6 Endogenous Growth Theory

In early neoclassical growth models economic growth emerged by exponential labor (population) growth, given capital or labor saving technological progress (Barro and i Martin, 1999, pp. 32ff.). The golden rule of capital accumulation indicates that maximal (constant) per capita consumption level is reached if marginal product of capital equals labor growth rate plus depreciation rate. An important extension of this rule was achieved by Ramsey (1928) by considering endogenous saving rates and intertemporal utility. The Ramsey rule therfore incorporates pure time preference rate ρ, elasticity of marginal utility θ and consumption growth rate $\hat{C}$ to equate the interest rate in the optimum by $r =$

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[13] Formal conventions used are listed on p. VII.

[14] Important assumptions responsible for his conclusions are: constant elasticity of resource demand, infinite time horizon and formulation of a mitigation target by using a damage function.

$\rho + \theta \hat{C}$. Nevertheless, these approaches of using exogenous technological change lack for an understanding and explaining of the forces and determinants of economic growth.

Romer (1986) introduced the concept of knowledge creation as a side product of investments: Firm's individual capital stock cause positive externalities in form of spillover effects for the entire sector. This form of modeling endogenous technological change (ETC) is called *learning-by-investing* or *learning-by-doing* (LbD) (Barro and i Martin, 1999, p. 146).

Alternatively, expenditures in research and development (R&D) generate endogenous technological change. While the pristine modeling approach with micro-foundation was introduced by Romer (1990), several modifications by Jones (1995) to eliminate scale-effects of the Romer model and finally for climate-economic modeling by Popp (2004, 2006a,b) lead to a more elementary mathematical description. Because of missing micro-foundation due to simplifications, R&D expenditures are public (paid by the government) and hence unfortunately cannot capture microeconomic considerations in private R&D efforts by firms (otherwise Zagler and Dürnecker (2003) and Greiner et al. (2005, Sec. 2.4) emphasize the meaning of public expenditures for economic growth).

However, both concepts – learning-by-doing and R&D expenditures – contribute to technological change and economic growth. Greiner et al. (2005) for example state with regard to time series analysis that learning-by-doing effect dominates in economies on a low stage of economic development, while R&D expenditures and other growth forces dominate in highly developed economies.

Market failures in technology markets occur due to two crucial properties of knowledge and innovation. The first refers to the very limited excludability of invented knowledge to competing firms, the second to the great uncertainties affected with research and their utilizable and profitable outcome. A third market failure can be seen in the slow diffusion of technological innovations, because firms and consumers do not know them or because they are not flexible enough in changing their consumption behavior.

For each of these failures there exist several policy instruments: Vollebergh and Kemfert (2005) emphasize the importance of a (temporal) monopoly position of the inventor, e.g. by holding a patent to exclude competitors to imitate their invention. Another common instrument is a capital subsidy for innovative investments that covers sectoral spillover-effects and hence aligns private and social rate of return. Jaffe et al. (2005) suggest beside capital subsidies several governmental activities like basic research programs, general education improvements, public-private-partnerships and public R&D expenditures to stimulate innovative technological change. On the demand side government can facilitate market entry and market share of new technologies by own consumption changes. However, technology distribution should always be technology-neutral – i.e. orientated on political targets (like emission standards) and not on a particular technical implementation – to avoid encouragement of technologies that are already outdated by (existing or potential) new ones. Hence, Jaffe et al. (2005) also mention the importance of information policies, energy standards and labels to change possible inertial consumption behavior of consumers.

In the context of global warming the question of interference with environmental policy emerges. How does technological change influence emission taxes and the timing of abatement? Several studies indicate, that endogenous technological change postpones abatement efforts in favor of overall productivity growth in near-term future (e.g. Grübler and Messner, 1998; Goulder and

Mathai, 2000). However, as there are several approaches to implement technological change, timing of abatement depends highly on the model structure. In an overview of existing model approaches, Löschel (2002) concludes that exogenous technological change approaches shift abatement most of all in the future because one can wait until efficiency is on the appropriate level. In contrast, learning-by-doing approaches cause early abatement efforts (because only actual "doing" and experience collecting makes a technology cheap for extensive future application). Models with R&D lie somewhere between learning-by-doing and exogenous technological change models, because research expenditures can generate relatively fast new technologies.

In respect to the GHG emission decreasing carbon tax Goulder and Mathai (2000) state that with induced technological change carbon taxes have to decrease due to lower abatement costs. Hart (2008) analyzes another interference between Pigovian tax and imperfect technology markets in a model of completely endogenized output and energy efficiency augmenting technological change. Increasing the carbon tax above the Pigovian level reduces the underinvestment in the energy technology market which may cause welfare losses or gains depending on the grade of underinvestment in the production sector. In an empirical analysis for the U.S. Hart estimates emission tax increases of about 10 % above the Pigovian level.

2.3.7 Industrial Organization

In a competitive economy all firms act as price takers and take prices as given. But there are many markets where single firms influence prices by changing supply or demand. A monopolist can change its output quantity q_m and observe the induced price change $p(q_m)$.[15] Thus, by knowing the inverse demand function, he optimizes his output level according to:

$$\max_{q_m} \quad p(q_m)q_m - c(q_m), \tag{2}$$

where $c(\cdot)$ constitute the production costs. In the case of more than one firm, the Cournot model describes simultaneous quantity choices of competitors to influence the market price. That is, the maximizing problem of the i-th firm reads:

$$\max_{q_i} \quad p(q_i + q_{-i})q_i - c_i(q_i), \tag{3}$$

with q_{-i} as the aggregate output of competitors, $q = q_i + q_{-i}$ overall output and $c_i(\cdot)$ the cost function of the i-th firm (Mas-Colell et al., 1995, pp. 389–391). The Cournot model subsumes the monopoly case where $q_{-i} = 0$ and the competitive case where $\frac{\partial p(q_i+q_{-i})}{\partial q_i} = 0$ as limits. In the Nash equilibrium market price is higher than the competitive price, and thus overall output is lower.

For the extraction sector Stiglitz (1976) investigates the impact of monopoly market structure for the resource extraction path. He shows that a monopolist conserves resources more than in the competitive case and that the time path of extraction is flatter. A more generalized study of several forms of market structure is given by Stiglitz and Dasgupta (1982). They confirm, that market power flattens extraction and price path and leads to higher resource conservationism.

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[15] An analog model holds for the price as control variable and the quantity as observed (demand) function of the price.

Beside the problem of negative environmental externalities, Im (2002) calculates different taxes (or subsidies) to achieve the socially optimal extraction path in a monopolistic resource extraction model with constant elasticity of demand and constant marginal extraction costs. As one important result, a profit tax does not serve to achieve efficient extraction. Daubanes (2007) shows that there are infinite optimal tax paths by using the fact that the resource monopolist has to exhaust asymptotically the whole resource stock (under the same assumptions as Im (2002)). He also considers a tax on the consumer side that results in an equivalent outcome as taxes on the supply side.

Back to environmental policy instruments, Buchanan (1969) criticizes the widely neglect of monopolistic market structures in the debate about internalizing external effects and mentioned that applying a Pigovian tax under monopolistic structures decreases efficiency and, hence, social welfare. The argument for his simple model (with constant unit costs) holds for the case, that the same Pigovian tax level is used as in the competitive economy and that the monopoly price is higher than the social (i.e. corrected) price. Another important point regarding differing firm's market power highlights Lee (1975): Firms with higher market power are less charged (or are even subsidized) than firms with small or no market power to reach the social optimum. Smith (1976) states that two instruments are needed to resolve both market failures: one for the monopoly power (output subsidy) and one for the pollution (effluent charge). Hence, with m firms there have to be $2m$ instruments. Neglecting individual differences between oligopolistic firms, Misiolek (1980) calculates the optimal effluent tax that covers both distortions – external costs (Pigovian tax) and monopoly power (output subsidy) – in one single instrument. The outcome can be a tax or a subsidy depending on available technologies, social costs and elasticity of demand.

Within the theory of the second-best, Hammer (2000) argues that monopolistic market structures can lower overall emissions due to overall output reduction. Bennear and Stavins (2007) cite several studies that calculate the optimal number of market participants so that the negative effect of externalities is exactly outweighed by the conservation effect of oligopolistic market structure.[16] Hence they advocate for a coordination of anti-trust and environmental policy.

Interplay of Market Failures Above considerations emphazised the complexity of climate protection policy that is caused by the interplay of several market failures. Bennear and Stavins (2007) distinguish three qualitative forms of interplay: (i) jointly ameliorating, (ii) jointly reinforcing and (iii) neutral (no mutual impact). Examples already mentioned were the case of emission reduction due to monopoly (which tend to jointly ameliorate) and the case of technological change and impact on emissions (which are in general ambiguous, depending on model assumptions).

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[16] But these studies are only in a very limited way transferable to the monopoly case of resource extraction with its own dynamic "nature" of resource stock exhausting. I get back to this question again in Sec. 4.3.

2.4 Review of Climate Economic Models

While bottom-up models contain a detailed energy system and hence handle several high-resolution technological options, top-down models focus on the macroeconomic system to determine global or regional demand for energy from further macroeconomic variables. Almost all IAMs are social planner models. Their scope is to determine endogenously an optimal concentration level or to calculate mitigation costs for a given temperature or concentration target.

One of the earliest climate economic cost-benefit analysis was performed by Nordhaus (1991) who improved his top-down model with integrated climate module and damage function by considering technological change and world regions in his DICE and RICE models (Nordhaus and Yang, 1996). Although he uses a simple (but maybe therefore charming) model structure neglecting renewable energy options and endogenous technological change, his model is a reference model.

The innovating contribution of the MERGE model (Manne et al., 1995) lies in its more detailed consideration of energy technologies and in its alternative approach to quantify damages of climate change by estimating the willingness to pay for a stable global climate.

The ENTICE model of Popp (2004) and its extension by backstop energy ENTICE-BR (Popp, 2006a) tries to apply existing theories of endogenous growth (orientated on Romer, 1990; Jones, 1995) to climate economic models, but also uses exogenous technological growth for overall output growth and fixed crowding-out ratios of endogenous energy R&D.

The cost-effective MIND model of Edenhofer et al. (2005) and its enhancement ReMIND contain a macroeconomic system of completely endogenized technological change which is hard-linked to a high-resolution energy system which allows for studying a broad mix of energy options including carbon capture and storage. Its important political implication is that ambitious climate protection targets – like the 2°C target of the WBGU (1995) – are feasible without dramatic welfare losses (i.e. approx. 0.8 % GDP losses neglecting damages of climate change).

The sensation causing *Stern Review* (Stern, 2007b) supports this assessment by the conclusion that costs of such ambitious mitigation are outweighed by the benefits of avoided future damages. After publishing of the *Review* several contorversal debates started about the adequacy of the low discount rate used for the exhausting estimation and quantification of economic damages which resulted in a high valuation of future benefits of undertaken mitigation.

The missing market equilibrium consideration of all the above IAMs is incorporated in a decentralized model of Grimaud et al. (2007) which looks about the ENTICE-BR model. However, fossil resource extraction, endogenous overall productivity growth and impacts on income distribution are neglected.

2.5 Evaluation Criteria

Most of the economic analysis of policy instruments concentrates on the criteria of economic efficiency. But there are several other criteria important for an integrative evaluation of policy instruments. Goulder and Parry (2008), for example, give four competing criteria subject to evaluation:

1. economic efficiency or cost-effectiveness

2. distribution of benefits and costs
3. minimizing the risk of failing the political goal due to uncertainties
4. political feasibility

While the first three criteria can be analyzed via quantitative model experiments, the last cannot be treated within a model but with plausibility considerations. Determinants of political feasibility are next to distributional effects the state's influence on the economy (state's share). Another normative criterion not primarely covered by the social welfare function is the claim for sustainability (e.g. Arrow et al., 2004) that guarantees welfare to future generations.

The IPCC (2007b, p. 751) states in principle the same four criteria (instead of risk minimizing he speaks of environmental effectiveness), emphasizing the importance of a fair distribution of costs and benefits: "[...] distributional considerations may be more important than aggregate cost effectiveness when policymakers evaluate an instrument." (IPCC, 2007b, p. 752)

2.6 Implications and Challenges

Above presentation showed that extensive research already exists on the problem of avoiding dangerous global change.

The shortcoming of existing integrated assessment models lies in their restrictive scope of aggregated socially optimal climate protection. Cost-benefit IAMs ask what might be optimal temperature levels while cost-effective IAMs calculate mitigation costs of given temperature or concentration levels. Policy instruments are only considered secondary, e.g. by assuming a Pigovian tax of the level of damage. Because these model frameworks neglect strategical behavior of important sectors they can neither compute nor evaluate appropriate policy instruments with respect to efficiency and distribution. Furthermore, these models cannot deal with second-best instruments and existing market distortions (Böhringer et al., 2007).

On the other hand, detailed analysis of policy instruments for specific market failures is often performed in partial equilibrium models which neglect important macroeconomic feedback effects. Common analysis of factor taxation within general equilibrium models widely concentrates on only one or two policy instruments like capital and labor tax (e.g. Judd, 1987) and does not consider environmental aspects.

Most of the policy instruments above mentioned can be categorized in three classes which will be considered in this thesis: taxes (including subsidies), quantity restrictions and R&D expenditures. Thus, an integrated assessment model which combines the general equilibrium approach of existing climate-orientated IAMs by strategical constraints of economic actors and simultaneously by a portfolio of policy instruments could provide important insights in concrete measures of effective and efficient climate protection. Such a model can also help to highlight distributional effects of mitigation policies by analyzing several factor and tax payment flows.

This approach allows to reconsider important policy design questions like the debate about price and quantity instruments and input–output taxation.

A further task of this work will be to investigate in more detail the interferences of multiple market failures and their consequences for climate protection and functional income distribution. None of the presented IAMs or climate policy models consider the impact of market power in the resource sector on climate policy instruments and income distribution although there is no fossil resource market of perfect competition in this world.

To avoid the problematic and controversial exercise of choosing a damage function and a social time preference rate to quantify (in a very sensitive way) future damages of global warming, I will follow the tolerable window approach by assuming a politically and socially accepted purpose of a maximal temperature change which should not be exceeded.[17]

The problem of an adequate modeling of endogenous technological change is constitutional (also for this work) because there are still lacks of a full (and mathematically descriptable) understanding of economic growth. Furthermore common growth theory widely neglects the problem of (exhaustible) resources and innovations in energy efficiency: The entire book of Barro and i Martin (1999), for example, does not consider exhaustible resources. Hence, climate economic models are confronted with imperfect growth theory to integrate in its models.

However, with regard to distributional effects no objective and widely accepted concept exists of what an optimal distribution might be. I limit this work on illustrating policy impacts to one kind of distribution, namely functional income distribution of households. This approach serves as indicator for the consequences of mitigation policy for two important social groups: capital income recipients (*capitalist household*) and labor income recipients (*labor household*).

Despite several criticism and dubiety to assumptions and simplifications of the standard neoclassical economic approach, the problem of economic analysis of mitigation policies still remains complex. Hence, policy implications and recommendations have to be considered carefully and in the light of assumptions which do not always describe reality perfectly.

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[17] From my point of view, not the idea of weighting costs against benefits is the problem, but the application of this approach in common scientific practice with inappropriate simplifications and overvaluation of the policy implications of CBA made with such simplified assumptions. Nevertheless, by using an appropriate sharp damage function and low social time preference rate, a cost-effectiveness analysis within the TWA (e.g. given temperature constraint) can be transformed to a cost-benefit analysis with the same outcome.

3 Model Development and Analysis

Based on the neoclassical Ramsey model of representative household and final good producing firms (Barro and i Martin, 1999, chap. 2) I consider several extensions concerning energy consumption and GHG disposals. The most important extension naturally concerns the use of fossil resources that is related with GHG emissions. Every climate related IAM has to regard at least this factor – many others do furthermore include several energy related modifications. Here, the key variables describing the economic system are capital K, labor L and fossil resources R which are the raw factor of every other economic good. Fossil energy E_{fos} is a product of capital and fossil resources, renewable energy E_{ren} is produced of capital only, and final goods Y are created from capital, labor and energy. Final goods can be consumed to raise well-being immediately, or they can be reinvested to raise capital stocks for a higher production (and consumption) in the future.

Figure 2 shows the macroeconomic structure of the economy considered in this work. To simplify matters only factor flows are shown – although every factor flow in one direction receives a payment flow in the opposite direction to symbolize factor payment in the market economy.

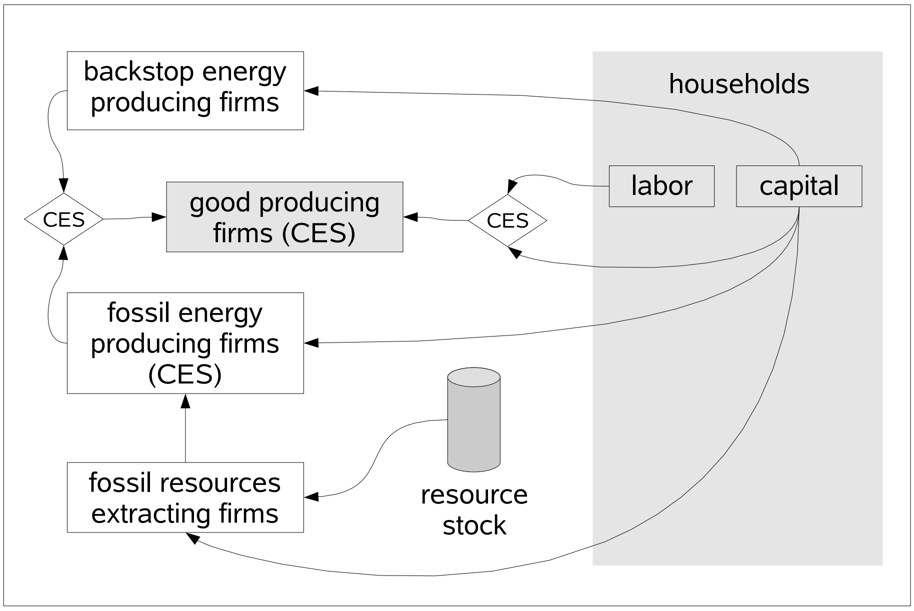

Figure 2: Macroeconomic model structure. Factor composites and sectors labeld with CES combine factors with constant elasticity of substitution.

Considering the decentralized system of market economy the ownership of all factors must be defined to allocate factor payments: The households provide labor and capital, the resource stock is owned by resource extracting firms and the produced final or factor goods are property of the specific production sector.

The influence of the government is restricted to taxation and R&D expenditures, that is the government can not influence economic behavior *directly* by dictating prices or quantities. But the conceptional construction of the government as Stackelberg leader makes it very powerful to manipulate almost arbitrarily prices and quantities *indirectly*. A crucial question is the choice of the objective function of the government that need not necessarily equal the objective function of the household sector (although in most IAMs it does).

Following a main theorem of tax theory it does not matter on which side of the market participants the tax is formally charged. Thus, the choice where to charge the tax is driven by practical considerations of easier technical implementation. Within this work, the concept tax generally allows for the possibility of positive as well as negative tax rates, i.e. subsidies.

Except for the unit resource tax ς_R and the non-distorting lump-sum tax Γ all taxes are ad-valorem taxes. Gross price p changes with tax rate τ to $\bar{p} := p(1+\tau)$. The tax income for the amount q of traded goods therefore is $p\tau q$.[18]

Following Edenhofer et al. (2005) I want to go the ambitious way to consider endogenous technological change in both – energy and production – sectors to analyze a potential bias in different technology enhancing measures. Technological change is implemented by a combination of learning-by-doing spillovers of investments and public R&D expenditures that augment knowledge stocks and hence efficiency.

Further Assumptions and Simplifications The model presented in this work does not contain a *climate module* that calculates future temperature changes as result of economic and political acting. The extraction path of fossil resources gives a first measure of emitted carbon because all extracted resources are transformed to energy with carbon emission as side-effect. Assuming a total and homogenous oxidation of fossil resources and the absence of carbon capture and sequestration technologies[19] each extracted fossil resource unit produces the same amount of GHG. The impact of economizing can therefore be evaluated by the analysis of the resource extraction path. Otherwise global warming is influenced by the concentration of GHG in the atmosphere and only indirectly by the yearly emissions of GHG. Neglecting decay and degradation processes of GHG in the atmosphere the integral over the emission path $\int R$ gives the change of the GHG concentration due to fossil energy consumption.[20] The purpose of this model is neither to predict GHG concentration or temperature changes nor to calculate exact values of mitigation costs. Thus above mentioned simplifications bring an easier handling of the model without significant restrictions in its explanatory power. With the shown link from extracted resources R to GHG concentration a mitigation goal is formulated as an upper bound of accumulated emissions $\int_0^T R$ for a specific time space (that in my numerical calculations corresponds to the time horizon).

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[18] Note, that although formally only $\bar{p}$ changes by charging a tax, the tax also influences net price p due to modified demand.

[19] Within several carbon dioxide capture and storage (CCS) technologies, emerging CO2 is separated from industrial and energy-related production process and transported to a storage location which provides a long-term isolation from the atmosphere (IPCC, 2005, p. 3; see the whole report also for further information about technical implementation, feasibility and remaining problems of CCS).

[20] As CO2 does not decay in the atmosphere (in contrast to other GHG with chemical degradation) it can only be absorbed by plants, oceans and further sinks. Hence, there is no exact lifetime of CO2 in the atmosphere computable and estimation of CO2 transfers to other sinks of the global carbon cycle is confronted with uncertainties and extremely diverging time scales (IPCC, 2007c, p. 824–825). However, Nordhaus and Boyer (2000, p. 60–61) estimate the remaining share of CO2 pulse after 100 years with about 30 %.

Although population growth is an important driving force of climate change I consciously neglect the influence of a changing population for my analysis to concentrate on the pure economic processes and to avoid confusing external influences that better can be investigated separately.[21]

Of course, this structure of industrial economic system contains further huge simplifications: Each produced final good can serve as consumption good or as investment good. Direct consumption of fossil resources in household and production sector is neglected as well as the application of labor in the resource and energy sectors. Other factors for production are totally ignored – mainly exhaustible resources like ores and renewable resources like landscape – while the considered factors are aggregated in a very undifferentiated way (e.g. no distinction for skilled or unskilled labor or no diversification of different fossil and renewable energy forms). This idealization is the price for a manageable system that nevertheless can give important insights in the understanding of essential economic forces and outcomes.

In the whole economy actors are usually treated as pricetakers except for the model extension which considers market power in the resource extraction sector explicitly.

Furthermore, the unique existence of a market clearing equilibrium price is assumed. As prices are seen exogenously by market participants profit maximizing factor quantity $q(p)$ is always determined as a function of given price. Under usual neoclassical convexity conditions, the welfare theorem admits the existence of a unique price p^* that covers demand and supply (Mas-Colell et al., 1995, ch. 17):

$$q^d(p^*) = q^s(p^*)$$

Further common neoclassical assumptions concern perfect information about present and future prices and rational behavior of all agents.

Normative Aspects Description and modeling of economic sectors seeks to approximate real-world behavior, i.e. belongs to the descriptive part of economics. Normative elements are integrated by using a social welfare function to measure well-being and by the regard of an mitigation goal. With the concept of the representative household, the social welfare function is equated with the descriptive utility function.[22]

In the following subsections I develop the model CliPIDE – Climate Policy Instruments in a Decentralized Economy. I introduce formally the sectors of the basic economic system and its extension by endogenous technological change and renewable energies. In each sector I start with a brief description followed by the equations specifying objective function, production technology, and budget constraints. By applying the maximum principle optimizing first-order conditions of the Stackelberg followers are deduced to consider their reaction respective to policy instruments of the Stackelberg leader (government).

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[21] The alternative – to model population growth endogenously in dependence of economic growth, welfare, environmental quality – is a challenge that existing IAMs even do not try to meet.

[22] However, the social welfare function remains a normative element of analysis even if representative household's utility function is used for welfare measuring.

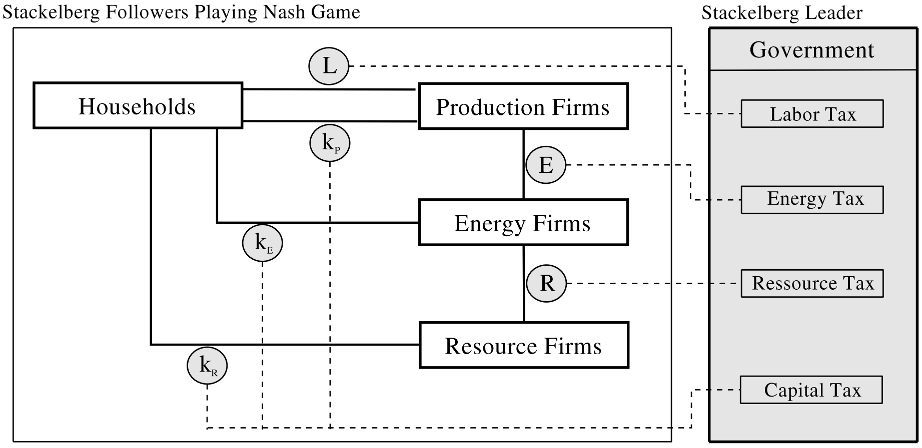

Figure 3: Game theoretic structure of the basemodel

3.1 Description of the Basemodel

The basemodel as introduced in this section is subject to later extensive analytical and numerical analysis. In order to highlight the theoretic structure of the Stackelberg game, Fig. 3 shows the players and their strategical variables subject to payoff maximization. As every economic sector maximizes intertemporal payoff given the optimal strategies of the other sectors, the market economic outcome is a Nash equilibrium. Imposed taxes of the government as Stackelberg leader who anticipates the reaction functions of the followers can influence the optimization behavior of economic sectors.

3.1.1 Households

Description of the Household Sector Utility u of the households depends for each point of time on consumption C and labor time L such that increasing consumption and decreasing labor time causes higher utility[23] but marginal utility declines over time.That is formally:

$$u'_C > 0 \; , \qquad u''_C < 0 \tag{4}$$

$$u'_L < 0 \; , \qquad u''_L < 0 \tag{5}$$

To consider utility for a whole space of time instead of a single point of time an intertemporal utility function J_H is used that depends on all time-point utilities. Usually the utility of each time weighted by a discount factor $f(t)$ is integrated to:

$$J_H = \int_{t_0}^{T} u(C, L)\; f(t)\; dt$$

---

[23] Consumption C and leisure $L_{max} - L$ are *goods* in the meaning that they are always preferable and more of them is always better than less. However this on the first view plausible assumption is indeed very disputable. The economy of happiness looks for a better understanding of the factors of well-being that are more sophisticated than the standard approach presented here. Thus, Layard (2006) shows that increasing income does not necessarily lead to a higher level of happines.

Here I confine to the established concept of constant-rate discounting $f(t) = e^{-\rho_H t}$ with ρ_H as the individual[24] pure time preference rate that expresses the impatience for future well-being (Barro and i Martin, 1999, p. 61). By choosing constant-rate discounting, time consistency of intertemporal utility is guaranteed (Strotz, 1956).

Households seek to maximize intertemporal utility J_H by a preferably high consumption level and low labor time, respectively. The amount of consumption is limited by the budget constraint, that consists of income minus savings. While labor income (the wage w for every unit of work time L) raises with higher labor time, future capital income (the net interest rate $\bar{r}$ of every invested capital unit K) raises with higher savings I. The household has to balance the trade-off between leisure and labor income and between present and future consumption due to savings, respectively. The lump-sum tax Γ and firm's profits Π modify the budget constraint but households consider tax and rent income level as exogenously given.

Capital depreciation with rate δ is also considered by households and changes the taxed interest rate $\bar{r}$ to the interest rate $\tilde{r} = \bar{r} - \delta$ net of tax and depreciation.

The Optimization Problem The household seeks to maximize the integral J_H of his discounted well-being u:

$$\max_{\{C,L\}} J_H$$

subject to:

$$\begin{aligned}
J_H &= \int_0^\infty u(C,L)e^{-\rho_H t}dt && (6)\\
C &= wL + \bar{r}K - I + \Pi + \Gamma && (7)\\
K &= K_Y + K_E + K_R + K_{E_2} && (8)\\
I &= I_Y + I_E + I_R + I_{E_2} && (9)\\
\Pi &= \Pi_Y + \Pi_E + \Pi_R + \Pi_{E_2} && (10)\\
\dot{K} &= I - \delta K && (11)
\end{aligned}$$

Capital stocks, investment and profit flows are subdivided into the economy's sectors (8 – 10). For the household sector only the total amount of K, I, Π is relevant and not the exact sector-specific allocation that is only stated to remain the budget relation.

The utility function with properties (4) and (5) measures the impact of a certain consumption C and leisure $L_{max} - L$ level to individual well-being of the household and has the following form:

$$u(C,L) = \ln(C) + \ln(L_{max} - L) \tag{12}$$

Optimizing Conditions To find the maximizing control path (C, L) for J_H one has to find the maximum of the Hamiltonian

$$H_H = u(C,L) + \lambda_H(wL + \bar{r}K + \Gamma + \Pi - C - \delta K) \tag{13}$$

---

[24] I consciously chose the adjective *individual* to highlight the difference to the commonly used but confusing notion of (normative) social time preference rate for ρ_H.

Because $u(C,L)$ is concave in $(C,-L)$ and $\dot{K}$ is linear in $(-C,L)$ it exists a local optimal solution that can be found by derivating H_H respect to C and L and setting these derivatives equal to zero. Together with the equation of motion for the costate variable λ_H and the transversality condition first order conditions read:

$$\begin{aligned} u'_C &= \lambda_H, && (14)\\ u'_L &= -\lambda_H w, && (15)\\ \dot{\lambda}_H &= \lambda_H(\rho + \delta - \bar{r}). && (16)\\ 0 &= \lim_{t\to\infty} \lambda_H K e^{-\rho t} && (17) \end{aligned}$$

Reaction Function Solving the differential equation for λ_H (16) at given initial value $\lambda_{H,0} = \lambda_H(0)$ yields:

$$\lambda_H(t) = \lambda_{H,0} e^{\int_0^t (\rho_H + \delta - \bar{r}(s))ds} \tag{18}$$

Transforming (14) and (15), gives the explicit reaction function of the household, which depends on λ_0, $\bar{r}(t)$ and $w(t)$:[25]

$$\begin{aligned} C(x,t) &= \frac{1}{\lambda_0} e^{-\int_0^t (\rho_H + \delta - \bar{r}(s))ds} && (19)\\ L(x,t) &= L_{max} - \frac{C(x,t)}{w(t)} && (20) \end{aligned}$$

Transversality Condition Assuming $\lim_{t\to\infty} K > 0$, applying the transversality condition (17) to the explicit solution for λ_H from Eq. 18 leads to the condition:

$$\lim_{t\to\infty} \lambda_{H,0} e^{\int_0^t (\delta - \bar{r}(s))ds} = 0, \tag{21}$$

that is, as long as the net interest rate is for $t \to \infty$ greater than the depreciation rate, the transversality condition is fulfilled for every $\lambda_{H,0}$. Otherwise, $\lambda_{H,0} = 0 = u'_C$ which is a contradiction to the assumption $u'_C > 0$. Thus, if $\lim_{t\to\infty} \bar{r} < \delta$, capital stocks has to break down to zero.

Ramsey Rule As a direct consequence of substituting (14) and its derivative respect to time in (16) the optimizing conditions state the Ramsey rule of optimal capital saving:

$$\begin{aligned} \bar{r} - \delta =: \tilde{r} &= \rho_H - \frac{\frac{\partial u'_C}{dt}}{u'_C} = \rho_H - \frac{u''_C}{u'_C}\dot{C} && (22)\\ \tilde{r} &= \rho_H + \eta \hat{C} && (23) \end{aligned}$$

where $\eta = -\frac{u''_C}{u'_C} C$ denotes the elasticity of marginal utility of consumption which equals 1 in the case of a logarithmic utility function (12).

---

[25] λ_0 depends on C_0 and L_0.

3.1.2 Production Sector

Description of the Sector The final good production sector[26] creates consumable and investable goods Y that are sold with numeraire price 1. Deployed factors physical capital K_Y, labor L, and energy E have to be paid with the respective factor prices r, $\bar{w}$, and $\bar{p}_E$. Wage w and energy price p_E can be charged with an ad-valorem tax τ_L and τ_E. Interest rate can be taxed by a sector-specific capital tax τ_{K_Y} which holds only for the production sector. Profit Π_Y results from the difference of income due to sells of output and costs due to factor use. The sectoral capital stock depreciates with the same rate as the global one (Eq. 11) and depreciation does not need to be considered by firms a second time.[27]

The produced amount of output Y with given factors (K_Y, L, E) depends on the production technology F. A wide range of production functions can be covered with the constant elasticity of substitution (CES) function of the general form:[28]

$$F(q_1, q_2) = (a_1 q_1^\sigma + a_2 q_2^\sigma)^{\frac{1}{\sigma}}$$

with input factors q_1, q_2 and factor shares a_1, a_2. The substitution parameter σ is calculated from the elasticity of substitution s for a given output level Y and is independent from (q_1, q_2):

$$\sigma = \frac{s-1}{s} \tag{24}$$

$$s = \frac{\partial \frac{q_1}{q_2}}{\partial \frac{\partial q_1}{\partial q_2}} \frac{\frac{\partial q_1}{\partial q_2}}{\frac{q_1}{q_2}} \tag{25}$$

While many IAMs[29] use Cobb-Douglas functions of the form $F = q_1^{a_1} q_2^{a_2}$ with the elasticity of substitution $s = 1$, some more recent IAMs use nested CES technology of (K, L, E) with a composite of two factors that are again produced by a CES technology (Kemfert and Welsch, 2000).[30] Hence, I use a nested structure of a CES function that combines the capital-labor composite $Z = CES(K, L)$ with energy E to the output Y.

The technology level parameters A_L and A_E are introduced to allow for factor efficiency increasing technological change. By setting them equal to one, technological change can be neglected. For the firms efficiency parameters A_L and A_E are seen exogenously given although their sectoral investment decisions in general influence its level (for further explanations concerning the modeling of technological change see section 3.2.3).

---

[26] In the following often mentioned as *production sector*.

[27] Because of the regard of the households (16) depreciation already is anticipated in the for the household relevant interest rate $\tilde{r} = r(1 - \tau_k) - \delta$.

[28] A detailed consideration of the CES function with their properties is given by Arrow et al. (1961)

[29] e.g. RICE, DICE, ENTICE, ENTICE-BR.

[30] Kemfert and Welsch (2000) give examples for two commonly used nesting structures $(KL)E$ and $L(KE)$ and make an empirical estimation for sector specific elasticities of substitution of the German economy (the parenthesis show which two factors are composed first). Van der Werf (2007) argues that the $(KL)E$ structure fits empiric data the best and emphasizes that because of the lower elasticities ($s < 1$) the Cobb-Douglas technology is not proper for energy relevant macroeconomic modeling.

The amount of total energy E is a function of fossil and renewable energy E_{fos} and E_{ren}, respectively. Although a CES function is common to combine both energy forms, I use a linear composition to study the consequences of the absence of renewable energy for climate policy instruments.[31]

The Optimization Problem Good producing firms seek to maximize their profit:

$$\max_{\{K_Y,L,E\}} \Pi_Y$$

subject to:

$$\Pi_Y = Y - rK_Y - \bar{w}L - \bar{p_E}E \tag{26}$$

$$Y = (a_1 Z^{\sigma_1} + (1-a_1)(A_E E)^{\sigma_1})^{(1/\sigma_1)} \tag{27}$$

$$Z = (a_2 K_Y^{\sigma_2} + (1-a_2)(A_L L)^{\sigma_2})^{(1/\sigma_2)} \tag{28}$$

$$E = E_{fos} + E_{ren} \tag{29}$$

$$\dot{K_Y} = I_Y - \delta K_Y \tag{30}$$

Optimizing Conditions Due to the strict concaveness of the production function in each input factor, there exists an interior maximum of Π_Y in (K_Y, L, E) that can be found by derivating Π_Y respect to the input factors and setting the derivatives equal to zero:[32]

$$r(1+\tau_{K_Y}) = Y'_{K_Y} \tag{31}$$

$$\bar{w} = Y'_L \tag{32}$$

$$\bar{p}_E = Y'_E \tag{33}$$

Further Considerations Because of the linear homogeneity[33] of the CES function optimal profits are zero (Arrow et al., 1961).

3.1.3 Fossil Energy Producing Firms

Description of the Sector Fossil energy firms produce final energy E_{fos} from the two input factors fossil resources R and capital K_E. Labor is neglected since it is no essential production factor and may not bring new insights for the policy analysis. To give a consistent description of the sectoral disaggregated economy I chose a CES function in analogy to the production sector.[34]

---

[31] Popp (2006a) and Grimaud et al. (2007) use a CES function that treats both energy forms as imperfect substitutes. Van der Zwaan et al. (2002) justify this by the existence of niche markets that make at least a small energy production always efficient. In contrast, Edenhofer et al. (2005) treats in MIND all energy forms as perfect substitutes by linear combination.

[32] Applying the Maximum Principle of dynamic optimization to an intertemporal objective function yields the same conditions as the static optimization problem, because no intertemporal decisions are made.

[33] A function $f(q_1, ..., q_n)$ is called homogene of degree a if $f(\lambda q_1, ..., \lambda q_n) = \lambda^a f(q_1, ..., q_n)$. Linear homogene means homogene of degree one.

[34] Several other approaches are common: Popp (2004, 2006a) and Grimaud et al. (2007) use a linear production function of fossil resources divided by an (decreasing) carbon efficiency variable. Nordhaus and Yang (1996) neglect the production of energy completely and assume carbon emissions as side-effect of production that decreases in the presence of technological change. In contrast, Edenhofer et al. (2005) use a CES function the same way as I will

The Optimization Problem Fossil energy producing firms seek to maximize current profit:

$$\max_{\{K_E,R\}} \Pi_E$$

subject to:

$$\Pi_E = p_E E_{fos} - rK_E - \bar{p}_R R \tag{34}$$

$$E_{fos} = (aK_E^{\sigma} + (1-a)R^{\sigma})^{(1/\sigma)} \tag{35}$$

$$\dot{K}_E = I_E - \delta K_E \tag{36}$$

Optimizing Conditions The necessary and sufficient first-order conditions together with the transversality condition for the fossil energy sector can be summarized to:

$$r(1+\tau_{K_E}) = p_E \frac{\partial E_{fos}}{\partial K_E} \tag{37}$$

$$\bar{p}_R = p_E \frac{\partial E_{fos}}{\partial R} \tag{38}$$

$$\tag{39}$$

Further Considerations Again, because of the linear homogeneity of the production function profits are zero.

3.1.4 Resource Extracting Firms

Description of the Sector Resource extraction firms extract fossil resources R from limited resource stock S by capital input K_R. Production function is linear in K_R and convex increasing in S, i.e. with advanced stock depletion, capital productivity κ falls because remaining resources need more effort to be extracted.[35] Thus, extraction costs are determined by capital use and interest rate, that can be charged with a sector specific capital tax τ_{K_R}. Resource price p_R can also be modified by unit tax ς_R. As resource firms are owned by the representative household, the discount rate for intertemporal optimization of profits Π_R equals net interest rate of households $\bar{r} - \delta$.

The quantity restriction instrument prohibits the resource firms to extract more than the mitigation goal admits. Due to this quantity restriction the leader's constraint $S \geq \underline{S}$ becomes a follower's constraint $S \geq S_c$ with $S_c = \underline{S}$. Otherwise, resource sector can deplete the whole resource stock if desireable, i.e. $S_c = 0$.[36]

---

do here. The advantage of doing so is in the intuitive explanation of the carbon intensity endogenously by deviding E_{fos} by R without referring to carbon efficiency variables that have to be described (and calibrated) separately. Furthermore the potential of reducing carbon intensity is completely determined by the elasticity parameter of substitution σ and the share parameter a of the production function.

[35] Formal description of κ is based on assessment of Rogner (1997) and looks about Nordhaus and Boyer (2000, p. 54) and Edenhofer et al. (2005).

[36] In contrast to common certificate trading schemes with fixed emission caps for a certain time interval, this approach used here gives resource extractors the freedom to allocate extraction over time arbitrarily as long as accumulated resources do not exceed the quantity

The Optimization Problem

$$\max_{K_R} J_R$$

subject to:

$$
\begin{aligned}
J_R &= \int_0^\infty \Pi_R e^{\int_0^t -\tilde{r}\ ds} dt \qquad (40)\\
\Pi_R &= (p_R - \varsigma_R)R - r(1+\tau_{K_R})K_R \qquad (41)\\
\tilde{r} &= \bar{r} - \delta = r(1-\tau_K) - \delta \qquad (42)\\
R &= \kappa K_R \qquad (43)\\
\dot{S} &= -R \qquad (44)\\
S &\geq S_c \qquad (45)\\
\kappa &= \frac{\chi_1}{\chi_1 + \chi_2 \left(\frac{S_0 - S}{\chi_3}\right)^{\chi_4}} \qquad (46)
\end{aligned}
$$

Optimizing Conditions With the associated Hamiltonian

$$
\begin{aligned}
H_R &= (p_R - \varsigma_R)R - r(1+\tau_{K_R})K_R + \lambda_R \dot{S}\\
&= (p_R\kappa - \varsigma_R\kappa - r(1+\tau_{K_R}) - \kappa\lambda_R)K_R, \qquad (47)
\end{aligned}
$$

first-order conditions for the interior solution evaluate to:

$$
\begin{aligned}
r(1+\tau_{K_R}) &= (p_R - \varsigma_R - \lambda_R)\kappa \qquad (48)\\
\dot{\lambda_R} &= \tilde{r}\lambda_R - \frac{\partial H_R}{\partial S}\\
&= \tilde{r}\lambda_R - (p_R - \varsigma_R - \lambda_R)K_R\frac{\partial \kappa}{\partial S} \qquad (49)
\end{aligned}
$$

Regarding constraint (45) the transversality condition has to be modified by considering de-facto depletable resource stock size $S_0 - S_c$. Thus,

$$0 = \lim_{t\to\infty} \lambda_R(S - S_c)e^{\int_0^t -\tilde{r}\ ds} \qquad (50)$$

Further Considerations Profits in the resource sector in the optimum are directly linked to the shadow price λ_R of resource stock. By applying condition (48) to Eq. 41, the profits are:

$$\Pi_R = \lambda_R\kappa K_R \qquad (51)$$

Hotelling rule Reformulating the maximizing problem (41) by substituting K_R by (43) yields:

$$J_R = \int_0^\infty ((p_R - \varsigma_R)R - \frac{r(1+\tau_{K_R})}{\kappa}R)e^{\int_0^t -\tilde{r}\ ds}dt \qquad (52)$$

---

cap.

With $\tilde{\kappa} := \varsigma_R + \frac{r(1+\tau_{K_R})}{\kappa}$ follows:

$$J_R = \int_0^\infty (p_R - \tilde{\kappa}) R e^{\int_0^t -\tilde{r}\, ds} dt \tag{53}$$

This is the traditional and widely used form of resource extraction with extraction costs $\tilde{\kappa}$ (e.g. Hanley et al., 1997, p. 248) based on the original but more particular model of Hotelling (1931) with zero extraction costs.[37] The extraction costs $\tilde{\kappa}R$ as modelled here are essentially capital costs rK_R going back to household's capital income.

Solving Eq. 48 to λ_R and derivating respect to time follows:

$$\lambda_R = p_r - \frac{r}{\kappa} \tag{54}$$

$$\dot{\lambda}_R = \dot{p}_R - \frac{\dot{r}}{\kappa} - \frac{r}{\kappa^2}\frac{\partial \kappa}{\partial S} R \tag{55}$$

Subsituting this into Eq. 49 yields:

$$\tilde{r} = \frac{\dot{p}_R - \frac{\dot{r}}{\kappa}}{p_R - \frac{r}{\kappa}}, \tag{56}$$

which equals to the modified Hotelling rule $r = \frac{\dot{p}_R}{p_R - \tilde{\kappa}}$ if extraction costs $\tilde{\kappa}$ are independent from changes in the interest rate ($\dot{r} = 0$) (see for example Dasgupta et al., 1981; Sinn, 2007b).

Reformulating Eq. 56 and considering $\lambda_R = \frac{\partial \pi_R}{\partial R}$ (marginal revenue) yields:

$$\tilde{r} = \frac{\dot{\left(\frac{\partial \pi_R}{\partial R}\right)} + \frac{\partial \kappa}{\partial S}\frac{r}{\kappa} K_R}{\frac{\partial \pi_R}{\partial R}} \tag{57}$$

3.1.5 Government

Description of the Government The government collects (positive) taxes and spends negative taxes (subsidies) τ_i on factor prices, unit tax ς_R for fossil resources as well as a non-disturbing lump-sum transfer Γ from the households. Furthermore the government spends R&D expenditures R_L, R_E, R_{E_2} that augment labor and energy productivity and the capital productivity in renewable energy sector, respectively.[38] The sum of all these incomes less expenses forms the government consumption C_{gov} that cannot be reduced nor extended by savings or credits.[39]

---

[37] The problem of the conventional approach of using extracting costs is the outflow of costs $\tilde{\kappa}R$ of the economic system. In contrast to the commonly applied model of exhaustible resources the approach of using extraction costs $\tilde{\kappa}$ depending on capital productivity κ and interest rate r is more consistent to the neoclassical general equilibrium analysis view of a closed economy without any losses leaving the system.

[38] For the basemodel without endogenous technological change and renewable energy, these R&D expenditures and renewable energy tax τ_{E_2} are set to zero.

[39] In all model runs in this work I assume $C_{gov} = 0$, that is no government consumption is allowed and all taxes, subsidies and public R&D expenditures must sum up to zero.

The mitigation goal (in terms of a carbon budget) is formulated as constraint for the government. Furthermore, by setting single taxes and tax combinations equal to zero, a detailed study of selected policy instruments is possible.

The applied utility function of the government is the same like the one of the households (12) – except for the social time preference rate ρ_G. This allows for the possibility to change the social time preference rate and to distinguish between personal impatience of someone's own future utility and the weighting of future well-being of following generations.[40]

The Optimization Problem of the government to maximize welfare is the following:

$$\max_{\{\{\tau_i\},\varsigma_R,\Gamma,R_L,R_E,R_{E_2}\}} \int_0^\infty u(C,L)e^{-\rho_G t}dt$$

with $i \in \{K, K_Y, K_E, K_R, E, R, E_2, L\}$

subject to:

$$\begin{aligned}
S \geq& \underline{S} && (58)\\
C_{gov} =& \Gamma + \tau_K rK + \tau_L wL + \tau_E p_E E + \tau_R p_R R + \tau_{E_{ren}} p_E E_{ren} && (59)\\
&+ \tau_{K_Y} rK_Y + \tau_{K_R} rK_R + \tau_{K_R} rK_R + \varsigma_R R &&\\
&- R_L - R_E - R_{E_2} &&\\
\bar{r} =& r(1-\tau_K) && (60)\\
\bar{w} =& w(1+\tau_L) && (61)\\
\bar{p}_E =& p_E(1+\tau_E) && (62)\\
\bar{p}_R =& p_R(1+\tau_R) && (63)
\end{aligned}$$

A full description of the Stackelberg leader problem with all constraints (including the model extensions of the following subsections) is listed in Appendix C.

---

[40] While ρ_H is a positive paremeter about the personal intertemporal distribution of well-being and occurs like a individual preference parameter, ρ_G is a normative parameter who touches questions of intergenerational justice and hence is a matter of social and political discussion (Schelling, 1995, 1999). An approach of combining the impatience character of ρ_H and the intergenerational justice aspect of ρ_G present Sumaila and Walters (2005) by derivating a hyperbolic discount formula.

3.2 Model Extensions

I extend above basemodel by several important features: the first refers to monopolistic and oligopolistic market power of the resource sector; secondly, a renewable energy sector is added, and thirdly, I model the interrelation between efficiency parameters A_L, A_E and A_{E_2} and other endogenous variables generating technological change.

3.2.1 Market Power of the Resource Sector

Assuming market power, the resource extracting firm knows about the change on the demand side $p_R(R)$. Thus, deducing first order conditions for the resource sector requires the consideration of the derivative $\frac{\partial p(R)}{\partial R}$.

The typical modeling of market power takes the reaction function as given, i.e. a linear demand curve or a constant elasticity of demand. The aim of the approach presented here is to estimate the demand function endogenously by using several already existing model properties.

Assuming that the resource extractor knows the indirect demand curve $p_R(R)$, Eq. 48 and 49 change to:

$$r = (p_R + \frac{\partial p_R}{\partial R} R - \lambda_R)\kappa \tag{64}$$

$$\dot{\lambda_R} = \tilde{r}\lambda_R - (p_R + \frac{\partial p_R}{\partial R} R - \lambda_R) K_R \frac{\partial \kappa}{\partial S} \tag{65}$$

With the modified λ_R as marginal revenue, Eq. 57 remains valid. Profits in the resource sector in the optimum (Eq. 51) change to:

$$\Pi_R = (\lambda_R - \frac{\partial p_R}{\partial R} R)\kappa K_R \tag{66}$$

The problem is now to determine the demand function $p_R(R)$ and its (total) derivative. Here I present a simple approach to approximate the derivative of $p_R(R)$ that is based on the information of first-order conditions of the fossil energy sector and production sector.

In a first step the change of resource price with respect to extracted resource volume $\frac{\partial p_R(R)}{\partial R}$ could be estimated by using the reaction function (38) of the fossil energy sector, i.e.

$$p_R(R) = \frac{p_E}{1+\tau_R} \frac{\partial E(K_E, R)}{\partial R} \tag{67}$$

Here, second-order effects like changes in K_E and p_E due to changes in p_R are neglected reflecting only very limited availability of information for the resource monopolist. That is, derivatives of K_E and p_E respect to R are assumed to be zero and thus the derivative of p_R is

$$\frac{\partial p_R}{\partial R} = \frac{p_E}{1+\tau_R} \frac{\partial^2 E(R, K_R)}{\partial R^2} \tag{68}$$

I call this information concept *first-stage anticipation of market power* and such a monopolist a *first-stage monopolist.*

In a next step, one can also assume, that the resource monopolist has information about the reaction of energy price due to changes in the resource extraction and hence energy production. That is, he does not assume $\frac{\partial p_E}{\partial R} = 0$. Instead, he uses reaction function (33) which describes energy prices in dependence of the capital stock, labor and energy, i.e:

$$p_E(E) = \frac{1}{1+\tau_E} \frac{\partial Y(K_Y, L, E)}{\partial E} \tag{69}$$

Again, second-order effects like changes in labor and capital demand due to changes in p_E are neglected but changes in energy production due to resource extraction change are anticipated (i.e. $E = E(K_E, R)$). Substituting Eq. 69 in Eq. 67 and derivating with respect to R yields:

$$\frac{\partial p_R}{\partial R} = \frac{1}{1+\tau_R} \left(p_E E_R'' + \frac{1}{1+\tau_E} Y_E''(E_R')^2 \right) \tag{70}$$

Due to the fact that the monopolist also anticipates the reaction function of the production sector respect to R, he is called a *second-stage monopolist.*

To improve the modeling of market power one can consider more and more of second-order effects which are determined by the remaining first-order conditions in fossil energy, production and household sector. But first-stage and second-stage anticipation already give a good approximation while deriving the total reaction function of the whole economy with respect to resource price changes would be an exhausting calculation task.

A more useful refinement lies in the parameterization of the degree of market power as in real world there might exist several competitive firms with market power who form an emerging sectoral market distortion. This is done by two conceptional parameters $\theta_1, \theta_2 \in [0, 1]$ which represent the degree of market power anticipation within the first stage (θ_1) and the second stage (θ_2). Hence, θ_1 and θ_2 express the degree of consideration of the reaction function (67) and (69):

$$\frac{\partial p_R}{\partial R} = \theta_1 \frac{1}{1+\tau_R} \left(p_E E_R'' + \theta_2 \frac{1}{1+\tau_E} Y_E''(E_R')^2 \right) \tag{71}$$

This concept also allows for a continuous transition from first-stage to second-stage monopolist by small increases of θ_2 from first-stage anticipation with $\theta_2 = 0$. For the scope of this work, the estimation of θ_1 and θ_2 and its interrelation with real world market structures is of no importance since the interest is to investigate the general implications of market power for climate protection efforts.[41]

Eq. 71 provides a flexible modeling of market power that can be easily switched off by setting $\theta_1 = 0$. The informational differences between first-stage and second-stage monopolist are summarized in Tab. 1.

---

[41] Nevertheless, θ_1 can be charged with a common meaning in monopoly modeling: For the n-Cournot oligopoly game with n identical firms (with same amount of capital stocks), θ_1 equals the reciprocal number of firms $\frac{1}{n}$. First order condition from Eq. 64 implies $r = (p_R(R) + R_i \frac{\partial p(R)}{\partial R_i} - \lambda_R)\kappa$. As $\frac{\partial p(R)}{\partial R_i} = \frac{\partial p(R)}{\partial R} \frac{\partial R}{\partial R_i} = \frac{\partial p(R)}{\partial R}$ and $R_i = \frac{R}{n}$ it follows that $\theta_1 = \frac{1}{n}$. Hence, the limit cases $n = 1$ represent the case of one monopolist and $n \to \infty$ the perfect competition case with $\theta_1 = 1$ and $\theta_1 = 0$, respectively.

	first-stage monopolist	second-stage monopolist
considered reaction functions	(67)	(67, 69)
neglected second-order effects	$\frac{\partial p_E}{\partial R} = \frac{\partial K_E}{\partial R} = 0$	$\frac{\partial K_E}{\partial R} = \frac{\partial K_Y}{\partial R} = \frac{\partial L}{\partial R} = 0$
degree of anticipation	$\theta_1 \in [0,1],\ \theta_2 = 0$	$\theta_1, \theta_2 \in [0,1]$

Table 1: Modeling of first-stage and second-stage market power

3.2.2 Renewable Energy Sector

Description of the Sector An alternative to fossil fuel based energy production forms a backstop energy technology which generates energy E_{ren} without the use of fossil resources.[42] Renewable energy is highly capital intensive. But once an equipment of wind or solar power is installed it produces energy with negligible costs for maintenance. Thus, there are only capital costs rK_{E_2} to cover by selling energy with energy price p_E which can furthermore be taxed by τ_{E_2}.

To regard physical limitations of restricted land-use, energy production function has decreasing returns to scale, i.e. the exponent of the production function ν is smaller than one. The scaling parameter κ_{ren} reflects the volume of energy production of one capacity unit that can be augmented by capital productivity augmenting technological change A_{E_2}.[43]

The Optimization Problem

$$\max_{\{K_{E_2}\}} \Pi_{E_2}$$

$$\Pi_{E_2} = p_E(1-\tau_{E_2})E_{ren} - rK_{E_2} \tag{72}$$

$$E_{ren} = \kappa_{ren} A_{E_2} K_{E_2}^{\nu} \tag{73}$$

$$\dot{K}_{E_2} = I_{E_2} - \delta K_{E_2} \tag{74}$$

Optimizing Conditions Due to strict concavity of the production function, static first-order condition evaluate to:

$$r = p_E(1-\tau_{E_2})\frac{\partial E_{ren}}{\partial K_{E_2}} \tag{75}$$

Further Considerations Without endogenous technological change, productivity A_{E_2} is set to 1. By putting Eq. 75 and 74 into Eq. 73, profits of renewable energy firms in the optimum are

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[42] Popp (2006a) explains backstop technologies as "[...] technologies, which are assumed abundant, and thus available at constant marginal cost [...]". Of course, in this context, marginal costs of renewable energy vary with the interest rate (and in reality with even other factor prices), but are more decoupled from fossil resource prices than fossil energy technologies.

[43] Formal description leans on Ströbele (1984, p. 104) and Edenhofer et al. (2005) who use $\nu = 1$.

$$\Pi_{E_2} = (1-\nu)p_E(1-\tau_{E_2})E_{ren} \tag{76}$$

Hence, with $\nu < 1$ and $\tau_{E_2} < 1$ profits are always positive as $E_{ren} > 0$ (which follows by Eq. 75).

3.2.3 Endogenous Technological Change

Technological change is usually expressed by productivity augmenting factors A_L, A_E and A_{E_2} which correspond to productivity of labor and energy in the production sector and of capital in the renewable energy sector, respectively.

While models of exogenous technological change assume a constant growth rate for productivity factors which is independent from other economic variables, endogenous change is driven by investment decisions of actors. In this model I consider two effects of growth that are discussed in endogenous growth theory: first a learning-by-doing effect (LbD) which causes intra-sectoral knowledge spillovers, and second the possibility to raise factor productivity by expenditures in research and development (R&D) generating new innovations.

Learning by Doing The underlying idea of the learning-by-doing effect is that the i-th firm's individual investments I_Y^i in its own capital stock K_Y^i raise sectoral factor productivities A_L, A_E due to increasing experience in optimizing the production process (cf. Romer, 1986, and Barro and i Martin, 1999, Sec. 4.3). But these emerging efficiency gains are largely non-excludable and non-rivalrous: one firm upgrading its procedure of production cannot hide this innovation from other firms who adopt these changes (non-excludability) without affecting the inventing firm negatively (non-rivalry). This so called spillover effect on the microfoundation layer is not anticipated by the single firm, that is, the firms maximizing deliberations neglect the influence of its own investments in the overall productivity, i.e.

$$\frac{\partial A_X}{\partial K_Y^i} = 0 \qquad \text{for} \quad X \in \{L, E\} \tag{77}$$

Hence, former first-order conditions of the basemodel do not change. Nevertheless, cumulative individual investments $I_Y = \sum_i I_Y^i$ do augment productivities and thus,

$$A_X = \xi_X K_Y^{\varsigma_L} \qquad \text{for} \quad X \in \{L, E\} \tag{78}$$

Ignoring the spillover effect (Eq. 77) yields to an underinvestment in the whole sector, which can be corrected by a capital subsidy (Romer, 1986). The empirical evidence of learning-by-doing is studied by Greiner et al. (2005) who shows that growth in a low stage of development is dominated by investment spillovers while in more developed countries other forces of growth dominate.

Implementation of LbD in the renewable energy sector is made analogously with sectoral capital stock K_{E_2} and sectoral capital productivity factor A_{E_2}.

Research and Development To allow for specific productivity increases R&D based knowledge stock enhancement is considered. Knowledge stock H_X

augments factor productivity by multiplication with factor input (i.e. the same way as factor productivity A_X). Building up the knowledge stock requires R&D expenditures R_X which experiences diminishing returns over time (Popp, 2006b). This is mainly caused by stepping-on-toes effects due to unproductive work and debilitating patent races (Jones and Williams, 2000; Edenhofer et al., 2005). On the other hand, existing knowledge stock also facilitates creation of new knowledge due to existing technologies.

These deliberations lead to the following formal description of endogenous technological change which looks about the approaches of Popp (2004) and Edenhofer et al. (2005):

$$\dot{H}_X = h_X R_X^b H_X^\phi - \delta_H H_X \qquad \text{with} \quad 0 < b, \phi, \delta_H < 1 \ , \tag{79}$$

where h_X is a scaling parameter. Furthermore, depreciation δ_H allows for knowledge decay over time.

Usually, endogenous technological change is only considered for energy efficiency increase and renewable energy improvements. Hence R&D investments in these sectors would cause crowding-out effects of R&D expenditures in non-energy related sectors, mainly production sector. To avoid rough crowding-out estimations, I consider endogenous R&D based knowledge increases also for labor productivity factor in the production sector, i.e. $X \in \{L, E, E_2\}$.[44]

Due to missing microfoundation of the strongly simplified R&D approach of Popp (2004), R&D expenditures have to be paid by the government (who has to generate additional tax incomes).

Combining LbD and R&D Overall factor productivity results from learning-by-doing spillovers as well as selective R&D expenditures.

Hence, endogenous technological change with initial productivity levels $A_{X,0}$ is described by:

$$A_L = A_{L,0} + \xi_L K_Y^{\varsigma_L} + H_L \tag{80}$$

$$A_E = A_{E,0} + \xi_E K_Y^{\varsigma_E} + H_E \tag{81}$$

$$A_{E_2} = A_{E_2,0} + \xi_{E_2} K_{E_2}^{\varsigma_{E_2}} + H_{E_2} \tag{82}$$

with equations of motion for knowledge stocks:

$$\dot{H}_L = R_L^b H_L^\phi - \delta_H H_L \tag{83}$$

$$\dot{H}_E = R_E^b H_E^\phi - \delta_H H_E \tag{84}$$

$$\dot{H}_{E_2} = R_{E_2}^b H_{E_2}^\phi - \delta_H H_{E_2} \tag{85}$$

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[44] Edenhofer et al. (2005) also provide with the MIND model a completely endogenously implemented technological change.

3.3 Model Calibration

Numerical treatment of the economic model needs a careful setting of model parameters. Although I do not provide a fitting of macroeconomic variables to real-world data, conceptual model analysis depends highly on parameters that describe the dynamic of economic behavior. In the following subsections I will discuss and justify the values of important parameters – beginning with the parameterization of resource extraction, followed by endogenous technological change modeling, renewable energy and further economic parameters. All parameters and its values used for numerical model runs are listed in Appendix E.2. Furthermore, for numerical treatment the continuous model is transformed into a discrete optimization model (see appendix A).

3.3.1 Parameters of Rogner's Curve

Resource extraction depends on four parameters – $\chi_1, ..., \chi_4$ – which describe the decrease of capital productivity in the resource sector with ongoing exploration of existing reserves. While χ_1 and χ_2 are scaling parameters, χ_3 represents the resource base and χ_4 the slope of the capital productivity curve. Within the huge parameter space Tab. 2 and Fig. 4 show a small selection of parameter vectors and their impact on extraction and consumption in the extended model with ETC (but without renewable energy).

The parameters are finally chosen that way that increasing extraction occurs in BAU scenario and that the capital productivity in resource sector falls to 0.5 at T_{end}. Popp (2006a) and IPCC (2007b, p. 187, Fig. 3.9) within the SRES A1 scenario assume a doubling of fossil resources and emissions, respectively, within the 21st century under the absence of mitigation policy. After the economic engaging phase within the first ten years parameter set *r8* causes such a doubling of resource flows. Thus, parameter set *r8* is used for parameterization of resource extraction.

	χ_1	χ_2	χ_3	χ_4
r0	0.01	2	162	3
r1	0.01	0.01	80	2
r2	0.01	1	300	3
r3	0.01	0.01	120	2
r4	0.01	0.01	140	2
r5	0.10	0.01	50	2
r6	0.01	0.01	400	2
r7	0.01	0.01	200	2
r8	0.01	0.01	100	2

Table 2: Parameter setting of Rogner's curve

3.3.2 Parameters Describing ETC

The high sensitivity of parameters can be seen in the substantially differing economic development under several parameter sets that vary hardly (see Tab. 3 and Fig. 5). The most important parameter for endogenous growth by R&D is

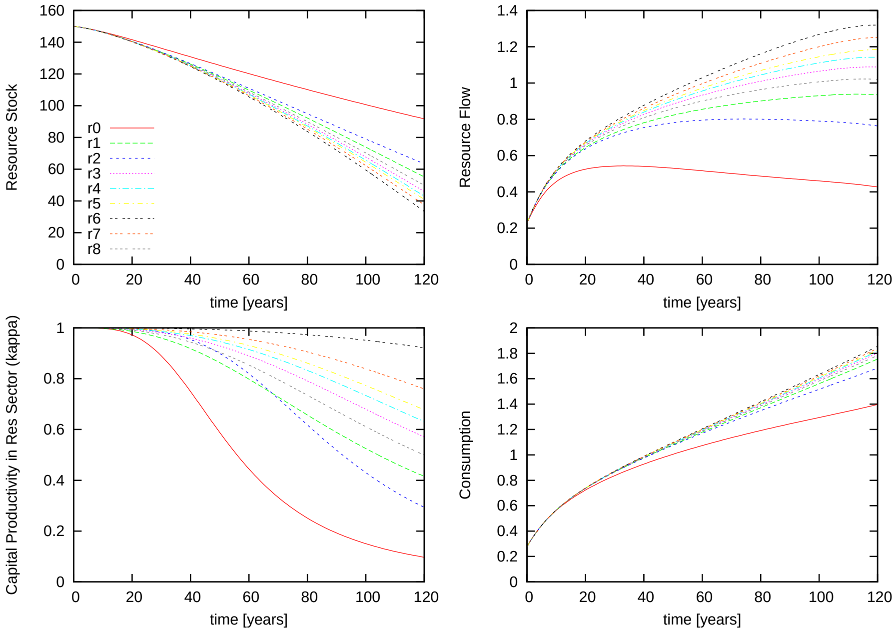

Figure 4: Parameter setting of Rogner's curve (see Tab. 2 for parameter set definition)

h_L. Parameterset *r7* fits the best to the results of Popp (2006a): output and consumption is in the end of the 21st century four times higher, emissions are doubled. The share of energy related R&D of GDP is with 0.07 % a little bit higher than in Popp (2006a) with ca. 0.05 % of GDP. Furthermore, shares of labor R&D and renewable energy R&D of 2 % and 0.008 % of GDP, respectively, seem to lie in plausible dimensions.[45]

Concerning the impacts of ETC parameters on economic dynamics, raising the exponents b_X and ϕ_X cause an augmenting of the shares of R&D to GDP while raising h_X leads to a higher influence of R&D to growth.

For parameters describing endogenous technological change in the renewable energy sector (BAU scenario) chosen values reproduce external growth rate of approx. 1%, and more than 2% in the RED scenario due to higher R&D investments.

3.3.3 Parameters Describing Renewable Energy

Parameterization of renewable energy production looks about the MIND 1.1 model (Edenhofer et al., 2005). Exact calibration is neither necessary nor easy to do because of differences in model structure (e.g. MIND uses more than two energy forms) and parameters (e.g. elasticities, mitigation goal). Again, parameters are chosen in order to reproduce plausible outcomes. Tab. 4 shows the share of renewable energy on total energy in both models under baseline and reduction scenario.[46]

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[45] See for example IPCC (2007b, p. 763) for historical data for energy and renewable energy R&D in the U.S.

[46] Note, that the mitigation goal $\underline{S}$ for calculation of Tab. 4 is relaxed from the value considered elsewise in this thesis to achieve a better compareability with the RED450 mitigation

	h_E	h_L	b_L	ϕ_L
r0	0.005	0.02	0.1	0.1
r1	0.005	0.025	0.05	0.1
r2	0.005	0.03	0.1	0.1
r3	0.005	0.02	0.1	0.05
r4	0.005	0.025	0.1	0.1
r5	0.005	0.04	0.15	0.15
r6	0.01	0.05	0.1	0.1
r7	0.01	0.04	0.1	0.1
r8	0.01	0.03	0.1	0.1

Table 3: Parameter setting of ETC

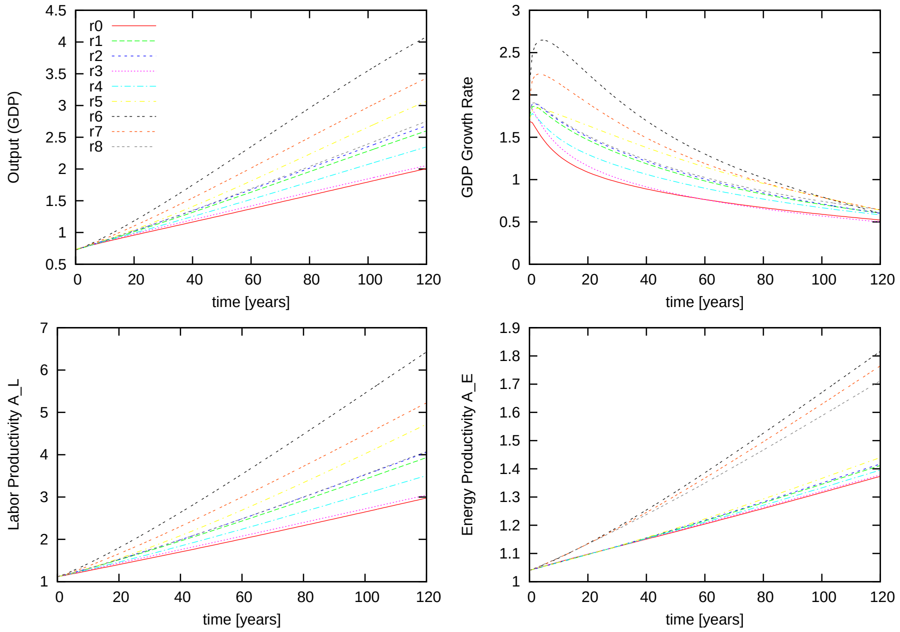

Figure 5: Parameter setting of ETC (see Tab. 3 for parameter set definition)

year	BAU		RED450	
	MIND	CliPIDE	MIND	CliPIDE
2050	0.84	1.39	1.36	2.74
2075	0.10	2.33	7.03	9.83
2100	1.59	4.12	37.98	56.06
2125	6.76	6.81	65.43	100.00

Table 4: Share of renewable energy on total energy [%] in MIND 1.1 and CliPIDE

3.3.4 Elasticities, Discount Rates and other Parameters

Remaining parameters concern factor shares, elasticities of substitution, depreciation and discount rates. As factor share parameters (a, a_1, a_2) serve only as scaling factors, they do not have an important meaning in the conceptual model analysis (except for the scaling of the finite fossil resources which however is already done by the parameterization of Rogner's curve and initial resource stock). Nevertheless, parameter values reflect estimation of Edenhofer et al. (2005). More important for the economic dynamic are elasticities of substitution that determine welfare losses of mitigation targets and several second-best policies. Parameterization of the nested CES function in the production sector is inspired by empirical studies of Kemfert and Welsch (2000) and van der Werf (2007). Elasticity of substitution in fossil energy sector is adopted from Edenhofer et al. (2005). The depreciation rate of 1 % p.a. is on a relatively low level in order not to overload the economic system with high capital-sustaining investments.

In contrast, choosing an adequate social time preference rate heats several discussions within the climate economics community. I use the straightforward value of 3 % p.a. and delay analysis of discount rate value or values (differing in household sector and government) to future research work. Although this issue is crucial for cost-benefit analysis, for cost-effectiveness solutions discounting does only affect timing of mitigation activities as the setting of mitigation targets already contains some implicit assumptions of damage discounting.

3.3.5 Mitigation Goal

The mitigation goal $\underline{S}$ is formulated as an upper bound of the accumulated extracted amount (as so-called *carbon budget*), i.e.:

$$\int_0^T R\, dt \geq \underline{S}$$

The choice of $\underline{S}$ influences mainly the timing of mitigation measures, that is improving energy efficiency and substituting fossil energy, but does not change qualitatively the behavior of the model. Hence, Fig. 6 shows the impacts of several mitigation targets starting with zero mitigation ($\underline{S} = 0$) to more ambitious mitigation targets ($\underline{S} = 175; 200; 230$).

In order to use a reduction scenario which forces the economy to deal with mitigation, $S_0 - \underline{S}$ should be around half or one third of the accumulated resources of the baseline scenario within the next 100 years. This corresponds with the 450 ppm scenario in MIND 1.1. However in this work I use a very ambitious mitigation target which is set to 2/5 of BAU extraction in the base model (without ETC) and to 1/5 of baseline extraction in the model with ETC (see Tab. 5). By using the same emission cap (for easier compareability) the common mitigation target in the basemodel turns out to be an ambitious mitigation target in the ETC model. However, the ambitious mitigation goal helps to highlight more clearly instruments and mitigation effects.

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goal (450 ppm CO2-equivalents) of Mind 1.1.

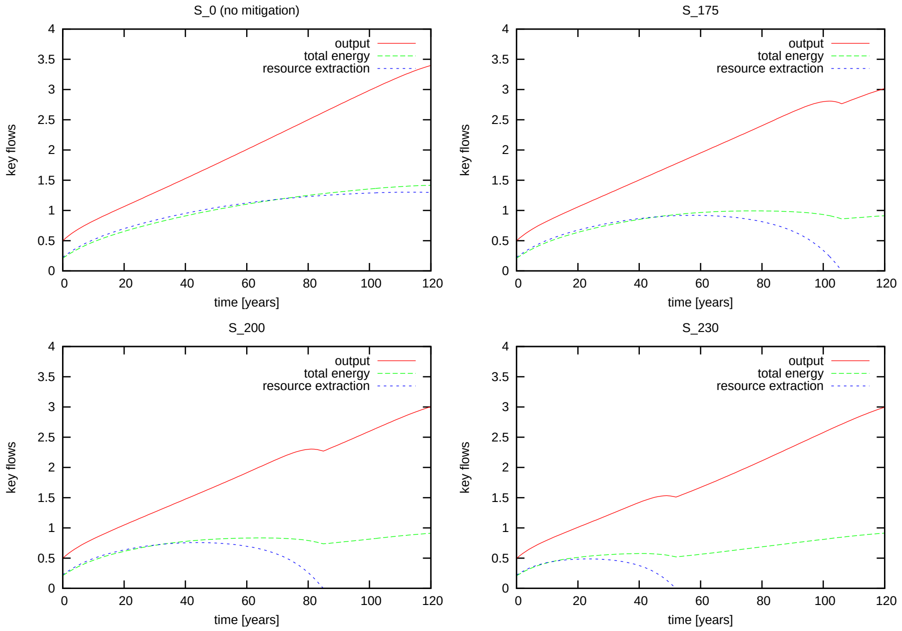

Figure 6: Different mitigation goals

	BAU ($t = 150$)	BAU ($t = 100$)	RED
base	72	50	20
ETC	150	95	20

Table 5: Accumulated resource extraction

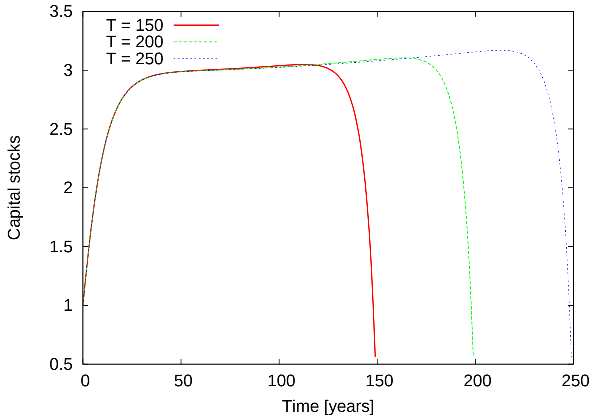

Figure 7: Impacts of different time horizons for the capital stock (BAU scenario)

3.3.6 Time Horizon

To solve the optimization problem numerically, one has to choose a fix time horizon for the planning period. Because of discounting, influence and meaning of long-term future events is downsized considerably. Nevertheless there could occur important differences in the qualitative dynamic of the economic system with the change of the time horizon. Therefore, several model runs are performed with differing final time T. The greater T is chosen, the more should the solution for the finite problem equal the solution for the infinite problem.

In a first observation capital stocks are cut down to augment consumption within the last years before end. This is an important difference in the dynamics for finite and infinite planning horizons, because for an infinite time horizon capital stock will not cut down some years before the end as there exists no end. But this artefact can be quite ignored because it has almost no influence on economic variables for the most of the time before economic breakdown (see Fig. 7). Restricting economic analysis on the time before breakdown is appropriate to obtain insights and conclusions that should also apply to the case of infinite timehorizon.

These observation also yields for the policy case. Fig. 8 shows the impact of the time horizon on resource tax and price as well as resource extraction and resource stock in the mitigation scenario. Again, although in the last time steps some numerical abnormalities occur, policy instruments and their impacts remain in principle the same.

Thus, in the following numerical calculations are performed with final time horizon $T = 150$ while plots and evaluations are performed on the first 120 time steps (i.e. years) to fade out terminal capital degradation effects.

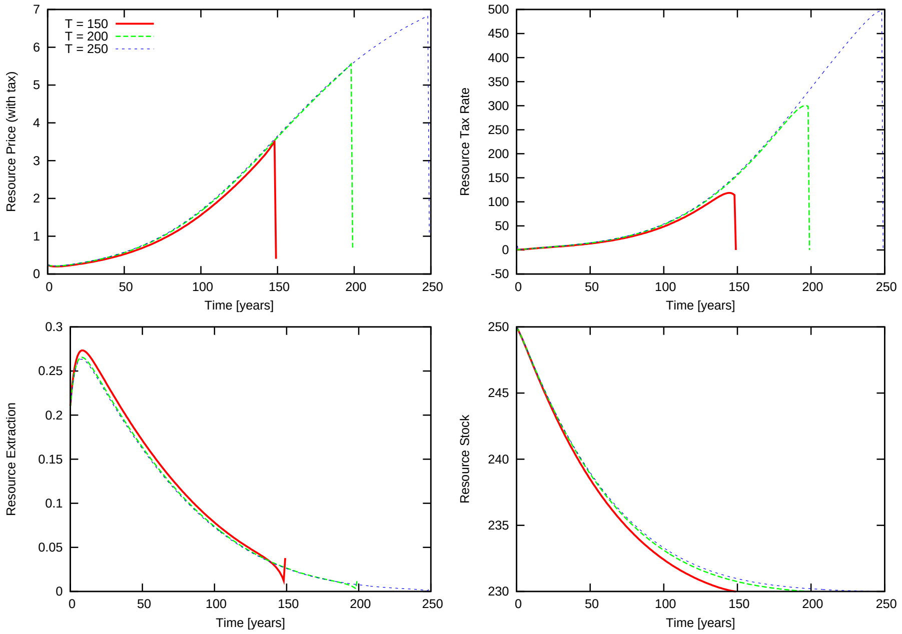

Figure 8: Impacts of different time horizons in the reduction policy scenario

3.4 Analysis

This subsection reflects some important general properties and characteristics of the economic system presented in above model description. Fist I analyze conditions for the socially optimal outcome of the market economy (Sec. 3.4.1). This is followed by some remarks about time consistency of policy instruments (Sec. 3.4.1). Finally I examine the question of macro-economic long-term behavior in the business-as-usual (Sec. 3.4.3) as well as in the reduction scenario (Sec. 3.4.4).

To keep analysis short, following considerations are made mainly on the basemodel with some brief outlooks to model extensions.

3.4.1 Social Optimality and Market Failures

The intuition of the *invisible hand* as formulated by Adam Smith which cares for the social optimality of private payoff maximizing market participants should also be applicable to the basemodel presented in Sec. 3.1 without mitigation target because no externalities and other market failures appear.

Beside existing general welfare theorems (e.g. presented in Mas-Colell et al., 1995, ch. 16) I analyze the conditions of a socially optimal outcome of the market economy of the basemodel. In order to do so, I start with the welfare maximizing first-order conditions of a social planner benchmark system and compare them with the first-order conditions of the decentralized market system.

Analytical Properties of the Socially Optimal Solution In order to reduce complexity of several production levels, analysis is performed on a single nested production function containing energy production and resource extraction function:

$$\tilde{F}(K_Y, K_E, K_R, L, S) := F(K_Y, L, E(K_E, R(K_R, S))) \tag{86}$$

Regarding the common budget constraint

$$C = \tilde{F} - I_Y - I_E - I_R, \tag{87}$$

the Hamiltonian reads:

$$\begin{aligned} H = & \, u(\tilde{F}(Y_P, K_E, K_R, L, S) - I_Y - I_E - I_R, L) \\ & + \lambda_Y (I_Y - \delta K_Y) + \lambda_E (I_E - \delta K_E) \\ & + \lambda_R (I_R - \delta K_R) - \lambda_S R(K_R, S), \end{aligned} \tag{88}$$

with λ_Y, λ_E and λ_R as costate variable for capital stocks K_Y, K_E and K_R and with λ_S as costate variable for the resource stock S.

Due to the concavity of $\tilde{F}$ and of equations of motions of capital and resource stock, there exist an interior optimal solution under the following first order conditions and equations for the costate variables:

$$u'_C = \lambda_Y = \lambda_E = \lambda_R =: \lambda, \tag{89}$$

$$u'_L = -\lambda \tilde{F}'_L, \tag{90}$$

$$\hat{\lambda} = \rho + \delta - \tilde{F}'_{K_Y} \tag{91}$$

$$= \rho + \delta - \tilde{F}'_{K_E} \tag{92}$$

$$= \rho + \delta - \tilde{F}'_{K_R} + \frac{R'_{K_R} \lambda_S}{\lambda}, \tag{93}$$

$$\dot{\lambda}_S = (\rho + R'_S)\lambda_S - \lambda \tilde{F}'_S. \tag{94}$$

Eq. 89 states that costate variables for all capital stocks have to equal in the optimum.

The mitigation constraint is formulated as

$$S \geq \underline{S}, \tag{95}$$

with $\underline{S} = 0$ in the BAU scenario. The resulting transversality conditions are

$$\lim e^{-\rho t} \lambda K = 0, \tag{96}$$

$$\lim e^{-\rho t} \lambda_S (S - \underline{S}) = 0. \tag{97}$$

Market and Planner Solution After the determination of the welfare optimizing first-order conditions I will show the equivalency with first-order conditions of the decentralized basemodel of Sec. 3.1 if all taxes are set to zero.

Let me start with equations (89–92). By setting $\lambda = \lambda_H$ Eq. 89 defines the same condition as (14). By substituting (32) in (15) and (31) in (16) one obtains (90) and (91), respectively. Eq. 92 follows from substituting r in (16) by:

$$r \overset{(38)}{=} p_E E'_{K_E} \overset{(33)}{=} F'_E E'_{K_E} \overset{(86)}{=} \tilde{F}'_{K_E} \tag{98}$$

The transversality condition for the capital stock (96) equals obviously those of the household (17).

For the remaining equations (93–94) and (97) one has to translate the costate variable λ_S of the centralized planner system into to costate variable λ_R of the resource sector in the decentralized market system by

$$\mu := \lambda_H \lambda_R \tag{99}$$

If $\mu = \lambda_S$ and $\lambda_H = \lambda$, I get from(93):

$$\begin{aligned}
\tilde{F}'_{K_R} - \frac{R'_{K_R}\mu}{\lambda_H} &= \tilde{F}'_{K_R} - R'_{K_R}\lambda_R \\
&\overset{(86)}{=} F'_E E'_R R'_{K_R} - \lambda_R R'_{K_R} \\
&\overset{(33,38)}{=} (p_R - \lambda_R) R'_{K_R} \\
&\overset{(43)}{=} (p_R - \lambda_R)\kappa \\
&\overset{(48)}{=} r,
\end{aligned} \tag{100}$$

and, hence, Eq. 93 states the same condition as in the decentralized economy (16). Recalling the definition of $\tilde{F}$ I get

$$\tilde{F}'_S = F'_E E'_R R'_S \overset{(33,38)}{=} p_R R'_S, \tag{101}$$

Thus, the derivative of λ_S stated in Eq. 94 can be transformed with $\mu = \lambda_S$ into:

$$\dot{\lambda}_S = \dot{\mu} \overset{(99)}{=} \lambda_H \dot{\lambda}_R + \dot{\lambda}_H \lambda_R \tag{102}$$

On the other hand Eq. 94 can be transformed into:

$$\begin{aligned}
\dot{\lambda}_S &\overset{(94,99)}{=} (\rho + R'_S)\lambda_H \lambda_R - \lambda_H \tilde{F}'_S \\
&\overset{(101)}{=} (\rho + R'_S)\lambda_H \lambda_R - \lambda_H p_R R'_S
\end{aligned} \tag{103}$$

Equating (102) and (104) and dividing both sides by λ_H yields:

$$\dot{\lambda}_R + \hat{\lambda}_H \lambda_R = (\rho + R'_S)\lambda_R - p_R R'_S \tag{104}$$

$$\begin{aligned}
\dot{\lambda}_R &= (\rho - \hat{\lambda}_H)\lambda_R + (\lambda_R - p_R)R'_S \\
&\overset{(91)}{=} (\tilde{F}'_{K_Y} - \delta)\lambda_R - (p_R - \lambda_R)R'_S \\
&\overset{(31)}{=} (r - \delta)\lambda_R - (p_R - \lambda_R)R'_S
\end{aligned} \tag{105}$$

Therewith, the equation of motion (94) of the central planner model can be transformed into the analog equation of motion of the decentralized market model (49).

Moreover, the transversality condition (50) and the solution of λ_H from (18) imply

$$\begin{aligned}\lim \mu(S - S_c)e^{-\rho t} &= \lim \lambda_R \lambda_H (S - S_c)e^{-\rho t} \\ &= \lambda_{H,0} \lim \lambda_R e^{\int_0^t (\rho+\delta-\bar{r})ds}(S - S_c)e^{-\rho t} \\ &= \lambda_{H,0} \lim \lambda_R e^{\int_0^t (\delta-\bar{r})ds}(S - S_c) \\ &= 0. \qquad (106)\end{aligned}$$

Thus, the market solution of λ_H and λ_R fulfills the optimality and transversality conditions of the social planner solution with the given transformation $\lambda_S = \lambda_H \lambda_R$ and anticipated mitigation goal $S_c = \underline{S}$. That is, the BAU scenario with $S_c = \underline{S} = 0$ is always socially optimal.

The solution of a RED scenario is equivalent to the social planner solution if the mitigation goal is anticipated by resource extractors.

Market Failures Above considerations showed the social optimality of the basemodel if mitigation is anticipated by the resource sector and all taxes are set to zero. In particular, introducing taxes unequal to zero on factor prices would distort social optimality and first-order conditions of decentralized economy would differ from those of the social planner. If the mitigation target is not anticipated by the resource sector due to an accumulated quantity restriction policy, overextraction would occur violating government's mitigation target. This demands for taxes to reduce resource demand. Further market failures would be introduced if knowledge spillovers or market power were considered. Public R&D expenditures are paid by the government and need public funding.

All these market failures mentioned will be treated in this work by studying several model refinements within the presented model framework. However, there are still further failures left for future research, for example considering differing discount rates (e.g. of capitalist and workers household) or considering damages due to climate change.

3.4.2 Time Consistency

Modeling the government as an actor participating as Stackelberg leader raises the question whether the government has an incentive to deviate from its former declared policy path at one time instant of the planning horizon. Such a behavior is called *time inconsistent* and motivates the research under which conditions the Stackelberg leader complies with her commitment.

In general there is no reason why open-loop Stackelberg games should be time consistent (cf. Dockner et al., 2000, ch. 5). An analytical proof of time (in)consistency of the model used in this work would be a challenging task if possible at all. A more pragmatic approach would be to make numerical tests of consistent optimization, i.e. solving the optimization program for the whole time horizon, then restarting the optimization program with initial state variables of a specific time instant t^* of the finished first optimization run and have a look on the re-calculated optimal policy paths for $t^* \leq t \leq T_{end}$. While differing optimal policy paths would "proof" the time inconsistency of the game, same policy paths show only the time consistency of this specific subgame $\Gamma(t^*)$ – at specific time instant t^* – and a specific parameter set.[47]

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[47] For formal definition of the subgame $\Gamma(t)$ see Dockner et al. (2000, ch. 4.3).

But there is a third consideration to deal with the problem of time inconsistency. As long as an optimal policy path achieves the social optimum, there cannot be an incentive to deviate from this path as no better outcome than the optimal one can be achieved. Thus, first-best policy instruments have necessarily to be time-consistent as long as the socially optimal solution is time consistent. The latter is only a problem of the "right" discounting method of the social utility function. Strotz (1956) demonstrates that the only time consistent discounting method is of constant-rate discounting (i.e. the standard approach also used in this model), such that the question of time inconsistent policy instruments can only rise for second-best solutions. Even in this case the model framework provides a useful benchmark of an optimal second-best policy which could be a starting point for further considerations of credible governmental commitments.

3.4.3 Economic Growth

In this section I consider briefly some aspects about the conditions for economic growth with exhaustible resources. First, some analytical reflections about conditions for steady-state and balanced-growth performed on the basemodel will sketch the crucial problems. Then, these considerations will be discussed in the more general theory of economic growth with exhaustible resources.

Before starting the analysis I have to clarify the differences between the terms *steady-state* and *balanced-growth* as they are used often synonymously in economics. In the mathematical analysis of dynamic systems a steady-state describes a state where one or more system variables do not change in time (e.g. Bossel, 1994, p. 356; Strogatz, 2000, p. 19). In many ecological and physical systems the steady-state forms the stable long-term equilibrium of the system (e.g. a constant population size in logistic growth models). However, economic analysis often focuses on efficiency terms – e.g. $Y/(A_L L)$ – instead of pure system variables. Thus, constant efficiency terms imply constant growth rates of system variables if efficiency grows with constant rate. This growth is donated as steady-state (because efficiency terms are in steady-state) or balanced-growth (because system variables growth with constant rate) (e.g. Barro and i Martin, 1999, p. 19; Lucas, 1988).

The differing use of the term *steady-state* in these two scientific contexts highlights the different assumptions and expectations about system's long-term behavior: While ecological, chemical and physical systems often converge to a state of no-change, economic systems are often assumed to grow continously and eternally.

However, in the following analysis I will use the term *steady-state* in the mathematical and natural scientific sense of zero-growth and the term *balanced-growth* for the constant-rate growth economy.

Steady State Economy In a steady-state, consumption and all economic input factors are constant, i.e. $\dot{C} = \dot{K}_Y = \dot{K}_E = \dot{K}_R = \dot{L} = 0$.

Regarding the budget function of the social planner model (87) and the nested CES technology structure, the derivative of C with respect to time reads:

$$\begin{aligned}\dot{C} &= \dot{Y} - \dot{I} \qquad (107)\\ &= Y'_{K_Y}\dot{K}_Y + Y'_E E'_{K_E}\dot{K}_E + Y'_E E'_R (R_{K_R}\dot{K}_R + R_S\dot{S})\dot{K}_R + Y'_L\dot{L} - \dot{I}\end{aligned}$$

Using zero growth rates for input factors, K_Y, K_E, K_R, L (as assumed in steady state) and using equations of motion of capital stocks $\dot{I} = \delta\dot{K} = 0$, one obtains:

$$\dot{C} = Y'_E E'_R R'_S \dot{S} = -Y'_E E'_R R'_S R \qquad (108)$$

Because of the neoclassical assumptions on production technology, $Y'_E > 0, E'_R > 0$ and $R'_S > 0$, $\dot{C}$ cannot be positive nor zero for any resource extraction path. Thus steady state is only possible for $R = 0$ and hence $Y = 0$ and $C = 0$ (independently from the finite or infinite size of the resource stock); there exists no non-trivial steady state.

From above considerations, one can derive the following properties for a steady state economy:

1. $R'_S = 0$ and $S_0 = \infty$, i.e. no decreasing capital productivity for resource extraction and infinite resource stock, or
2. $Y > 0$ if $R = 0$, i.e. production of final goods is – at least at a certain level – possible without resource use (resources are substituteable).

Balanced Growth Economy The impossibility for an even non-trivial steady-state economy may give the intuition for the impossibility of a non-trivial balanced growth path where the economy grows with constant rate (i.e. $\hat{Y} > 0$ and constant). A short analysis – neglecting depreciation to simplify matters – shows which model assumptions and properties make constant longterm-growth impossible.

By using the definition of elasticity of production $\sigma_X = Y'_X \frac{X}{Y}$, growth rate for overall output reads:

$$\hat{Y} = \sigma_{K_Y}\hat{K}_Y + \sigma_{K_E}\hat{K}_E + \sigma_{K_R}\hat{K}_R + \sigma_L\hat{L} + Y'_S\dot{S}$$

Because of $C = Y - I$, long-term growth is impossible if $\hat{Y} < \hat{I} = \hat{K}$ and thus

$$\sigma_{K_Y}\hat{K}_Y + \sigma_{K_E}\hat{K}_E + \sigma_{K_R}\hat{K}_R + \sigma_L\hat{L} - Y'_S R < \hat{K} = \hat{K}_Y + \hat{K}_E + \hat{K}_R \qquad (109)$$

As I use homogenous production technology, $\sum_i \sigma_i = 1$. However, $\hat{L} > 0$ cannot hold because of $L \leq L_{max}$. Also constant rising resource extraction $(K_R > 0)$ is not possible due to finite resource stock.

Therefore I can summarize some necessary conditions for the existence of a balanced growth path, if capital productivity in resource sector does not decrease $(Y'_S = 0)$:

1. infinite resource stock, constant rate growing labor supply (at least with $\hat{K}$), or
2. with limited labor supply and infinite resources: constant or increasing return to scale production function with respect to K_i, i.e. $\sigma_{K_Y} + \sigma_{K_E} + \sigma_{K_R} \geq 1$, or

3. with limited labor supply and limited resource stock: constant or increasing return to scale production function with respect to K_Y and K_E, i.e. $\sigma_{K_Y} + \sigma_{K_E} \geq 1$

Allowing for decreasing capital productivity, i.e. $Y'_S > 0$, above criteria are even more restrictive because the growth eating effect of $-Y'_S R$ in the left side of Eq. 109 has to be outweighed by even higher elasticities of factor production. In case 3 of finite resources, $\lim_{t\to\infty} R = 0$ (cf. Sinn, 2007b), and thus extraction decreasing productivity effect diminishes in the long run, because Y'_S is bounded (continuously differentiable function in the interval $[0, S_0]$). Then, for every $\varepsilon > 0$, growth is possible if $\sigma_{K_Y} + \sigma_{K_E} \geq 1 + \varepsilon$.

As this considerations showed, obtaining constant long term growth presumes a good substitutability of limited production factors like labor and fossil resources. Endogenous technological change may help to overcome this problem and augment factor productivities, but higher elasticities of production – i.e. $\sum \sigma_X > 1$ – may only be possible by giving up neoclassical convexity properties. Thus new problems of existing market equilibria arise which have to be treated carefully.

General Conditions for Economic Growth with Exhaustible Resources
Ströbele (1984) investigates conditions for economic long-term growth if resources are finite. He generalizes former researches by using a CES production function with capital and resources as input factors instead of a Cobb-Douglas function as many other economists had done before (e.g. Stiglitz, 1974a; Hartwick, 1977). As he demonstrates, the crucial parameter for economic growth is the elasticity of substitution s between resources and capital and hence he distinguishes three cases:

1. for $s > 1$ eternal economic growth is possible;
2. for $0 < s < 1$ no growth is possible and the economy (and consumption) has to break down;
3. in the limiting case for $s = 1$ (Cobb-Douglas function) zero-growth is possible with constant consumption level and increasing capital stock to substitute diminishing resource flows.[48]

However, exogenous technological growth can augment resource efficiency and therfore actually enlarge resource stocks (up to infinity), if growth rates are suitably high (c.f. Stiglitz, 1974a, for Cobb-Douglas case). Nevertheless, Ströbele disallows all these approaches and assumptions ($s \geq 1$, eternal technological change, zero capital depreciation) because they contradict crucial laws of thermodynamics of energy conservation and entropy raise. Hence, only a backstop energy technology can solve the problem of limited resource availability.

In the course of this thesis, this question will also be touched, but not discussed in detail. Former considerations made on the basemodel give reason to the conjecture, that only technological change and renewable energy are capable to generate long-time growth.

Beside the problem of limited resources, growth theory usually neglects this point when characterizing and modeling economic growth (e.g. the entire book

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[48] If also capital depreciation is considered, then even the Cobb-Douglas case cannot provoke stable consumption levels.

of Barro and i Martin (1999) about economic growth does not treat this issue). Nevertheless I want to examine my approach of modeling endogenous technological change in the light of stylized qualitative properties of economic growth.

Kaldor's Stylized Facts Parameterization of endogenous technological change (Sec. 3.3.2) was performed to reproduce plausible growth paths in the case of abundant resource deposits (BAU scenario). But there are also some more qualitative characteristics of economic growth, stated by Kaldor (Greiner et al., 2005) as stylized facts:

1. Output per workers grows at a rate that does not diminish over time.
2. Capital per worker grows over time.
3. The rate of return to capital is constant.
4. The capital/output ratio is roughly constant.
5. The share of capital and labour in net income are nearly constant.
6. Growth rates differ across countries.

While the last property is not subject to this work which is limited to a one-economy-system, the remaining properties can be assigned to the model with endogenous technological growth. At the most there are deviations in the beginning phase where the economy starts far away from a almost-balanced growth path. Anyhow, ETC is constructed that way, that diminishing returns to scale of R&D appear in the long run which expresses in an decreasing growth rate. This allows for the important empirical observation, that growth rates decline with increasing wealth (Greiner et al., 2005). Whether growth rate declines to zero or reaches a limit value greater than zero cannot be verified by numerical model runs, because only limited time horizons can be treated. In numerical calculations GDP growth rate falls to 0.5 % (see again Fig. 5 of the calibration of ETC parameters).

3.4.4 The Consequences of Mitigation

To compare the impacts of mitigation I focus on the social planner basemodel with and without mitigation goal, that is the baseline scenario (BAU) and the reduction scenario (RED). In contrast to the baseline scenario where an almost stable consumption level is achieved after a short growing phase in the beginning, in the reduction scenario consumption falls rapidly after a short period of economic growth (see numerical run in Fig. 9).

Because of the simple model structure considered here (without renewable energy and ETC) there are only to ways to deal with the scarcity of fossil resources: (1) reduction of consumption and (2) factor substitution. The reduction of consumption affects the whole production chain and also decreases fossil energy and resource demand. This causes high welfare losses although consumption reduction can be compensated partly by higher leisure. The substitution effects of mitigation are shown in Fig. 10. In the production sector fossil energy is partly subsituted by higher capital and labor input. The fossil energy sector substitutes resources by higher capital input.

The higher the elasticities for resources and fossil energy substitution are the better is the substitution of fossil resources and the lower are welfare losses

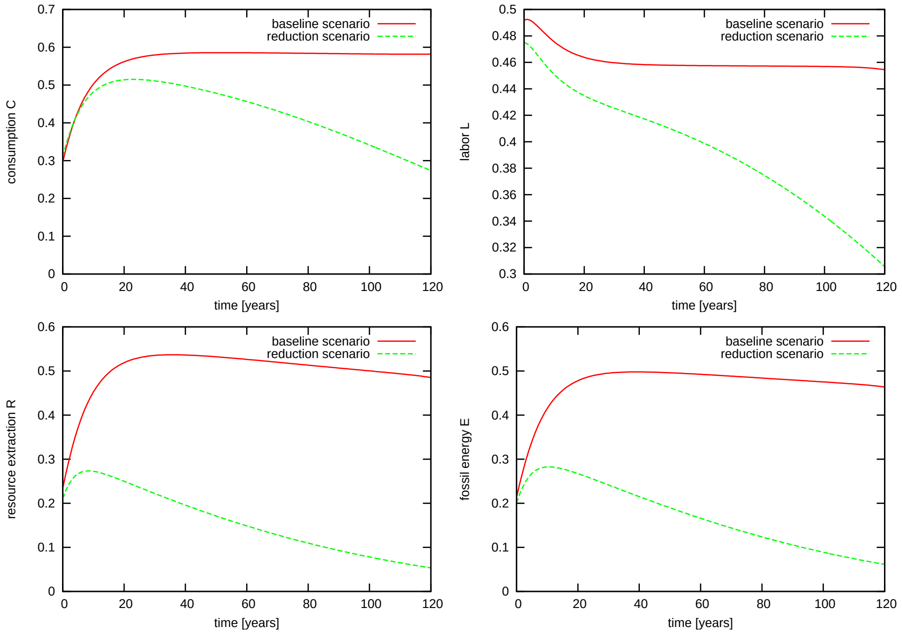

Figure 9: Key flows in baseline and reduction scenario without ETC and renewable energy.

due to consumption reduction (Fig. 11). The dramatic fall of consumption level shows the importance of the crucial factor fossil resources for the whole economy and the difficulty to deal with an (artificial) resource scarcity.

In contrast to the social planner model where key flows simply are set by the planner, the market economy with the government as Stackelberg leader faces the problem to enforce market actors to reach the mitigation goal. As I will show, the success of a certain policy lies in its capability to set the "right" price signals to actors and hence to achieve the optimal combination of consumption reduction and factor re-allocation. In the following analysis this capability to efficient factor allocation is analyzed. Next to efficiency criteria, policy instruments are also discussed respect to their distributional effects.

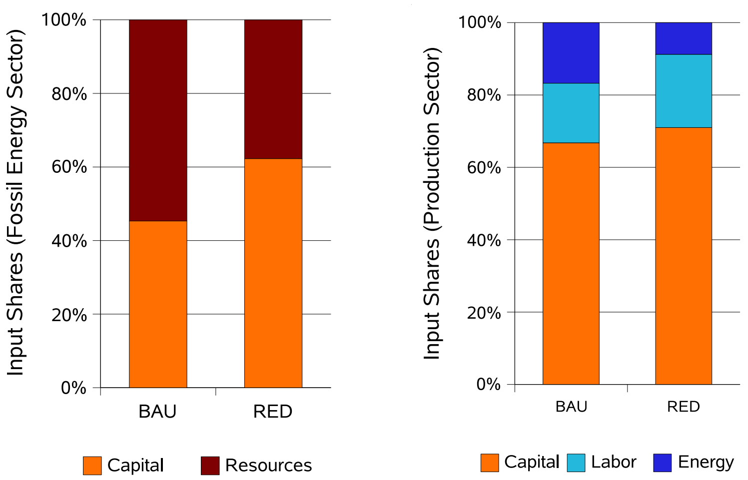

Figure 10: Shares of factor input in fossil energy and production sector

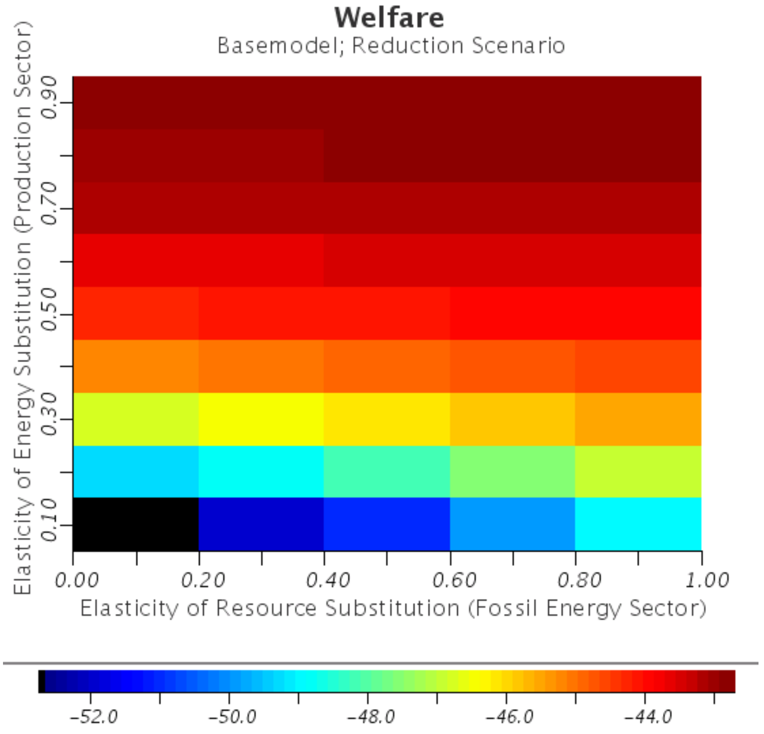

Figure 11: Welfare subject to elasticities of substitution s (x-axis; energy sector) and s_1 (y-axis; production sector).

4 Evaluation of Policy Instruments

The analysis of policy instruments is based on numerical model runs, analytical reflections and plausibility considerations. The parameters used are listed in appendix E.2; differing parameters used for parameter and sensitivity studies are explained separately.

The following policy design decisions are considered in detail:

1. price vs. quantity policy
2. input vs. output taxation
3. competition policy
4. technology policy

Evaluation of mitigation policy is orientated on efficiency of outcome, distributional effects and further considerations reflecting insights from Sec. 2.3. In BAU scenarios, also the impacts of several technology options and market failure correcting policies on the emission paths are investigated.

Distributional Effects Income of households is decomposed by separating the budget constraint in their income forms, namely labor income, capital income, profits, and lump-sum tax transfer that can be positive or negative. Income shares are calculated as discounted sum to reduce the influence of longterm-future effects and to regard household's positive time preference rate. However, a non-discounted distribution shows qualitatively the same effects of policy instruments with a small (quantitative) distortion of the observed discrepancies but with a conservation of the order of relative changes. As the biggest part of the income is consumed, income is discounted at household's time preference rate of utility ρ_H instead of using the net interest rate. Using the latter for discounting furthermore complicates the comparability of the results because of different (capital) tax rates and therefore distinct discount rates.

State's Share To obtain a criteria for bureaucracy and governments control of economic flows, state's share is computed as sum of the absolute values of all tax flows divided by overall output Y:

$$Gov = \frac{\sum_i |\tau_i p_i q_i|}{Y}, \tag{110}$$

where p_i and q_i donate factor price and quantity of the i-th factor and τ_i denotes the ad-valorem tax. This ratio can be greater than one, because the sum of absolute tax flow augments state's activity due to subsidies although the latter decrease state's net income.

Acronyms In order to handle different model and policy scenarios I use the acronyms explained in Tab. 6. The combination of these symbols specifies the applied policy instruments in the specific model run. The acronym `m_e_ke`, for example, stands for the market model with energy and energy sector-specific capital tax.

model type and scenario		policy instruments (only valid for reduction scenario)	
`p`	social planner model	`r`	resource tax
`m`	market economic model	`e`	energy tax
`bau`	business as usual	`k`	capital tax
		`ke`	sector-specific capital tax (energy sector)
		`ky`	sector-specific capital tax (production sector)
		`kr`	sector-specific capital tax (resource sector)
		`l`	labor tax
		`q`	quantity restriction policy

Table 6: Acronyms for model and policy types

4.1 Price vs. Quantity Policy

This subsection analyses the regulative quantity restriction instrument and the resource tax as one representative of the class of price instruments. The resource tax is chosen for its efficiency (to anticipate this result here) and its simplicity in respect to other first-best price instruments. In the following, both instruments are discussed separately before their main differences are emphasized at the end of this subsection. To simplify matters, analysis in this subsection is restricted to the basemodel without ETC and renewable energy; I will catch up these extensions in Sec. 4.4.4.

4.1.1 Quantity Restriction Policy

The quantity instrument restricts accumulated resource extraction directly to resource extractors which anticipate the mitigation goal in their transversality condition by setting

$$S_c = \underline{S}$$

(see description of resource sector in Sec. 3.1.4 for technical details). All taxes are set to zero.

The numerical calculations confirm the social optimality of the quantity approach without the need of any taxes. The resource price raises enormously reflecting the scarcity of resources (compared to the baseline scenario of the market model without taxes). All flow variables equal the optimal trajectories of the social planner solution (RED). With respect to the baseline market model, profits of the resource sector rise dramatically and form a significant source of household's income.

As demonstrated in Sec. 3.4.1, the social optimality of the quantity approach is a direct consequence of the optimality of the market model if the mitigation goal is anticipated in the transversality condition. The high resource price induces factor reallocation in the fossil energy sector. The indirectly augmented energy price (due to high resource price) enforces again the production sector to a re-allocation of its energy input to the efficient level (see Fig. 10 for sectoral factor allocation which is also discussed in detail in the following subsection). The raise of profits in the resource sector needs further explanations. Anticipating the mitigation goal S_c is equivalent to downsizing the initial resource stock S_0 by the amount $S_0 - S_c$ and omitting the mitigation goal: In both cases the extractable amount of resources is $S_0 - S_c$ and extraction costs remain the same

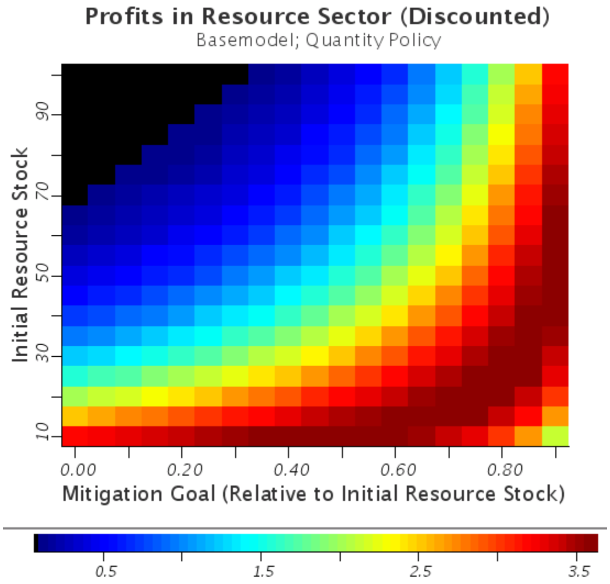

Figure 12: Resource rent subject to the initial resource stock and the mitigation goal. The mitigation goal (x-axis) is the fraction of mitigation goal S_c and initial resource stock S_0 (i.e. S_c/S_0).

as they depend on the extracted amount $S_0 - S$. Thus, an ambitious mitigation goal can be translated to a reduced stock of available resources. Fig. 12 shows this interrelation for several values of initial resource stock and relative mitigation goal: The fewer resources being available to extract on a fixed time horizon, the higher is the resource price and the more powerful is the resource sector providing an essential production factor that cannot be subsituted easily (cf. Dore, 1992).[49] The interrelation between initial resource stock and initial resource price can be seen in the simple model of Dasgupta et al. (1981) for infinitive time horizons and negligible extraction costs, where (referring to Eq. 2 ibid.)

$$\int_0^\infty D(p_R(t))dt = \int_0^\infty D(p_R(0)e^{rt}dt = S_0 - S_c, \tag{111}$$

with $D(\cdot)$ denoting the demand function. Thus, the lower $S_0 - S_c$ is (right side of Eq. 111), the lower has to be accumulated demand (left side). This implies – under usual neoclassical conditions for the demand function – a higher $p_R(0)$ and hence higher profits in the resource sector.

The capability of the economy to substitute fossil resources or their derivatives like fossil energy is another main determinant of the level of profits in the resource sector because it influences the demand function $D(\cdot)$. As shown by a parameter study in Fig. 13, the lower the elasticity of substitution in fossil energy and production sector is, the higher are resource profits due to mitigation.

The quantity approach is a simple and efficient way to reach the mitigation target without purchasing any taxes. The role of the government is limited to enforce resource extractors to anticipate the mitigation goal (e.g. by giving away

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[49] Note, that both axis in Fig. 12 are not independent, because the outcome depends on both values S_0 and S_c in the way, that only the difference $S_0 - S_c$ matters.

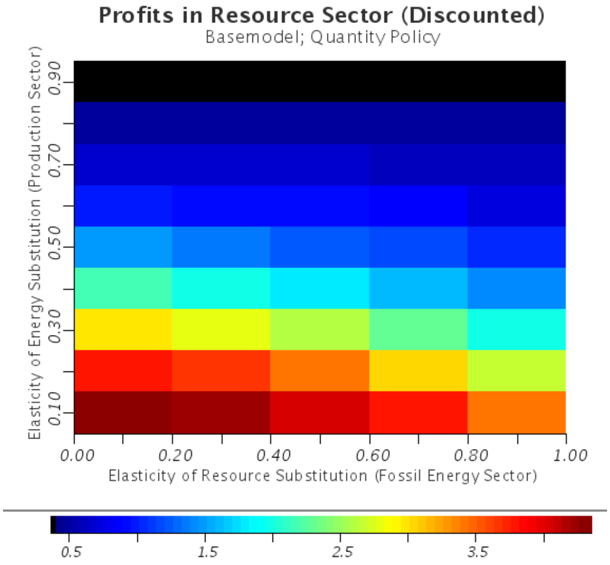

Figure 13: Resource rent subject to elasticities of substitution s (x-axis; fossil energy sector) and s_1 (y-axis; resource sector).

pollution certificates whose accumulated amount is restricted). The quantity policy can generate profits in the resource sector that exceed the profits of the baseline scenario by a multiple[50]. Thus, the more ambitious the mitigation goal is, the lower the available reserves of fossil resources are and the lower the elasticities of substitution for fossil resources or fossil energy are, the higher are the profits in the resource sector.

4.1.2 Resource Tax

The ad-valorem tax on the resource price drives a wedge between selling price p_R of fossil resource sector and purchase price $\bar{p}_R$ of fossil energy sector (see description of fossil energy sector, household sector and government in Sec. 3.1 for technical details). The tax income is lump-sum transfered to households.

In the numerical solution of the optimization problem the mitigation goal is achieved without welfare losses respect to the planner's reduction scenario solution. All factor flow variables are equal to the planner model (and especially to the quantity restriction instrument). The resource tax rate increases permanently with declining growth rate and reaches the value of 80 at $t = 120$. The profits in the resource sector fall slightly compared to the baseline market model. Tax income due to resource taxation is very high and almost identical with resource profits in the quantity policy scheme (Fig. 14).

A comparison of the purchase price of resources shows that the tax is exactly on that level such that taxed purchase price $\bar{p}_R$ equals the resource price in the quantity restriction model. Therfore the resource tax can set the right price signals to the fossil energy sector to re-allocate factor inputs in the same optimal way as in the quantity approach or in the planner model.

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[50] Fig. 12 shows the baseline scenario on the first vertical line where the relative mitigation goal is zero. In standard model runs there are plenty of resources available, that is, $S_0 > 80$.

To characterize the socially optimal resource tax algebraically, all system variables have to equal those of the quantity instrument (labeled with an asterisk), except for p_R, τ_R and λ_R. Substituting the values of the quantity instrument in Eq. 48 yields

$$r^* = (p_R - \lambda_R)\kappa^*. \tag{112}$$

Since, by Eq. 38, $p_R(1+\tau_R) = \bar{p}_R = p_E^* \frac{\partial E}{\partial R}(K_R^*, R^*) = p_R^*$, one can transform this to

$$1 + \tau_R = \frac{p_R^*}{\frac{r^*}{\kappa^*} + \lambda_R}. \tag{113}$$

Given the (unique) solution for $\lambda_R(\cdot)$ from Eq. 49 and Eq. 50 and the system values p_R^*, κ^*, r^* of the quantity policy scheme, the resource tax is determined explicitly for every instant t. Charging a resource tax as stated in Eq. 113 is sufficient to reach the social optimum of the RED scenario as all other variables and first-order conditions equal those of the quantity policy scheme.

The high tax rate is necessary because the demand side is very inelastic in regard to price changes due to low s and s_1 values. A parameter study about the tax income subject to elasticities shows the same results as Fig. 13 because high profits due to resource scarcity are almost completely absorbed by government. Thus, the taxation dynamic of resource reduction is primarily driven by the demand side and their price elasticities.

As the tax income reaches almost the (high) levels of the profits in the resource sector in the quantity approach, the price policy generates high tax incomes that can be redistributed to members of the society. Nevertheless, high tax rates might be politically difficult to implement and resource extractors would gain even less profits than in the baseline scenario.

4.1.3 Comparison and Conclusions

As already mentioned in Sec. 2.3 a main difference between price and quantity policy design is traditionally seen in the unequal consequences with uncertain economic parameters and variables – and its impacts on the resulting resource price or quantity. Neglecting this important point, this section highlighted the distributional effects of both policy instruments. The results confirm the more general considerations of Helfand et al. (2003) and specific studies of Buchanan and Tullock (1975) and Maloney and McCormick (1982) (see also Sec. 2.3.4).

As a consequence of mitigation, additional income is generated – either as profits or as tax income – which changes the income distribution with respect to the baseline scenario (see Fig. 14). The volume of this additional income depends on the mitigation goal and on the elasticities of substitution of resources and fossil energy.[51] High profit and tax income levels for standard parameterization

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[51] The extension of the base model by a renewable energy sector could be – in a first approximation – estimated by a higher elasticity of substitution in the fossil resource sector, as the renewable energy sector generates energy from capital only. The results presented in this section remain valid as there is (currently) no competitive backstop energy in the real world that would raise s substantially. Of course, this may change if technological change is considered as a relevant force of the economic system. Again, the impact of both model

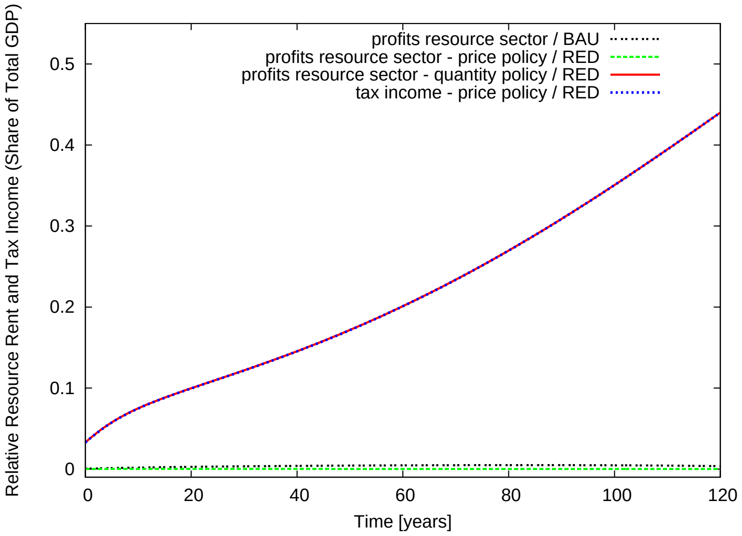

Figure 14: Resource profits and tax income for price and quantity policy relative to output. Rents in the resource sector under the quantity policy almost equal tax income under price policy.

(and their variation in parameter studies) indicate that there might be potent conflicts about the distribution of this income due to political power of actors who want to influence political decision processes. Resource extracting countries should be deeply grateful for a climate protecting quantity restriction instead of no political measure, while the working household who does not own fossil resources, has to bring higher sacrifices for emission reduction than the price approach with positive tax transfers would enforce.

I terminate this consideration by the conclusion that both approaches achieve the mitigation goal in an efficient way but with different distributional effects: the quantity regulating policy benefits the resource extractors by an enormously increased scarcity rent while the tax-driven price instrument transfers this income to the household sector. However, labor and capital income remain the same under both instruments.

4.2 Input vs. Output Taxation

This subsection inquires on which location in the economic system an instrument should operate. To concentrate on this point there are only price instruments considered, e.g. taxes on the prices of resources, energy, labor, and capital. Fig. 15 shows the production chain of the (base model) economy with its factor flows that are matter of taxation: there are seven single tax instruments that can be combined combinatoryly.[52]

A typical classification of environmental taxes concerns input factors and output goods of a production process which causes environmental damages and

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extensions can be estimated by higher elasticities in the energy and production sector.

[52] Furthermore there is the possibility to charge taxes on profits, e.g. cash flow taxes. As there are only profits in the resource sector and every cash flow tax is equivalent to a combination of a specific resource tax and resource sector specific capital tax, the case of profit taxation can be covered by common factor taxes.

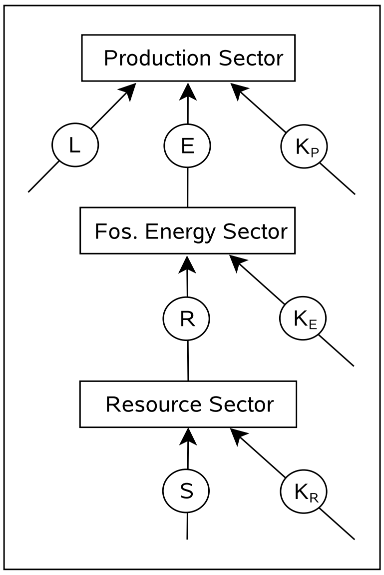

Figure 15: Factor flows in the production chain of the base model.

are therefore called input and output taxes. As emissions are mostly futile by-products, their taxation is not classified as an output tax but as an emission tax.

Since the emission causing sector of the economy is the fossil energy sector, classification of taxes as input and output tax refers to that sector. That is, resource and capital taxes are input taxes while the energy tax is an output tax. Since resources and emissions are assumed to be proportional, the resource tax can also be interpreted as an emission tax.

To reduce the number of possible instruments this subsection focuses on some important instruments that are often subject to economic and political discussion:[53]

`m_r` resource tax $\{\tau_R\}$

`m_e` energy tax $\{\tau_E\}$

`m_e_ke` energy and energy sector specific capital tax $\{\tau_E, \tau_{K_E}\}$

`m_k_l` capital and labor tax $\{\tau_K, \tau_L\}$

`m_ke` pure abatement subsidy for capital stock in the fossil energy sector $\{\tau_{K_E}\}$

Capital and labor tax – affecting the two control variables of the household – are very unspecific operating taxes as they are applied to factors that are weakly related to carbon dioxide emissions. Nevertheless, both taxes are important taxes in existing tax systems and it is worth analyzing, whether those unspecific taxes can achieve the mitigation goal. The abatement subsidy is motivated by the review of environmental economics which considers it a possible policy instrument (Sec. 2.3.4).

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[53] This selection of instruments is already motivated by the results of this analysis. At the end of this subsection there is a short note about neglected instruments and their impacts.

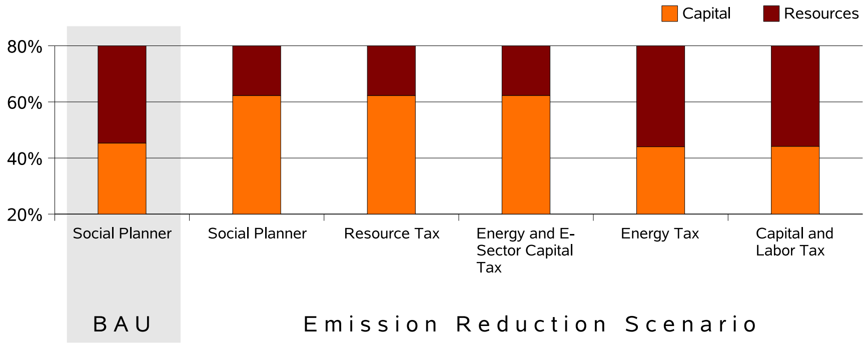

Figure 16: Share of factor inputs in the fossil energy sector.

Again, policy instruments are analyzed within the base model neglecting renewable energy and endogenous technological change in order to emphasize outstanding mechanisms of the impacts of several taxes.

The scope of the presentation of several tax instruments lies in its economic efficiency (that complies with social optimality). In the concluding consideration and comparison, further aspects like distributional and feasibility aspects are discussed briefly (Sec. 4.2.5).

4.2.1 Input Taxation: Resource Tax

As already stated in Sec. 4.1, the resource tax achieves an optimal allocation of economic flows and stocks, such that the social optimum of the reduction scenario is reached. If in addition the government can use further taxes than necessary, these additional taxes are calculated to be zero by the numerical model.

The taxation of fossil resources affects the whole chain from the resource sector up to the production sector: Modified resource prices again influence fossil energy, capital and labor prices.

4.2.2 Output Taxation: Energy Tax

Analog to the resource tax, the energy tax changes the purchase price $\bar{p}_E$ of energy for the final good producing firms. Other taxes are set to zero and tax income is lump-sum transfered to households.

Applying an energy tax is indeed a feasible instrument to reach the mitigation target in the numerical run but it is not socially optimal: Consumption and labor paths fall with respect to the socially optimal trajectory. The energy tax rate increases to a high level (up to 50 at $t = 120$), but is always lower than the optimal resource tax rate.

The following short argument sketches the problem of the pure energy tax. The demand for energy E depends on the energy price p_E and the energy tax τ_E. In order to reach the mitigation goal, the resource path R has to be changed by decreasing the demand via taxes on p_E or p_R. Due to the CES technology in the fossil energy sector, the ratio of factor inputs is known to be characterized

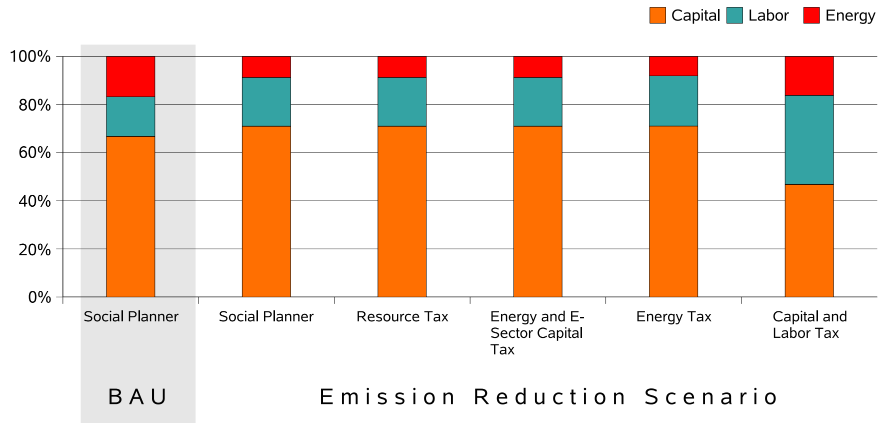

Figure 17: Share of factor inputs in the production sector.

by:[54]

$$\frac{K_E}{R} = \left(\frac{p_R(1+\tau_R)}{r(1+\tau_{K_E})}\frac{a}{(1-a)}\right)^s = \left(\frac{1+\tau_R}{1+\tau_{K_E}}\right)^s \left(\frac{p_R}{r}\frac{a}{(1-a)}\right)^s \tag{114}$$

That is, the ratio of factor inputs depends only on prices r and $\bar{p}_R$. An energy tax would decrease energy demand and due to output reduction of E_{fos} also R and K_E. But, the ratio of K_E/R remains unchanged as no changes occurred in the prices r and p_R.[55] The incapability of a pure energy tax to re-allocate factor inputs in the fossil energy sector in a socially optimal way can also be seen in Fig. 16: The ratio of resource and capital input remains almost the same as in the baseline scenario, while in the optimal resource tax and quantity restriction schemes a higher resource substitution by capital arises. As the energy tax changes the purchase price of energy in the production sector, the factor allocation is optimal (see Fig. 17). In short, with reference to the Slutsky equation, an energy tax has an income effect, but no substitution effect in the energy sector. It is only capable of achieving a mitigation goal by reducing overall energy consumption (in the production sector), resulting in an inefficient mix of capital and resource inputs in the energy sector.

Regarding Eq. 114 leads to the advisement that with adequate small elasticity of substitution s the allocation correcting influence of the resource tax τ_R should diminish to zero (factor shares become independent from prices if $s = 0$). A numerical parameter study confirms this result by calculating welfare losses of the pure energy tax compared to the optimal resource tax regime. Fig. 18 shows model runs with several elasticities s that are connected by a dashed line. With s going towards zero, welfare losses of pure energy tax disappear.

As shown above, a pure energy tax cannot be socially optimal if $s > 0$. Nevertheless, the real value of s is difficult to determine and always afflicted with uncertainties. But even for typical assumed values $0.2 \leq s \leq 0.8$ (e.g. $s = 0.3$ in Edenhofer et al., 2005) welfare losses are greater than one percent.

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[54] For a derivation of this formula see Arrow et al. (1961).

[55] Of course, this argument only holds in the partial equilibrium analysis. In the general equilibrium analysis the prices r and p_R can change due to secondary effects of a higher energy price p_E. But, numerical results confirm that such secondary effects turn out to be negligible.

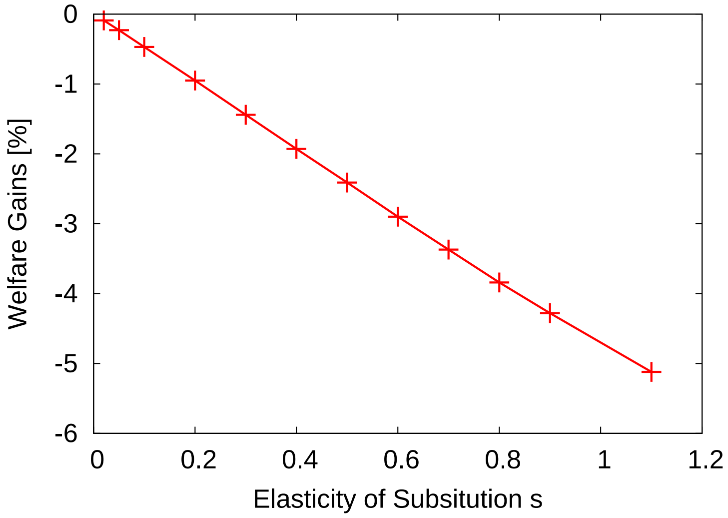

Figure 18: Welfare losses of the pure energy tax (relative to the socially optimal reduction policy) subject to sector specific elasticity of substitution.

As they can be avoided easily by the resource tax or quantity approach there is no good reason to solve the mitigation problem with a pure energy tax. Only net monitoring costs of emissions or resource extraction being higher than social welfare losses of the energy tax would justify this tax scheme (Schmutzler and Goulder, 1997). Nevertheless Eq. 114 gives a hint for another solution of the re-allocation problem in the fossil energy sector that will be examined in the following paragraph.

4.2.3 Hybrid Taxes

Energy Tax Combined with Capital-Energy Tax The energy tax is enhanced by a sector specific capital tax that only affects K_E in the fossil energy sector. Both taxes can be positive or negative while all other taxes are set to zero. Again, tax income (or subsidy expenditures) are lump-sum transfered to households.

The combination of the two taxes is in accordance with the social optimum. While the energy tax rate is higher than under the pure energy taxation, the sector specific capital tax rate is negative starting from -20 % reaching -99 % at $t = 120$. That is, capital in the fossil energy sector is almost completely subsidized at the end of the time horizon. All this leads to the same sector specific resource and energy allocation as in the socially optimal policy schemes (see Fig. 16 and 17).

Given the optimal resource tax τ_R^* of the `m_r` policy scheme where $\tau_{K_E} = 0$, one can calculate the equivalent optimal capital tax $\tau_{K_E}^*$ that enforces the same factor share of K_E/R without using a resource tax. Utilizing the identity of the factor share under both tax approaches ($\tau_R = \tau_R^*, \tau_{K_E} = 0$) and ($\tau_R = 0, \tau_{K_E} = \tau_{K_E}^*$) Eq. 114 leads to:

$$\frac{p_R(1+\tau_R^*)}{r} = \frac{p_R}{r(1+\tau_{K_E}^*)} \tag{115}$$

that can be solved to

$$\tau^*_{K_E} = \frac{1}{1+\tau^*_R} - 1. \tag{116}$$

If $\tau^*_R > 0$ (which is the case in `m_r`), $\tau^*_{K_E}$ has to be negative and for high values of τ^*_R the capital tax goes to -1 which coincides with the numerical observation. As a side effect of the optimal re-allocation, the capital subsidy cheapens fossil energy and increases therefore energy demand in the production sector. In order to reach the mitigation goal, the energy tax has to be on a level which reduces energy demand as far as it is compatible with the mitigation goal. The numerical calculated energy tax is on the level that energy purchase price $\bar{p}_E$ is the same like under the pure resource taxation.

Considerations above show the need to enforce an efficient factor allocation in each sector. By applying very specific taxes like τ_{K_E} one can solve the problem of the rather unspecifically working energy tax only affecting the allocation in the production sector. Indeed, a system-wide subsidy of capital, that is $\tau_{K_P} \equiv \tau_{K_E} \equiv \tau_{K_R}$, would be easier to implement politically and practically, but causes further distortions in all capital-dependend sectors and therefore hardly increases efficiency compared to the pure energy taxation.

Capital and Labor Tax If a specific capital tax can have a correcting effect, one may ask whether a general capital tax can achieve this. Some numerical experiments show that this is generally not the case. Another option is to use the general capital tax combined with labor tax while other taxes are set to zero.

Applying a system-wide capital and labor tax leads to significant lower consumption and higher leisure; welfare is considerably worse than in the pure energy tax scheme. Resource extraction is shifted forewards compared to other reduction schemes while total extracted amount remains the same and the mitigation goal is reached. Both taxes are positive: capital tax rate increases from 10 % up to 95 % within 120 years; labor tax rate increases from 2 % to 21 %.

The high capital tax leads to lower capital accumulation allowing more consumption in the present. By augmenting the interest rate, resource extractors shift extraction forwards as considered by Dasgupta et al. (1981) and Sinn (2007b). The labor tax has two effects: augmenting welfare by higher leisure and reducing production in the production sector to reach the mitigation target by reducing consumption. However, as shown by Fig. 17, the relative share of labor input is higher than in other reduction schemes and in the baseline scenario, because the higher capital tax dominates the labor tax. As it is the case with the pure energy tax, an income effect but not a substitution effect is achieved further down the production chain. Therefore the ratio of inputs in the energy sector is almost the same as in the BAU scenario (Fig. 16).

In regard to social welfare this is the worst possibility for climate policy as the mitigation goal is achieved mainly by a consumption reduction effect. However, the capital-labor-tax is attractive as it manipulates the two control variables of the households. Thus, the `m_k_l` scheme gives a benchmark for the capability of an environmentally aware household to reach the mitigation goal by "climate friendly" labor and consumption levels without the need of governmental interaction.

Further Taxes Other taxes have been analyzed numerically: The taxation of capital in the resource sector only (`m_kr`) achieves the mitigation goal in an efficient way. Applying such a capital tax has two effects: (1) It changes the amount of resource extraction by modified extraction costs due to the taxed interest rate and (2) it changes the time profile of extraction by a (slightly) modified discount rate in the exponent of Eq. 41. Although the interest rate $\bar{r}$ in the exponent is not influenced by the sector-specific capital tax directly, it is changed due to indirect effects in the distorted capital market.

Another possibility is the combination of energy, labor and uniform capital tax (`m_k_l_e`) which is a slightly more efficient option than the pure energy taxation or the capital-labor taxation. However, low labor tax and capital subsidy rates can hardly help to approximate the efficient factor allocations of the resource tax.

Further combinations are imaginable but discussing them would not bring any new insights as highlighted by the considered cases of resource and energy taxes and their modifications.

4.2.4 Abatement Subsidy

A capital subsidy for the fossil energy sector is applied to augment carbon efficiency while other taxes (except lump-sum transfers) are set to zero.

With numerical model runs no feasible abatement subsidy could be found which complies with the mitigation target. Using the values of the optimal sector-specific capital subsidy from the `m_e_ke` policy scheme, resource extraction is even higher than in the BAU case although carbon efficiency is higher.

The capital subsidy provokes a cheaper energy production for the fossil energy sector and hence lowers energy price (which falls under the price in the BAU scenario). Low energy prices in turn increase energy demand and thus energy production. Despite higher carbon efficiency, energy production increase accelerates resource extraction over the levels of the BAU path. This phenomenon is also called *rebound effect* because higher efficiencies provoke higher demand due to several feedback effects (Sorrell and Dimitropoulos, 2008)

Hence, an abatement subsidy alone is not appropriate to achieve the mitigation goal. But, combined with an output tax lowering energy demand rebound effects can be neutralized as the analysis of the `m_e_ke` policy scheme has shown.

4.2.5 Comparison and Conclusions

After the analysis above on the efficiency criteria with explanations for optimality and suboptimality, I discuss shortly presented policy schemes with respect to further criteria mentioned in Sec. 2.5. Now, the focus is on the distributional effects and the political practicability of several measures.

Distribution Fig. 19 shows the different distribution of profits and tax incomes under several policy instruments (including quantity policy): the energy tax increases the share of transfer incomes, and taxation of capital and labour even more. The resource sector-specific capital tax as well as capital-labor tax raises profits in the resource sector by debiting transfer incomes, so profits equal those of the BAU scenario. Although second-best policies `m_e`, `m_k_l`, and

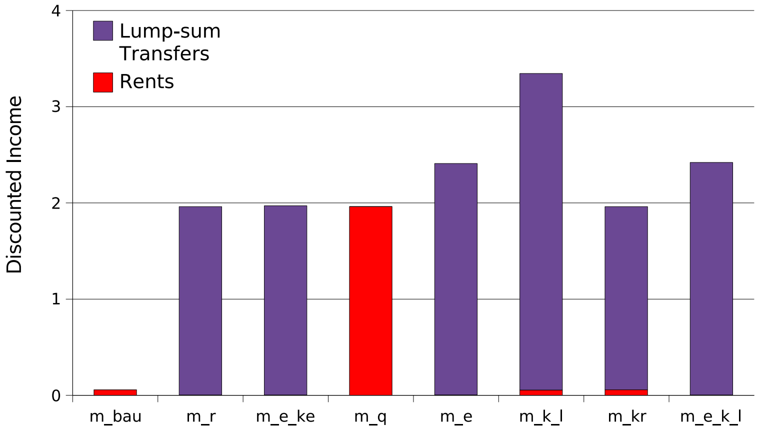

Figure 19: Distribution of rents and tax income

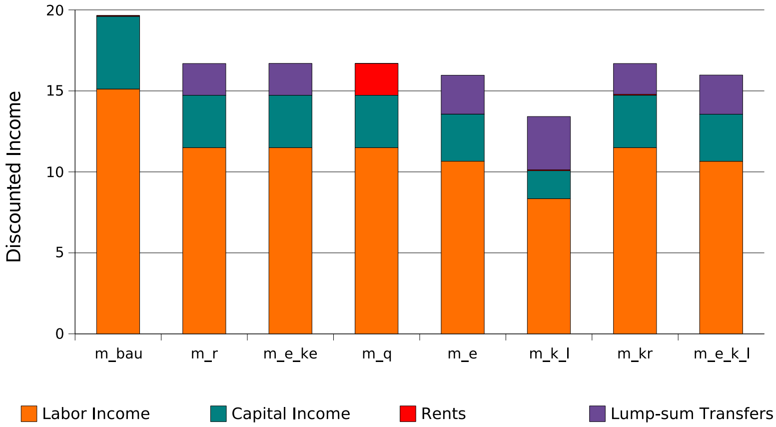

Figure 20: Distribution of functional income

`m_e_k_l` have the highest total transfer income, total income including labor and capital income is lower due to inefficient factor allocation (see Fig. 20).

Reduction of labor income is caused due to decreasing wages and labor supply whereas the former dominates the total effect (Fig. 21). Capital income decreases mainly due to lower capital stocks. All considered mitigation policies stress capital income more than labor income and second-best policies do not change this qualitative result.

Political Feasibility As introduced in Sec. 2.5 the *Gov* variable is a gross indicator for government's fiscal activity and hence for officialism. Tab. 7 depicts averaged *Gov* values of numerical runs. The degree of government intervention for first-best policies can differ although they have the same welfare and the same tax income distribution (e.g. `m_r` and `m_e_ke`). The reason lies in the capital subsidy, which increases *Gov* although it decreases total net tax-income. The resource sector-specific capital tax has the lowest *Gov* value as a small part of the potential tax-income remains as scarcity rent in the resource sector.

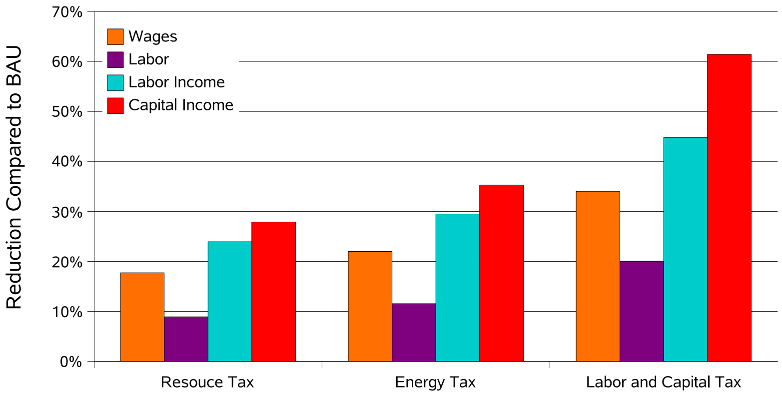

Figure 21: Reduction of wages, labor and incomes due to mitigation (compared to the business as usual scenario)

	`m_r`	`m_e_ke`	`m_e`	`m_k_l`	`m_kr`	`m_k_l_e`
Gov (mean) in %	43.1	47.0	53.7	82.7	42.5	54.2

Table 7: Comparison of state's share (mean values)

The higher *Gov* values of the second best policies coincide with the observed higher tax transfer in Fig. 20. The consideration of *Gov* values as well as the regarding of the number of used tax instruments leads to the advisement that a straightforeward policy instrument with fewer officialism should be preferred if social welfare remains optimal.

Regarding the resource-sector specific capital tax there emerges a problem of political feasibility connected with the different treatment of interest rates. Furthermore, in the context of international economies with only few countries owing fossil resources and others with an ambitious mitigation goal, the climate anxious government of one nation hardly can charge a tax on the capital market of fossil resources exporting countries. A tax or – in the case of division in resource exporting and importing countries – a tariff on resources would be indeed easier to implement.

Efficacy In the real word exist many unobservable and uncontrollable flows and branches of fossil resources up to the final consumer so that a resource tax (or tariff on imported resources) can capture more of the emissions than a tax scheme on a higher and more ramified stage of the production process can do. In contrast, there are only few power plants and monitoring electricity production does not cause significant transaction costs. Thus, an energy tax might be more successful in countries where resource flows and their taxation due to institutional framework is hardly controllable.

Generalization The analysis of optimality of policy instruments leads to general results that can be applied to similar models: The success of a certain policy instrument lies in its capability to set price signals to the market that contain the information about the limited availability of fossil resources. These signals should meet the sectoral level of the economy that creates the emissions and that can make an allocation decision, i.e. the fossil energy sector. If it knows about the politically constituted scarcity of the resources it changes the share of its factor input. The quantity approach gives the exact price signals because scarcity is anticipated by resource owners; a resource tax augments the resource price artificially to that level of the quantity case. If price signals only meet higher levels of the economy – like the good producing sector or the household sector – misallocation in lower levels as in the fossil energy sector cannot be resolved and mitigation is reached due to a higher consumption reduction although there still exist the potential for wellfare augmenting substitution effects (see Fig. 16 and 17). The extend of welfare losses under those unspecific tax schemes depends on the elasticity of substitution in the fossil energy sector; for realistic values of s losses are significant high (i.e. more than one percent) and thus even would not justify the energy tax in case of moderate monitoring costs for the resource flow. The height of tax rates depends on several model parameters, but elasticities of substitution in fossil energy and good producing sectors play a crucial role as well as the size of the effective resource stock $S_0 - \underline{S}$, because the resource dynamic is mainly driven by the demand side.[56] An environmentally aware household can achieve the climate protection goal without any taxes only by consumption and investments reductions but far away from social optimum. All mitigation policies debit capital incomes more than labor income.

Consideration of renewable energy and ETC does not affect the results of above analysis substantially. In a first approximation, these features can be expressed in higher elasticities of substitution augmenting welfare losses of second-best policies and diminishing scarcity rent in the resource sector that is taxed away.

4.3 Competition Policy

Regarding market power in the extraction sector takes into account existing real-world market structures especially in oil and gas markets. In this subsection the consequences of market power in the resource sector are analyzed with respect to climate relevant accumulated extraction amount and the time-profile of the consumption path. Again, the basemodel is used neglecting ETC and renewable energy. Furthermore, I analyze policy instruments which correct inefficiency due to market power and their interaction with mitigation instruments.

4.3.1 Market Power and Resource Conservationism

Remember the parameterization of market power in Sec. 3.2.1 by the parameters θ_1 and θ_2 which express the capability to anticipate the reaction functions of the fossil energy and the production sector, respectively. A parameter study across θ_1 and θ_2 is done to analyse the impact of different stages of market power to the extracted resource quantity in the BAU scenario without regarding a certain mitigation goal.

Fig. 22 shows the accumulated extracted resource quantity varying with θ_1 and θ_2. The more the monopolist anticipates the reaction function of energy and production firms ($\theta_1 \to 1$ and $\theta_2 \to 1$, respectively) the higher is the final

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[56] The comparison of price and quantity policy in Sec. 4.1 showed that tax income in the efficient price policy almost equals resource profits in the quantity policy. Thus, parameter studies mapped in Fig. 12 and 13 are transferable to tax incomes and tax rates.

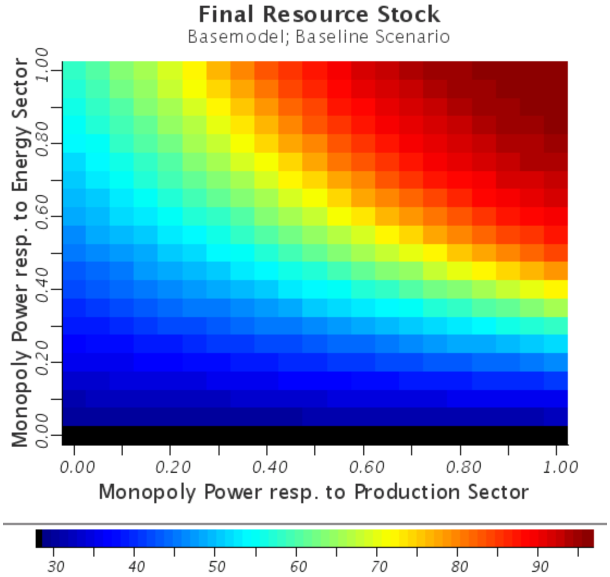

Figure 22: Extracted resource quantity with respect to the market power of the resource extraction sector (θ_1 on the x-axis and θ_2 on the y-axis)

resource stock and the lower are the emissions of GHG in the atmosphere. The isocline of the final resource stock equal to 80 corresponds with the mitigation goal of the former reduction scenario of the basemodel. All points (θ_1, θ_2) on this isocline in Fig. 22 have the same extraction, price and consumption path and the welfare on this isocline is lower than in the optimal reduction scenario with the same amount of extracted resources.

Fig. 23 compares one point of that isocline with the socially optimal reduction scenario of the competitive economy. Although final resource stock equals at the end of the time horizon, extraction and price paths differ. Stiglitz (1976) and Stiglitz and Dasgupta (1982) already showed that a monopolistic (or even Cournot oligopolistic) resource sector has a flatter extraction and price than in the perfect competitive case, which is also confirmed by the numerical results. The resource price starts on a high level and remains on a high level – in contrast to the optimal reduction path where the resource price starts on a low level and increases within time considerably above the monopoly price (see also Fig. 23). This leads to a different consumption path where consumption is not shifted foreward as in the optimal RED scenario (with a breakdown of consumption levels in future periods where resource consumption decreases to almost zero). Instead, consumption and extraction stay on an almost constant level which is (in the long run) higher than in the competitive economy.[57]

In regard to climate protection, market power results in a more climate-friendly resource extraction that could – given the right value of market power (i.e. the right number of resource extracting firms) – achieve the mitigation goal without any governmental interventions. But this way is not socially optimal as the time path of extraction does not correspond with that of the socially optimal reduction scenario.

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[57] This result is robust respect to other values of θ_1, θ_2 as long as the resource stock is not exhausted completely.

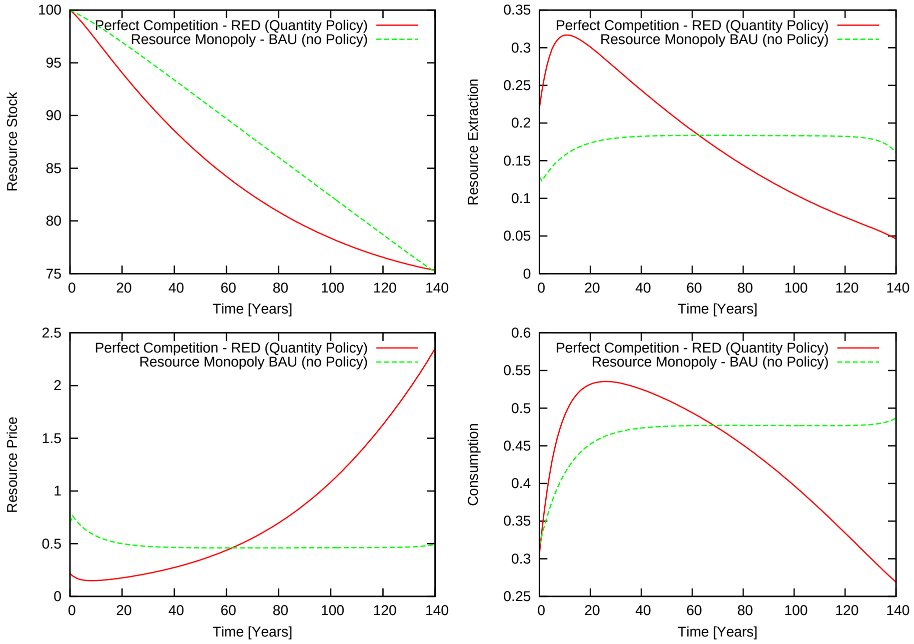

Figure 23: Comparison of the perfect competition reduction scenario and the resource monopoly baseline scenario ($\theta_1 = 0.7, \theta_2 = 0.5$) with the same amount of extracted resources.

4.3.2 Taxes to Correct Market Power

Next to the problem of mitigation, several taxes are studied to correct the distortion that is caused by low resource extraction in the BAU scenario:

- ad-valorem tax τ_R on the resource price,
- unit tax ς_R on the resource price and
- ad-valorem tax τ_E on the energy price

These instruments were compared in numerical runs to each other and to the *laissez faire* monopoly as well as to the perfect competition model. Fig. 24 shows the different distributional effects of explained instruments for the BAU scenario without mitigation goal.

Resource related taxes (that turn out to be subsidies) can solve the problem and achieve the same extraction and consumption paths as in the perfect competitive model. The energy tax does not achieve the optimal social welfare but marks an improvement compared to the *laissez faire* monopoly situation. Although both resource taxes reach the social optimum they differ with respect to the income distribution in the household sector: While the ad-valorem resource tax forms a huge subsidy for the resource sector that has to be financed by lump-sum transfered taxes from the households of the same amount, the unit tax leads to the same extraction path with considerably fewer redistribution.

To explain these differences between ad-valorem and unit resource tax, I derive the market failure correcting taxes analytically. Considering the first-

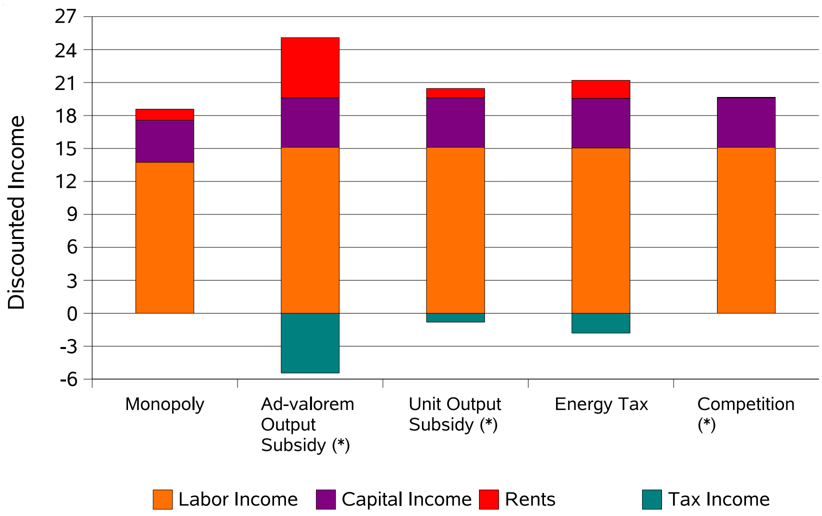

Figure 24: Income distribution under market power and different policies in the baseline scenario. $\theta_1 = 0.5, \theta_2 = 0.2$. (*) denotes social optimality.

order conditions of the monopoly (64) and (65) the **unit tax** has to be

$$\varsigma_R = -\frac{\partial p_R}{\partial R} R \tag{117}$$

in order to achieve the same first-order conditions as in the competition case (48 – 49) (see also Daubanes, 2007). Note, that because of $E''_R < 0$ the tax is a subsidy for the monopolist to augment production to the socially optimal level. Although the equation describing the profits (66) remains the same, profits change due to taxation as λ_R, κ, K_R also are modified by ς_R.

In the same way, one can derive the market failure correcting ad-valorem tax: Let $\tilde{\tau}_R$ be the tax on the supply side, that is, the selling price of the resource is $p_R(1 - \tilde{\tau}_R)$. Again, equating first-order conditions in the competition case with the monopoly case with ad-valorem tax $\tilde{\tau}_R$, one obtains for the tax rate:

$$1 - \tilde{\tau}_R = \frac{p_R}{p_R + \frac{\partial p_R}{\partial R} R} \tag{118}$$

Transforming this to the **ad-valorem tax** so far applied on the demand side yields:[58]

$$\tau_R = \frac{\partial p_R}{\partial R} \frac{R}{p_R} = \frac{1}{\eta_R}, \tag{119}$$

where η_R is the elasticity of demand. While the derived value for $\tilde{\tau}_R$ equals the one calculated by Im (2002, Eq. 32), the unit tax ς_R differs (but all three tax

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[58] If p is the selling price and $p(1 + \tau)$ the purchase price, than the equivalent taxation on the supply side with $\tilde{p}$ as purchase prise and $\tilde{p}(1 - \tilde{\tau})$ as selling price is:

$$\tilde{\tau} = 1 - \frac{1}{1 + \tau}$$

equations are confirmed by numerical model runs). On the one hand, Im uses the simplified model of resource extraction with constant (capital independent) extraction costs. On the other hand, there generally is more than one efficient tax possible (Daubanes, 2007).

Understanding the different outcome respect to profits is not obvious – and literature about resource-monopolistic taxation does not consider this question (eg. Im, 2002; Daubanes, 2007). Nevertheless, it is easy to see, that unit and ad-valorem resource tax unequal to zero imply different profits in the resource tax, as otherwise

$$p_R(1-\tilde{\tau}_R)R - rK_R \equiv (p_R + \varsigma_R)R - rK_R, \tag{120}$$

and thus the ad-valorem tax τ_R had to equal the ad-valorem tax $\tilde{\tau}_R$:

$$\tilde{\tau}_R \overset{(120)}{=} -\varsigma_R/p_R \overset{(117)}{=} \frac{\partial p_R}{\partial R}\frac{R}{p_R} \overset{(119)}{=} \tau_R. \tag{121}$$

The formula for the optimal profits under ad-valorem tax $\tilde{\tau}_R$ reads:[59]

$$\Pi_R = \left[\frac{p_r^2 r}{\left(p_R + \frac{\partial p_R}{\partial R}R\right)(p_R - \lambda_R)} - r\right] K_R \tag{122}$$

On the first view, it is not clear whether profits of the ad-valorem tax in Eq. 122 augment profits in the unit tax case (Eq. 66) with same values for r, p_R, λ_R, R. Therefore, the reason for different profits in the resource sector remains nebulous.

So far, one can extend the insight of Daubanes (2007) that there are infinite many efficient tax schemes. In fact, there are also infinite (but not necessarily arbitrary) possibilities to distribute profits and tax-incomes as one can combine ad-valorem and unit tax in infinite many ways. Understanding distributional effects of such taxes enforces further investigations.

4.3.3 Mitigation under Market Power

Previous analysis considered monopoly power in the baseline scenario without mitigation. In this section both market failures – the mitigation goal and the monopoly power – are combined in order to evaluate the interplay of both effects. In this regard, a main question is, whether one single tax instrument can deal with both market failures and how possible instruments may differ from each other.

A first class of model runs considers the quantity restriction policy to achieve the mitigation goal extended by an output subsidy to correct monopoly inefficiency. These subsidies are ad-valorem and unit resource taxes τ_R and ς_R, respectively. A second class of model runs passes the quantity restriction and achieves mitigation by a modified resource or energy tax (former price policy instruments). Within this class, the specific tax has to correct two market failures.

Resource taxes combined with the quantity restriction achieve the socially optimal solution and show the similar distributional effects as in the BAU sce-

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[59] As derivation of this formula is straightforeward like the former equations describing the profit, I pass detailed deducing.

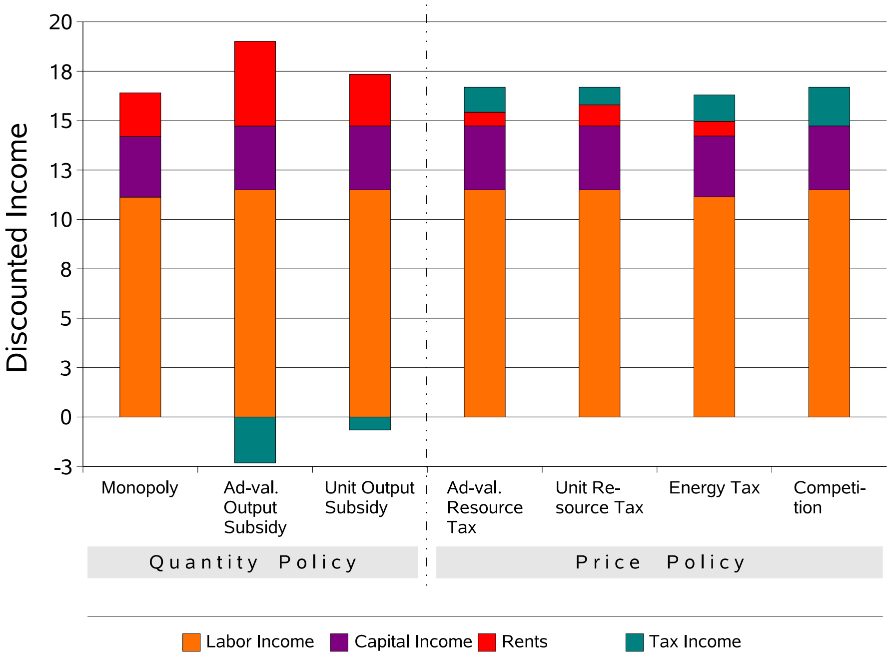

Figure 25: Income distribution under market power and different policies in the reduction scenario. $\theta_1 = 0.5, \theta_2 = 0.2$

nario considered in the previous part (compare 2nd and 3rd bars of Fig. 24 and 25). The analytically calculated optimal tax rates (117) and (119) remain valid. But if no quantity restriction holds, resource tax also aims to achieve the mitigation goal and thus tax rates have to change to reflect the mitigation goal. Again, the social optimum can be achieved with both unit and ad-valorem resource tax, but income distribution has changed qualitatively. Now, the ad-valorem tax collects higher tax incomes at the expense of resource rents and the unit tax benefits resource owners (see Fig. 25). In both cases the government cannot absorb the whole scarcity rent. The impact of an energy tax is also analyzed confirming the former result of inefficiency. In the mitigation scenario, energy tax (reflecting the mitigation goal as well as monopoly power) has even a slightly worse welfare than the pure monopoly outcome in the quantity reduction scenario. The dynamic development of unit taxes is shown in Fig. 26. Within the pure price instrument class one can see the double-function of the resource tax by the change from a subsidy (after six years) to a positive tax.

The capability to correct multiple market failures by one single instrument depends on the structure of market failure (Bennear and Stavins, 2007). As both market failures – unanticipated mitigation goal and market power – can be corrected by a change in the resource price, one single tax suffices to solve the problem (Misiolek, 1980). Thus, because of the high monopoly price, mitigating resource tax is lower than in the competitive case with the same resulting net resource price.

If the government neglects the market power when it calculates the optimal mitigating resource tax, the mitigation goal will be overfulfilled (Fig. 27). However, the difference between resource extraction becomes smaller with increasing

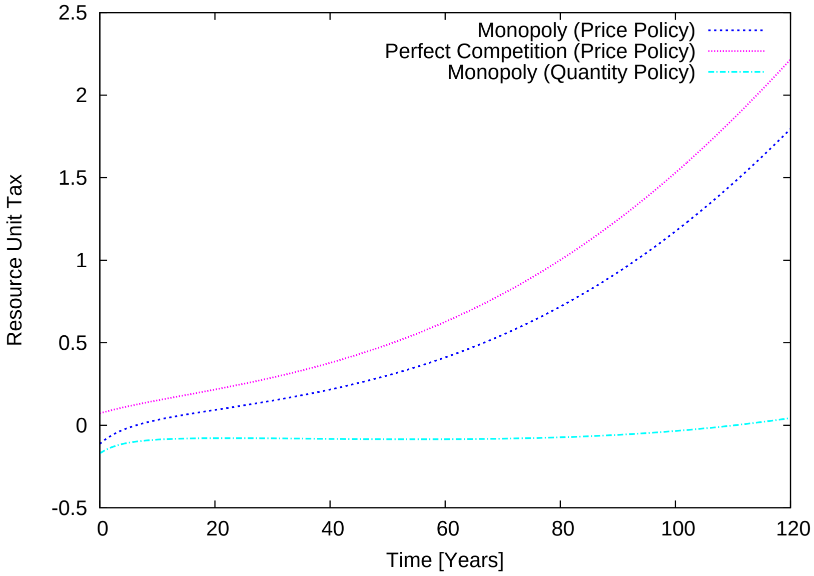

Figure 26: Resource unit tax under monopoly in the reduction scenario. $\theta_1 = 0.5, \theta_2 = 0.2)$

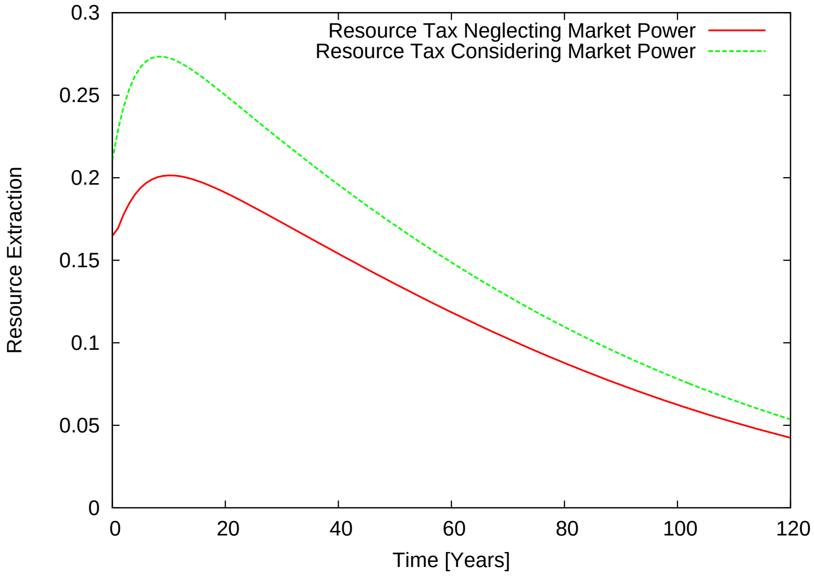

Figure 27: Resource extraction under resource tax which anticipates monopolistic market structures and neglects them although attendant, i.e. government applies resource tax from the perfect competitive economy $(\theta_1 = 0.5, \theta_2 = 0.2)$

time. Thus, in the long run the meaning of the monopolistic market situation diminishes as the resource tax dominates due to permanent increasing taxes.

4.3.4 Conclusions

It was shown that certain levels of monopoly power without further taxes can lead to the same amount of extracted resources as in the competitive reduction scenario. Thus, competition policy which achieves that level of market power is able to solve the mitigation constraint – but in a social suboptimal way, because time paths of extraction and consumption are suboptimal (Fig. 23). Another problem of such anti-trust policy raises if the end of the planning horizon is reached, where the monopolistic resource extraction is still on a high level while in the competitive reduction scenario extraction is almost disrupted. As stated in Sec. 3.3.6, price policy can be continued after the time horizon by continuing to increase tax rates. In contrast, development of resource extraction and resource flows of the monopolistic economy shown in Fig. 23 will lead to the excess of the mitigation goal after reaching the time horizon.

Furthermore market failure correcting taxes were derived and analyzed. Although resource specific ad-valorem and unit tax enforce the socially optimal extraction path, both instruments differ substantially in their distributional effects (Fig. 24). This result remains valid under an additional mitigation constraint, although the order of unit and ad-valorem tax respect to tax volume might change (Fig. 25). Both market imperfections – monopoly extraction and mitigation goal – can be corrected with one single instrument, namely, an appropriate resource tax. Regarding optimal mitigation tax rates, monopolistic or oligopolistic market structure leads to lower optimal resource taxes compared to the competitive market case. Neglecting monopolistic market structures in optimal tax calculating drops resource extraction significantly but in the long run ($t > 100$) extraction rates approximate.

4.4 Technology Policy

In this subsection I investigate the impacts of several technology policy instruments, mainly subsidies for investments in spillover capital stocks, public R&D expenditures and second-best tax instruments. In a first step, the analysis is concentrated on the model without a mitigation goal in order to isolate impacts of several policy instruments. The focus lies on welfare (due to endogenous economic growth), resource extraction impacts (due to possible rebound effects) and changes of the income distribution.

After that I analyze the role of technological change in the climate protection world with respect to mitigation instruments, distributional effects and timing of mitigation.

4.4.1 Learning-by-Doing Spillovers

I start the analysis with the basemodel extended by the renewable energy sector and the Learning-by-Doing effect. Public R&D efforts are set to zero and there is no mitigation goal to be considered. Several model runs were performed:

- `no tax` – without any taxation,
- `m_e2` – renewable energy tax only,

	`no tax`	`m_e2`	`m_k`	`m_ky`	`m_ky_e2`
welfare	6.68	6.68	7.79	8.21	8.21
consumption	9.63	9.63	20.62	21.67	21.67
output	9.88	9.88	30.91	33.48	33.49
labor	0.11	0.11	7.14	7.21	7.21
total capital	8.03	8.03	72.40	81.84	81.85
energy	6.67	6.67	47.11	22.78	22.80
resources	5.36	5.33	42.05	20.80	20.80
rents (resource sector)	19.51	19.43	183.55	84.99	84.75

Table 8: Comparison of discounted key variables under LbD and their relative changes compared to the basemodel (in %) with respect to different policy regimes (BAU scenario)

- `m_k` – global capital tax,
- `m_ky` – production sector-specific capital tax,
- `m_ky_e2` – production sector-specific capital tax and renewable energy tax.

The results of numerical model runs are listed in Tab. 8 which can be concluded as follows: (1) LbD augments welfare even if no taxes are present;[60] (2) The tax (respective subsidy) in the renewable energy sector has almost no influence on welfare, energy production and resource extraction. This is the case for one single instrument as well as for a mix of instruments. (3) The most successful instrument is a sector-specific capital subsidy for the production sector. It reaches the social optimum if it is combined with a renewable energy subsidy. (4) A global capital tax (i.e. subsidy) can also augment welfare but fails the social optimum. (5) All model runs result in an increased energy consumption and resource extraction, although (6) resource and energy efficiency increase except for the global capital tax (see Tab. 9). (7) A similar observation can be made on the labor supply that increases under all policy instruments while labor efficiency also raises. (8) Rents in the resource sector increase considerably, at most under the global capital tax policy. (9) Concerning the functional income distribution, the LbD effect augments both labor and capital income under the absence of taxes by around 10 percent while under more optimal policy instruments capital income increases more than twice as labor income (see Fig. 28).

The differing increase in capital and labor income (Fig. 28) is mainly based on a volume effect. While wages increase by around 40 %, the net interest rate (on the household side) raises only by around 8 %. But, changes in labor supply and capital stocks dominate price differences as capital stocks raise by more than 70 %, while labor supply only raises by about 7 % (see Tab. 8 and 9). Because capital in the production sector causes positive externalities, it is an

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[60] The comparison of Tab. 8 refers to *two* structural model changes at one time: the LbD effect and the renewable energy sector. However, the meaning of renewable energy in the BAU scenario is negligible and relative changes of the LbD effect would remain almost the same if there is no renewable energy available.

	without LbD	with LbD				
	`no tax`	`no tax`	`m_e2`	`m_k`	`m_ky`	`m_ky_e2`
energy efficiency (Y/E)	1.32	1.36	1.36	1.18	1.45	1.45
resource efficiency (E/R)	0.94	0.94	0.94	0.98	0.94	0.94
labor efficiency (Y/L)	1.32	1.48	1.48	1.72	1.77	1.77
wages	1.05	1.17	1.17	1.45	1.47	1.47
net interest rate (%)	4.72	4.81	4.81	5.09	5.13	5.13
energy price	0.10	0.10	0.10	0.07	0.12	0.12
resource price	0.06	0.06	0.06	0.05	0.07	0.07

Table 9: Efficiencies and prices (average values)

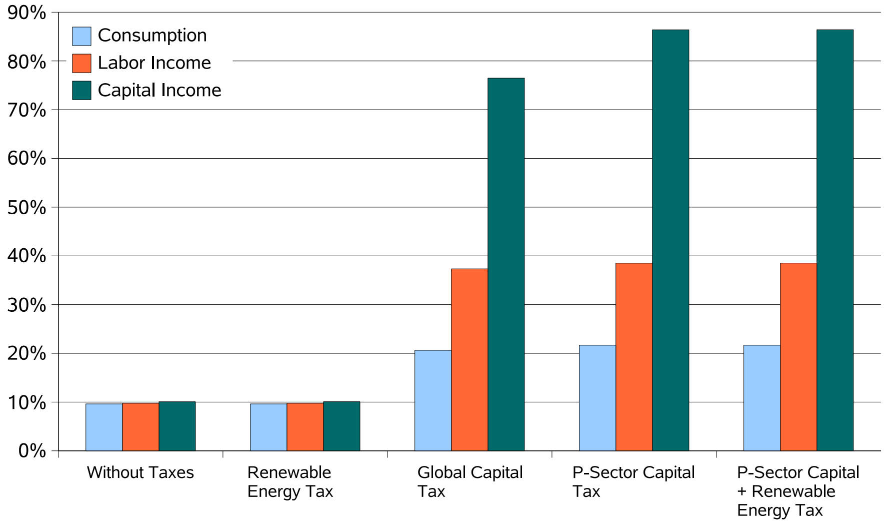

Figure 28: Impact of LbD: Change of incomes under several policy instruments compared to the basemodel without LbD

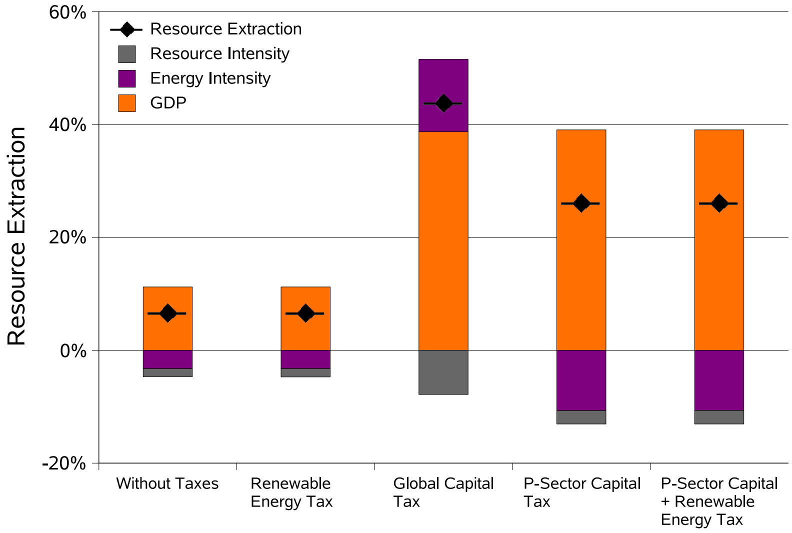

Figure 29: Decomposition analysis of resource extraction under LbD (average values)

important factor for the dynamic of the economic system and mainly responsible for economic growth.

In order to analyze the higher resource extraction despite increasing energy efficiency due to LbD and optimal tax policy a decomposition analysis is performed that decomposes the changes of resource extraction into the main driving forces: change in output production, change in energy intensity and change in resource intensity (for technical details see Appendix D). Fig. 29 shows that in all policy cases with increased energy efficiency resource extraction is dominated by higher output production and energy consumption. This outcome – also referred as rebound effect – depends primarily in the wide availability of fossil resources. As long as resources are cheap there is no incentive for saving or substitution. Another reason for the rebound effect lies in the unspecific impact of the capital spillover: It augments labor as well as energy efficiency and thus stimulates overall production. The higher energy intensity under the global capital tax causes an even higher resource extraction than under other policy instruments. The unspecific capital subsidy leads to cheaper resource and energy prices (as capital is also cheaper for resource extracting and fossil energy firms; see Tab. 9) which augments resource and energy consumption and lowers substitution of resources and energy.

Optimal taxes internalizing the spillover effect can also be calculated analytically. The learning-by-doing effect described in Sec. 3.2.3 is modeled as a positive sector-wide externality of investment that is not considered by good producing and renewable energy producing firms in their profit maximizing deliberations. Therefore these two sectors lack for a chronical underinvestment in physical capital that bases on the difference between sectoral and individual rates of return on investment. This discrepancy can be eliminated by subsidizing investments through a negative tax on the interest rate. But, changing the global interest rate for households r by a tax τ_K to $\bar{r} = (1 - \tau_K)r$ causes distortions in the resource extraction and the fossil energy sector where an investment subsidy raises production (and resource extraction) to a socially suboptimal level. One possibility is to countersteer the production boost by the sector-specific capital taxes, τ_{K_E} and τ_{K_R}. But the easier and straightforeward solution would be to introduce a sector-specific capital tax that only effects spillover capital stocks, i.e. K_Y and $K_{E_{ren}}$.

Remember the formulation of technological progress where ETC augments factor productivity of energy and labor by a higher value of A_E and A_L, respectively:

$$Y = Y(K_Y, A_L L, A_E E) \tag{123}$$

As mentioned in Sec. 3.2.3, an individual firm i on the micro-level neglects the spillover effect of its individual capital stock $K_{Y,i}$ on the aggregated capital stock $K_Y = \sum_i K_{Y,i}$, that is, the derivatives $\frac{\partial A_X}{\partial K_Y}$ are zero. As a direct consequence of this assumption the private rate of return to capital is:

$$r_{priv} = \frac{\partial Y}{\partial K_Y} \tag{124}$$

The social rate of return is higher because A_E and A_L depend on the sectoral capital stock K_Y. Therefore the total derivative of Y with respect to K_Y is:

$$r_{soc} = \frac{dY}{dK_Y} = \underbrace{\frac{\partial Y}{\partial K_Y}}_{\text{private return}} + \underbrace{\frac{\partial Y}{\partial (A_L L)} \frac{\partial (A_L L)}{\partial K_Y}}_{\text{labor augmenting SO}} + \underbrace{\frac{\partial Y}{\partial (A_E E)} \frac{\partial (A_E E)}{\partial K_Y}}_{\text{energy augmenting SO}} \tag{125}$$

To internalize the external effect of capital spillover a sector-specific capital subsidy has to bring together private and social rate of return. The specific unit subsidy t_{K_Y} is the difference between $r_{priv} - r_{soc}$, that is:

$$t_{K_Y} = -\left(w A_L^{-1} L \xi_L \varsigma_L K_Y^{\varsigma_L - 1} + p_E A_E^{-1} E \xi_E \varsigma_E K_Y^{\varsigma_E - 1} \right) \tag{126}$$

Transforming the specific subsidy t_{K_Y} to an ad-valorem tax τ_{K_Y} yields:

$$\tau_{K_Y} = \frac{t_{K_Y} - r}{r} + 1 \tag{127}$$

An analog consideration yields for the renewable energy sector:

$$t_{E_2} = -p_E A_{E_2}^{-1} E_{ren} \xi_{E_2} \varsigma_{E_2} K_{E_2}^{\varsigma_{E_2} - 1} \tag{128}$$

$$\tau_{E_2} = \frac{t_{E_2}}{p_E \frac{\partial E_{ren}}{\partial K_{E_2}}} \tag{129}$$

Note, that both instruments are negative taxes, i.e. subsidies for the specific capital stocks. Those analytically derived subsidies equal the optimal tax of the numerical calculation.

As the meaning of renewable energy is very limited due to cheap resources and expensive renewables that remain only a niche product (around 1 percent of total energy), underinvestment in renewable energy does not play a significant role. Thus, differences between `m_ky` and `m_ky_e2` policy are almost vanishing.

	without	R&D expenditures			
	R&D	ren. energy	energy eff.	labor eff.	combined
energy efficiency	1.32	1.31	1.46	1.56	1.74
resource efficiency	0.94	0.96	0.94	0.97	0.99
labor efficiency	1.32	1.32	1.33	3.30	3.35
wages	1.05	1.05	1.06	2.50	2.60
interest rate (%)	4.72	4.72	4.74	5.92	5.97
energy price	0.10	0.10	0.10	0.15	0.15
resource price	0.06	0.06	0.06	0.10	0.09

Table 10: Efficiencies and prices (average values)

Considerations above lead to the following summary of the results and their evaluation: Even without any policy instruments there is a raise of welfare, but specific policy instruments can augment welfare to the socially optimal level: a sector-specific capital subsidy and a (not very important) renewable energy subsidy. The model framework is capable to calculate optimal taxes that equal analytical considerations. The second-best instrument, a global capital subsidy, augments welfare but causes further distortions in other capital intensive sectors. Generally, rebound effects dominate energy efficiency increases. Under the second-best global capital taxation high rebound effects cause considerable impacts on resource extraction running contrary to climate protection efforts.

Capital incomes always raise stronger than labor incomes which can be explained by the economic importance of high capital stocks due to capital spillover effects. This implies the idea that economic growth might come along with diverging capital and labor incomes – a very actual and sensitive political problematic.

Without the possibility of sector-specific R&D expenditures and without the political pressure of emission reduction, renewable energy is a niche energy form with about 1 % of total energy supply.

The insignificance of renewable energy and the emission augmenting rebound effects motivates the modeling of more selective instruments inducing technological change. Therefore, the next subsection considers several public R&D expenditures to augment specific efficiencies.

4.4.2 Public R&D Expenditures

In the following, several R&D expenditures are analyzed regarding their impact on emissions, consumption and functional income distribution. The basemodel without R&D and without renewable energy is compared with the extended model with renewable energy and specific R&D expenditures in $R_L, R_E, R_{E_{ren}}$ – i.e. labor efficiency, energy efficiency and renewable energy efficiency – and their combinations (for technical details of R&D modeling see Sec. 3.2.3). The Learning-by-Doing effect is neglected as well as mitigation policy targets, in order to concentrate on the nature of R&D induced economic growth; combinations of both growth concepts and mitigation policies are presented in the next two subsections.

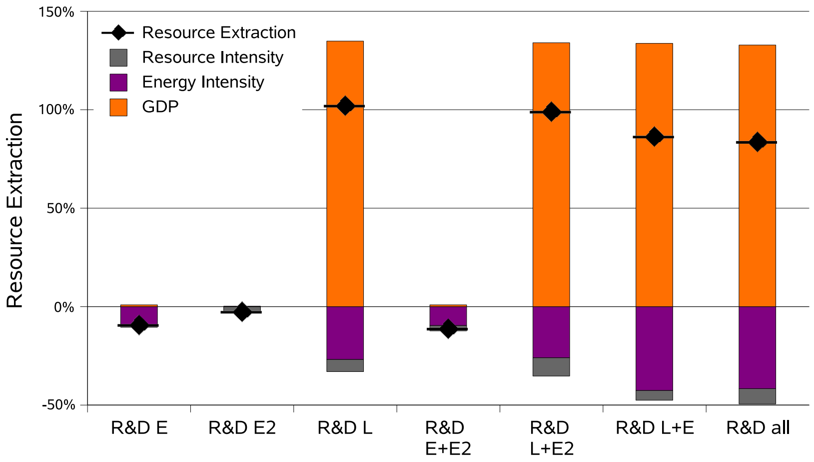

Figure 30: Decomposition analysis of resource extraction under R&D (average values)

A selection of important numerical results are listed in Tab. 10. The impacts of specific R&D instruments can be described as follows:

Labor R&D (R_L) increases wages and labor efficiency dramatically (by almost the same factor, i.e. around 150 %). While labor supply increases hardly, resource extraction (see Fig. 30) and energy consumption raise considerably, although resource and energy prices also increase by around 50 % and 40 %, respectively. High resource prices and extraction cause immense rents in the resource sector by a multiple higher than in the basemodel. Capital stocks augment by around 50 % (discounted value) and interest rates by around 25 %. Overall consumption is increased by more than 60 % (discounted value).

Energy R&D (R_E) has only little impacts on prices. Nevertheless, it cheapens energy and resource prices by 1-2 %. Resource extraction falls by 5 % compared to the base model, and thus rents in the resource sector also fall slightly. Energy efficiency is higher than in the basemodel but lower than under the pure labor R&D.

Renewable Energy R&D ($R_{E_{ren}}$) has similar impacts as energy R&D, but in even smaller dimensions. In contrast, it augments carbon efficiency but it cannot reach efficiency levels of the labor R&D.

The most important R&D instrument concerns the increase of labor productivity, while energy efficiency and renewable energy R&D expenditures have only little impacts on the economic system. Combining the particular R&D instruments leads to a domination of the labor R&D effect with only little influences of the two other efficiency raising processes (at least in the BAU scenario with plenty availability of fossil resources). Again, renewable energy remains a relative unimportant niche product.

The dominance of labor R&D depends on the parameterization of ETC and coincides with common assumptions that economic growth depends mainly

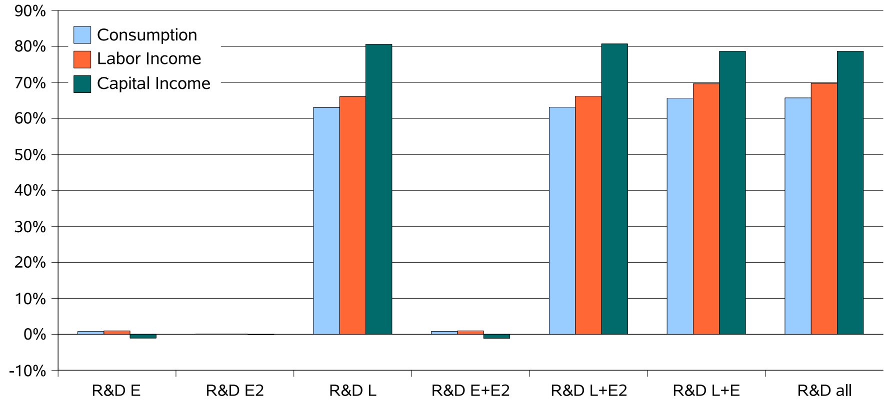

Figure 31: Change of functional income under R&D (compared to the basemodel without R&D)

on augmented labor productivity (because labor is the limiting factor in the economic system with enough fossil resources). This also explains the high increase in wages although labor supply remains almost constant.

Labor and capital incomes diverge not as strong as in the pure LbD case because growth is not coupled on high physical capital stocks, but on R&D expenditures (see Fig. 31). Energy and renewable energy R&D have almost no impact on consumption and income increase.

Although R&D expenditures in energy efficiency and backstop energy influence in a very specific way energy and carbon efficiency, respectively, labor R&D is superior to both instruments with respect to these two efficiencies. The decomposition of resource extraction (Fig. 30) shows that even the single labor R&D instrument stimulates carbon and energy efficiency increase that compensate emission augmenting by GDP growth in a stronger way than the other two R&D instruments. The reason lies in a higher (relative) capital share in fossil energy and production sector that causes conventional efficiency increases that exceed those of specific R&D efforts. The latter can not stimulate economic growth and therfore capital stocks K_E and K_Y which substitute resources and energy remain on a low level.

Above consideration lead to the following conclusion: Labor R&D is the driving force of economic growth *and* overall efficiency increase while energy and renewable energy R&D have only little impacts on economic growth and efficiency changes.

4.4.3 Combining LbD and R&D

After analyzing learning-by-doing effects and research and development expenditures separately, I want to study briefly the combination of both economic growth describing processes under the absence of mitigation policy.

Fig. 32 shows the consumption path of the basemodel without endogenous technological change and its extensions by learning-by-doing and R&D. Adding both consumption growth changes of the sole LbD and the sole R&D effect (curve `sum(LbD, R&D)`) yields to a lower consumption than the model with both effects integrated jointly (curve `LbD and R&D`). This synergy effect is also

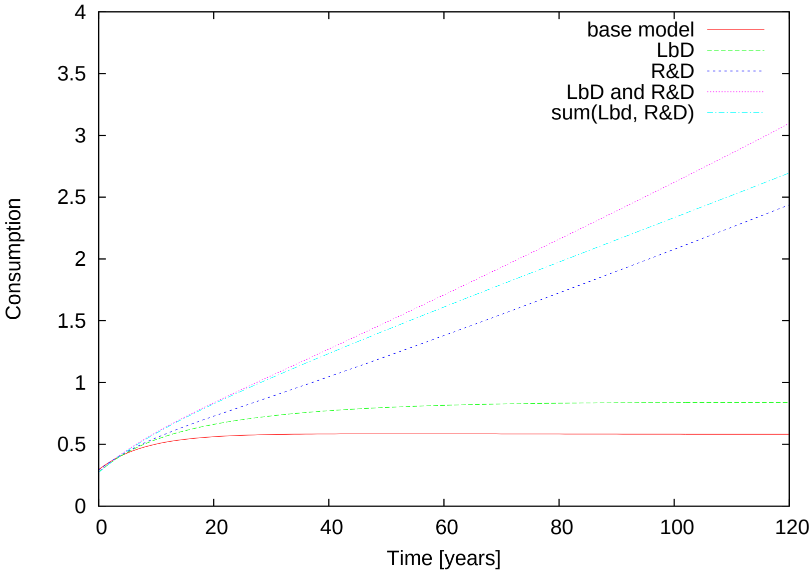

Figure 32: Comparison of consumption under LbD and R&D

confirmed by Tab. 11 which shows the change of important key variables and efficiencies. All efficiencies raise more than the sum of sole LbD and sole R&D effects, and thus labor, energy and resource consumption increases less than the sum of the pure LbD and R&D cases.

With respect to income distribution the divergence of higher raising capital income and lower raising labor in come is fortified due to the importance of high captial stocks for economic growth stimulating spillover effects. Rents in resource sector exceed rents in the R&D case because resource prices are slightly higher and resource extraction is considerably higher. Thus, rents of the resource sector form almost 1 % of total consumption volume.

Renewable energy remains a niche product in the beginning but its share on total energy increases up to 10 % after 100 years.

Thus, the combination of both effects describing endogenous technological change creates new synergy effects that exceed the sum of the sole effects because both growth processes can stimulate each other.

	LbD	R&D	LbD and R&D
welfare	8.21	29.49	36.01
consumption	21.67	65.70	95.66
output	33.49	72.52	114.23
labor	7.21	1.82	6.61
energy	22.80	42.43	63.77
resources	20.80	37.74	55.76
labor income	38.52	69.72	118.16
capital income	86.40	78.67	177.06
rents (resource sector)	84.75	300.77	455.26
energy efficiency	9.91	32.16	44.76
resource efficiency	2.18	5.40	8.60
labor efficiency	34.00	153.41	211.18

Table 11: Change of key variables (discounted values) and efficiencies (average values) compared to the basemodel (in %)

4.4.4 Mitigation Policies under Technological Change

This subsection follows three leading questions concerning endogenous technological change and mitigation policy: (1) How do technology instruments of the BAU scenario (Sec. 4.4.3) change if additionally mitigation is considered? (2) How does the consideration of ETC change the mitigation policy as developed in the basemodel (Sec. 4.1 and 4.2)? In particular, what determines the timing of mitigation and the resource tax rates? And (3) are there new distributional effects of mitigation under ETC and do the differences between price and quantity instruments remain?

Impact of Mitigation on Technology Policies If the government has to consider an additional mitigation goal, both quantity restriction and resource taxation achieve the socially optimal outcome. However, optimal levels of ETC instruments like R&D expenditures and LbD subsidies change and hence are not independent from the mitigation goal. First, absolute R&D expenditures in labor productivity decrease by around 10 % while such expenditures relative to total output remain almost unchanged. In contrast, R&D expenditures to increase energy efficiency and renewable energy productivity raise enormously which reflects the mitigation goal. Although relative change in renewable R&D is enormous, absolute volume of such expenditures is very small with respect to labor R&D. LbD subsidies change similarely: subsidies which are connected to production output augmenting spillovers are reduced, while subsidies in the renewable sectors increase. However, total LbD subsidies fall about 15 % (see Tab. 12 and Fig. 33). As LbD spillovers are coupled only on capital stock size, subsidies modifications result by a change in respective capital stocks.

Labor R&D	Energy R&D	Renewable energy R&D	LbD subsidies
−10.5	54.1	2163.5	−15.2

Table 12: Relative change in % of transfer volumes from BAU to RED

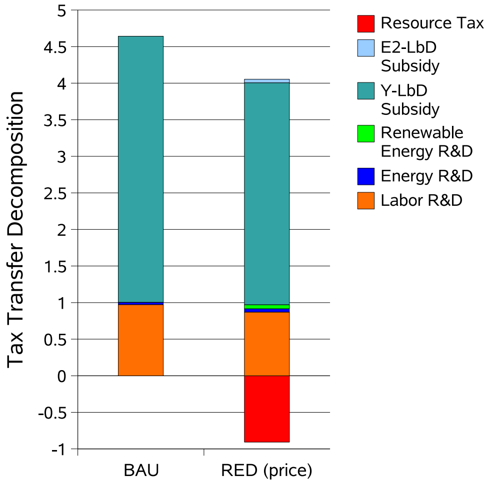

Figure 33: Comparison of transfer volumes of BAU and RED

Impact of Technologies on Mitigation Policy To study the impacts of renewable energy and ETC for mitigation policies, the following model runs are analyzed and compared:

- Basemodel (standard parameters)
- Basemodel (high elasticity of resource substitution, i.e. $s = 2.0$)
- Basemodel (high elasticity of energy substitution, i.e. $s_1 = 2.0$)
- ETC model without renewable energy
- ETC model with renewable energy

Fig. 35 shows the impact of such technological options on the optimal resource tax. As already the parameter study of elasticities (Fig. 13) showed, resource tax rates fall with a better substitutablilty of fossil resources and energy. In contrast, if ETC augments overall as well as energy productivity, tax rates increase considerably if no renewable energies are available. Thus, although energy and carbon efficiency increase, demand for resources also grows due to rebound effects (as already examined in Sec. 4.4.1 and 4.4.2) and has to be dropped by high resource taxes. This changes substantially if renewable energy is available. The latter becomes already competitive at small scales with sectoral ETC and increasing resource prices (due to the Hotelling rule) in the BAU case. With additional moderate resource taxes and higher R&D expenditures, renewable energy replaces fossil energy completely in the RED scenario.

Furthermore technological options have an important impact on the time-path of resource extraction and hence on mitigation. Fig. 35 shows that higher

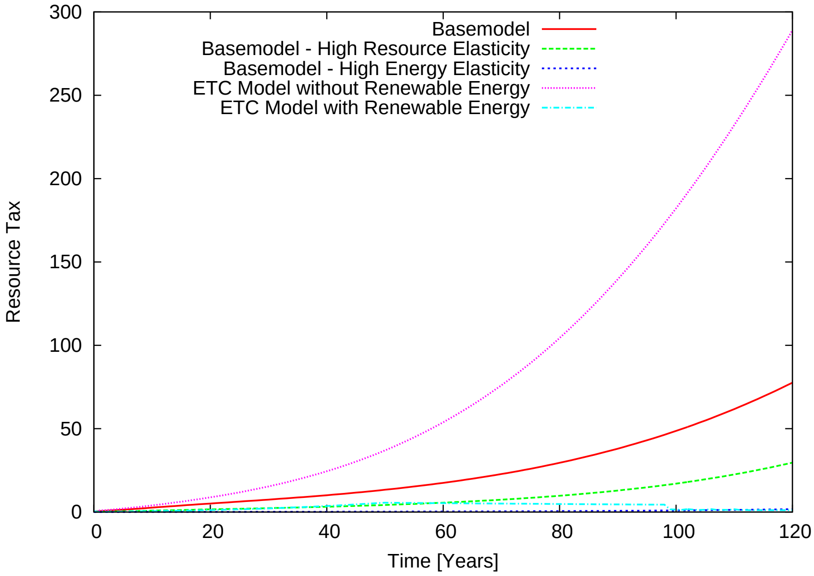

Figure 34: Resource tax under several technology and policy options

energy substitutability leads to a flatter extraction path while high resource substitutability and renewable energy shift extraction foreward. In contrast, the ETC model without renewable energy does not influence the timing considerably. Increased energy and resource efficiency are mainly used for output augmenting under the mitigation constraint but not for a shifting of mitigation across time.

Abatement is usually shifted to the future because a positive pure time preference rate discounts future costs. The dynamic of the finite resource stock even amplifies this effect because – according to Hotelling's rule – the price of not extracted resources has to increase over time. This augments opportunity costs of early abatement and thus impides a more uniform extraction path with considerable resource depletion in long-term future. As renewable energy provides a backstop price for fossil resources, all the resources which can be depleted without exceeding the mitigation goal, have to be extracted before the backstop price is reached. Thus, renewable energy drives on resource dynamics and leads to early extraction.

Above results confirm the qualitative similar behavior of an additional renewable energy option and a higher elasticity of resource extraction. This can justify the technical approximation of an renewable energy sector by a higher substitutability of resources by capital.

Furthermore Fig. 34 and 35 highlight the high sensitivity of an optimal resource tax respect to elasticities and availability of renewable energy. As estimation of the "real" parameters, learning curves and technological development in the renewable energy sector is afflicted with high uncertainties, the efficacy of the price instrument in reality is very dubious.

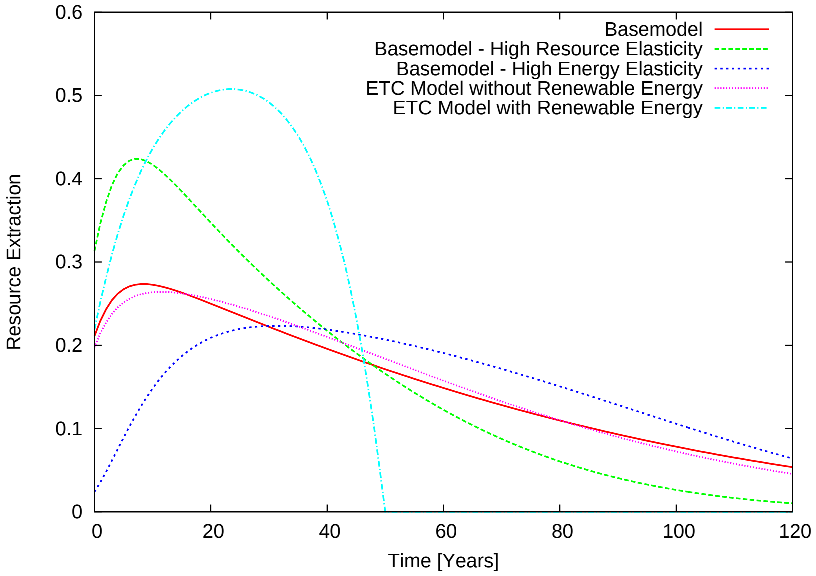

Figure 35: Timing of optimal mitigation under several technology options. High elasticity of resource substitution: $s = 2.0$; high elasticity of energy substitution: $s_1 = 2.0$.

Distributional Effects Fig. 36 shows functional income decomposition of BAU and RED scenario under price and quantity policy. The differing distribution of the mitigation scarcity rent under price and quantity as stated in Sec 4.1 remains. However, the relative amount of the mitigation rent is smaller than in the basemodel, because substitutability is higher. Thus, mitigation scarcity rent forms 28.8 % of total tax volume (within price policy) and cannot outweigh negative tax incomes due to R&D expenditures and LbD subsidies. Nevertheless, mitigation reduces overall lump-sum tax by 32.2 % under price policy and 12.7 % under quantity policy, respectively. This reduction is caused mainly due to lower LbD subsidies in the production sector and – in the case of a resource tax – by positive tax incomes (Fig. 33).

Furthermore, labor income decreases by 11.8 % stronger than capital income (8 %). Reduction of labor income is mainly caused by lower wages (12.1 % wage decrease and 2.2 labor decrease) while reduction of capital income is caused mainly by lower capital stocks (6 %) – the interest rate falls by only 2.1 %. (Fig. 37). Although resource price increases considerably, energy price only doubles due to substitution by capital and backstop energy. The high factor prices reflect the mitigation goal and propagate until wages and interest rates. However, stronger wage decrease than interest rate decrease indicates again the meaning (and value) of high capital stocks for overall consumption levels.

Within the capital income, sectoral capital allocation changes due to mitigation: Capital income from renewable energy sector raises at the expense of capital income from fossil energy and resource extraction sector (Fig. 38). Assets in the production sector are only party affected, as they are again important for overall consumption (and welfare).

Mitigation leads to a considerable tax relief – under price instruments more than under quantity restriction. Furthermore, labor income recipients are slightly

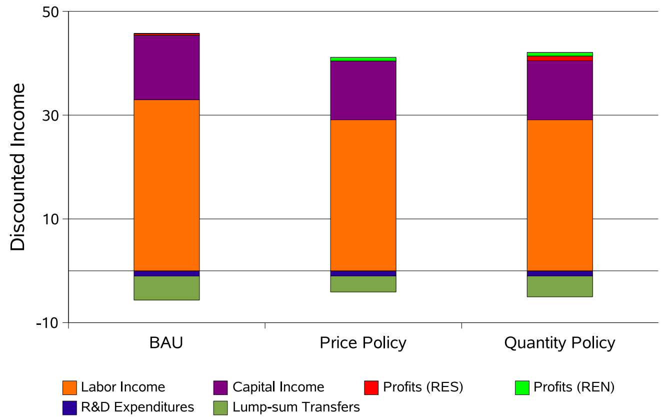

Figure 36: Functional income distribution

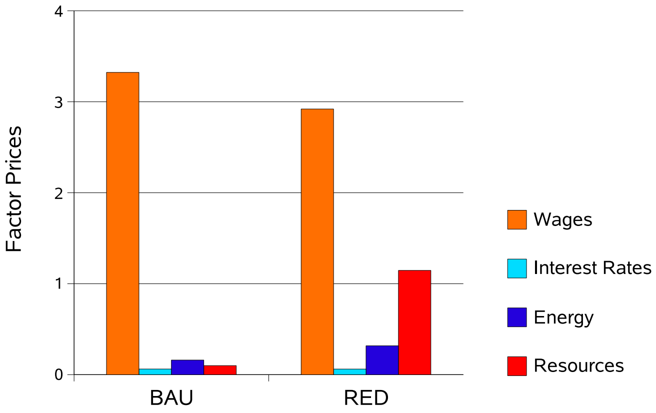

Figure 37: Prices in BAU and RED scenario

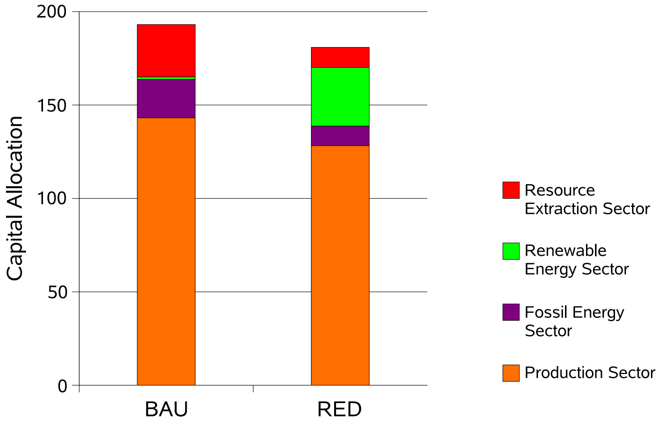

Figure 38: Capital allocation across economic sectors

stronger affected than capital income recipients due to reduction effects.

Conclusions Regarding high uncertainties in future technological development of carbon and energy efficiency and renewable energy production, determing an optimal resource tax is also afflicted with such uncertainties. A quantity policy shifts these uncertainties to emitting enterprises who have to estimate future demand for allowances, but guarantees a complying with the mitigation target. Otherwise a resource tax path announced by the government may fail the mitigation target due to false estimated technological development. Correction of such a tax path decreases government's credibility and may give fatal signals to enterprises with respect to their abatement strategies.

5 Concluding Remarks and Reflections

The model I developed determines and explains first-best and second-best taxes and other instruments to achieve climate protection, which is not possible with established integrated assessment models. It considers several market imperfections as well as strategic interactions of e.g. the resource sector and the government. Furthermore, it provides a detailed assessement of a set of prominent climate policies by estimating their distributional effects for the first time.

In the following, I evaluate briefly the general Stackelberg approach and summarize important concrete results with respect to the questions posed in the introduction: What are efficient instruments against global warming if several market failures are considered and what are the distributional effects of different mitigation policies? Finally, I mention some implications for actual climate policy measures and give a short outlook on future economic problems linked to the consumption of exhaustible resources.

Model Purpose and Features The developed and employed Stackelberg game framework allows to reproduce several findings from economic theories of market failures. The model combines numerous parts of economic theory: Within game theory as general framework, several subdisciplines from environmental economics and endogenous growth theory to economics of exhaustible resources, industrial organization and theorems of welfare economics as well as economics of taxation are touched.

It is common for IAMs to regard environmental as well as technological constraints. This model goes beyond this by regarding strategical constraints of profit and utility maximizing economic sectors and households. Hence, in a decentralized market economic model, not only first-best instruments of single market failures can be obtained. Also second-best instruments and multiple market failures can be analyzed within a general equilibrium model.

A further important strength of this approach is to evaluate in detail impacts of several first-best and second-best policies on market prices and especially on functional income distribution. This is a first step to explore greater in detail distribution of costs and benefits of climate policies for different income groups.

By using the cost-effectiveness approach, policy implications obtained depend with respect to normative assumptions mainly on the amount of permitted GHG concentrations and not on the quantification of damages and the choice of a discount rate for these damages.

Efficient Instruments against Climate Change As proved in Sec. 3.4.1, the decentralized economy without market failures achieves the socially optimal outcome.

To enforce emission reduction, a resource tax as well as a cumulative quantity restriction are efficient instruments (Sec. 4.1). In contrast, a pure energy tax causes welfare losses, which depend on elasticities of substitution of fossil resources and turn out to be considerable (more than 1%) for realistic parameter values (Sec. 4.2.2). This inefficiency of such an output tax can be eliminated by a capital subsidy in the fossil energy sector which augments carbon efficiency for energy production and hence achieves an optimal factor allocation (Sec. 4.2.3). Although a pure capital subsidy in the fossil energy sector increases carbon efficiency, it also increases overall emissions due to higher energy production as a consequence of the decreased energy price and emerging rebound effects

(Sec. 4.2.4). Finally, a combination of capital and labor tax causes the highest welfare losses because emission reduction is mainly achieved by reductions of consumption. This result indicates, that an environmentally aware household which tries to achieve the mitigation target by adequate consumption and investment decisions has to suffer higher welfare losses than an appropriate governmental policy measure would cause (Sec. 4.2.3).

The inefficiency of monopolistic or oligopolistic market structures in the resource extraction sector can be solved by an output subsidy which augments resource extraction to the socially optimal level (Sec. 4.3.2). If in addition a mitigation target has to be considered, the resulting pristine mitigating resource tax must be lowered in order to achieve a dynamic efficient extraction path (Sec. 4.3.3). Although being dynamically inefficient with respect to social welfare, it benefits future generations to neglect monopolistic structures for optimal resource tax calculation due to the more conservative extraction path (Sec. 4.3.1).

Finally, learning-by-doing spillovers in the production and renewable energy sectors can be internalized by a capital subsidy in both sectors (Sec. 4.4.1) while R&D expenditures have to be paid by the government due to higher tax incomes (Sec. 4.4.2). Combining both approaches to model endogenous technological change yields synergy effects higher than the sum of both single growth effects (Sec. 4.4.3). Optimal mitigation policy leads to a decrease of R&D and LbD subsidies which are linked to overall productivity growth; in contrast, R&D expenditures and LbD subsidies related to energy efficiency and renewable energy have to increase (Sec. 4.4.4).

The volume of the resource tax depends mostly on the availability of substitutes. If fossil energy is substituteable (due to renewable energy or efficiency improvements by capital), resource tax can be on a low level. If resources cannot be substituted and mitigation is mainly achievable by consumption reduction, resource price has to be very high (Sec. 4.4.4).

Distributional Effects of Policy Instruments Endogenously determined market prices allow to decompose functional income and to analyze the impact of several instruments on different income recipients.

A robust and important insight of this work is that every mitigation policy generates an additional scarcity rent at the expense of labor and capital income. In the the extended model with renewable energy and endogenous technological change, income reductions for salary recipients are harsher than for interest payments recipients, because capital is more valuable due to spillover effects (Sec. 4.4.4). A crucial difference between price and quantity restriction policy concerns the distribution of the additional mitigation scarcity rent to several income groups: The quantity instrument transfers this rent to the resource extraction sector while the price instrument allows for lump-sum redistribution to any income group as well as reduction of existing tax burdens (e.g. LbD subsidies) (Sec. 4.1 and 4.4.4). The volume of the mitigation scarcity rent increases with the strictness of the effective mitigation target and with declining elasticity of resource and energy substitution (Sec. 4.1.1). Under the presence of a competitive renewable energy, resources do not play an important role and thus scarcity rent is low.

Beside the distributional effects of mitigation policies, several model extensions in the business as usual scenario change the functional income composition. Regarding the output subsidy to correct under-extraction of resources due to market power, ad-valorem tax provokes higher rents in the resource sector at the expense of lump-sum tax payers than a unit tax would cause (Sec. 4.3.2).

Endogenous technological change augments capital income as well as labor income. The first mainly due to higher capital stocks, the latter due to higher labor productivity and wage increases (Sec. 4.4.3). However, capital income again rises considerably more than labor income which depends mainly on the economic importance of high capital stocks in the production sector, which cause positive technology spillovers and thus provoke economic growth (Sec. 4.4.1).

Future Extensions and Research Questions An important task on the way to a useful integrated assessment model would be a calibration to derive concrete tax rates applicable to real-world economic systems.

The model can easily be extended by further constraints reflecting strategical behavior and market failures. An interesting research question concerns overcoming the concept of a representative household to heterogenous households. In a first step, without changing existing model equations, differing discount rates in the social welfare function and the representative household can be analyzed. Additional constraints accounting for the political reality should be considered, for example the limited feasibility of lump-sum taxes. Furthermore, governments need a certain amount of revenues to finance important public expenditures. Thus, the interplay of environmental motivated public revenues and double-dividend effects of cutback of existing tax distortions are worth being studied. Without renouncing the tolerable window approach or temperature guardrails, damages of GHG emissions can be considered additionally in cost-effectiveness analysis.

To overcome another important simplification of the one-good-economy, heterogenous goods with limited substitutability should be considered (e.g. technically produced conventional consumption goods, food and water and general natural goods).[61]

Policy Implications The results of this thesis suggest the following implications for policy makers.

The most efficient instrument for combating dangerous climate change is a high carbon price (obtained by a resource tax or by a quantity restriction). Second-best instruments like energy tax or voluntary consumption reduction of climate aware households should be avoided as they cause considerably high welfare losses. In case of quantity restrictions, these should be cumulative and not restricted to years. This proceeding augments dynamic efficiency of the timing of abatement and furthermore gives firms higher planning security. However, this recommendation applies only in the case of a “correct” discount rate[62], if no other instruments are available to correct the resulting suboptimal extraction path.

The occurrence of diverging labor and capital incomes seems to be immanent to the market economic system. Economic growth induces – with or without mitigation policy – larger benefits via ETC for capital income recipients than for labor income recipients. Furthermore, in the presence of endogenous technological change, mitigation charges labor income more than capital income.

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[61] However, this important modification should first be performed for social planner models because such a diversification would not touch directly aspects of strategical behavior.

[62] I.e. pure time preference rate of households equals social time preference rate of the social welfare function.

Thus, further policy measures might be necessary to compensate labor income recipients and let them participate in the higher capital income.

To prevent enterprises from benefiting from mitigation at the expense of taxpayers, all explicit and implicit quantity restricting policies without full revenue collecting (e.g. auctioning) should be avoided if affected factors are difficult to substitute. This holds in particular for claims for a coal extraction restriction, coal moratorium, oil and gas import restrictions or free allocated pollution emissions. Rather government incomes from revenue collecting environmental instruments should be used to reduce existing distortions due to taxes or to redistribute wealth within the society.[63] However, complete revenue collecting may not be politically feasible in the presence of powerful lobbying. In this case, free or partly auctioned allowances may reduce resistance because enterprises even profit relative to BAU.

Monopolistic market structures in the resource sector conserve resources by shifting extraction to the future. Although this may help combating climate change and may establish higher intergenerational equity, social welfare can be raised by output subsidies or (hardly implementable) anti-trust policies. Using market power to achieve the mitigation goal without further mitigation instruments is no long-term possibility because optmal degree of market power depends to a great extend on the planning horizon being considered.

Regarding high uncertainties in future technological development of carbon and energy efficiency raising and renewable energy production, auctioned emission allowances might be a more adequate instrument to avoid time-inconsistent corrections of an announced tax path that turns out not to be sufficient in the course of time.

Prospects Beside exertive and important disputes about optimal mitigation targets, efficient instruments and international free-riding, I want to focus on the close link between global warming and depletion of exhaustible resources. Formulating a mitigation goal intensifies the problem of limited availability of exhaustible fossil resources. It does not create a "new" economic growth problem. It does not claim to sacrifice all our wealth to the survival of corrals. It just brings keenly into mind, that fossil resources are finite and that our way of economizing cannot be continued with business as usual. It just curtails the time a bit to change back again to a form of economizing by using only as much energy as it is "renewable", i.e. flowing from the sun.

Fossil resources have been depleted for many decades with a naive matter of course. It has neither been worried about how long this practice is feasible nor which generation and which country actually has the right to destroy these reserves created for millions of years. Now some people seem to be surprised or even angry about doubting the image of an eternal growing economy based on a never ebbing fossil fuel flow. But with or without the problem of climate change, economy is faced with the problem of limited and – even worse – exhaustible resources.[64] Thus, the big challenge is to overcome the dependence on exhaustible resources and to develop substitutes.

Hence, referring to Stern's quotation in the opening of this thesis, ambitious

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[63] The latter will milden but not suppress the occurrence of diverging labor and capital incomes.

[64] The difference is, that limited resources can also be renewable, i.e. limited only in the use for a certain time instant. In contrast, exhaustible resource are limited in their cumulative use, i.e. consuming them reduces resource stock continously.

climate policy not only may help to correct the greatest market failure. It will also accelerate the transformation of the actual economic system based on dissaving exhaustible natural resource stocks to a sustainable economic system of steady state relations to such resource stocks.

A Reformulating the Discrete Optimization Problem

Implementing the model in GAMS for numerical calculations calls for time-discretization. Budget and production equations and all static first-order conditions remain the same. Only terms expressing equations of motion and transversality conditions are effected. Time-dependent variables $y(t)$ with $t \in [0, T]$ are now written indexed y_t with $t \in \{0, 1, ...T\}$.

Discrete Maximum Principle The general form of the discrete problem with state variable x_t and control variables u_t is[65]:

$$\max \ J = \max \sum_{t=0}^{T} \alpha^t g(x_t, u_t) \tag{130}$$

$$\text{s.t. } \ x_{t+1} - x_t = f(x_t, u_t) \tag{131}$$

The discrete current-value Hamiltonian is:

$$H_t = g(x_t, u_t) + \lambda_t f(x_t, u_t)$$

Maximizing J is to maximize H_t respective to u_t with the equation of motion of the costate variable λ_t:

$$\lambda_t - \frac{1}{\alpha}\lambda_{t-1} = -\frac{\partial H_t}{\partial x_t}$$

The transversality condition states:

$$\lambda_T x_{T+1} = 0$$

Reformulated Equations for Stock Variables

$$K_{t+1} - K_t = I - \delta K_t \tag{132}$$

$$S_{t+1} - S_t = -R \tag{133}$$

Reformulated Equations for Costate Variables

$$(1 + \tilde{r})\lambda_{H,t} = (1 + \rho)\lambda_{H,t-1} \tag{134}$$

$$(1 - \delta)\lambda_{K_E,t} - (1 + \rho)\lambda_{K_R,t-1} = r_t - p_{E,t}\frac{\partial E_{fos,t}}{\partial K_{E,t}} \tag{135}$$

$$\lambda_{R,t} - (1 + \tilde{r})\lambda_{R,t-1} = (\lambda_{R,t} - p_{R,t})K_{R,t}\frac{\partial \kappa_t}{\partial S_t} \tag{136}$$

$$(1 - \delta)\lambda_{K_R,t} - (1 + \tilde{r})\lambda_{K_R,t-1} = r_t + (\lambda_{R,t} - p_{R,t})\kappa_t \tag{137}$$

Reformulated Transversality Conditions

$$\lambda_{X_i,T} X_{T+1} = 0 \tag{138}$$

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[65] For further details of the discrete maximum principle see Clark (1990, pp. 234), and Hanley et al. (1997, pp. 202)

Reformulated Discount Factor The discount rate ρ of the continuous system is replaced by the discount factor

$$\alpha = \frac{1}{1+\rho}$$

in the discrete system. By the limit equation for Euler's number $(1+\rho)^{-t}$ is a first approximation for $e^{-\rho t}$ and hence the integral:

$$\int_{t=0}^{T} e^{-\rho t} g(x,u) dt$$

converges to the sum:

$$\sum_{t=0}^{T/\Delta} \left(\frac{1}{1+\rho}\right)^{t\Delta} g(x,u)\Delta$$

as $\Delta \rightarrow 0$. That means by choosing an adequate small step size Δ, the difference between the integral and the sum can be made arbitrarily small and the substitution of α by $1/(1+\rho)$ is appropriate for the reformulation.

B Derivatives of Several Functions

B.1 Utility Function

$$u = \ln(C) + \ln(L_{max} - L) \tag{139}$$

$$\frac{\partial u}{\partial C} = \frac{1}{C} \tag{140}$$

$$\frac{\partial u}{\partial L} = -\frac{1}{L_{max} - L} \tag{141}$$

B.2 Nested CES Production Function of Good Producing Sector

Production Technology

$$Y = (a_1 Z^{\sigma_1} + (1 - a_1)(A_E E)^{\sigma_1})^{(1/\sigma_1)} \tag{142}$$

$$Z = (a_2 K_Y^{\sigma_2} + (1 - a_2)(A_L L)^{\sigma_2})^{(1/\sigma_2)} \tag{143}$$

First Derivatives

$$\frac{\partial Y}{\partial Z} = a_1 Y^{1-\sigma_1} Z^{\sigma_1 - 1} \tag{144}$$

$$\frac{\partial Y}{\partial E} = (1 - a_1) Y^{1-\sigma_1} E^{\sigma_1 - 1} A_E^{\sigma_1} \tag{145}$$

$$\frac{\partial Z}{\partial K_Y} = a_2 Z^{1-\sigma_2} K_Y^{\sigma_2 - 1} \tag{146}$$

$$\frac{\partial Z}{\partial L} = (1 - a_2) Z^{1-\sigma_2} L^{\sigma_2 - 1} A_L^{\sigma_2} \tag{147}$$

$$\frac{\partial Y}{\partial K_Y} = \frac{\partial Y}{\partial Z} \frac{\partial Z}{\partial K_Y} = a_1 Z^{\sigma_1 - \sigma_2} Y^{1-\sigma_1} a_2 K_Y^{\sigma_2 - 1} \tag{148}$$

$$\frac{\partial Y}{\partial L} = \frac{\partial Y}{\partial Z} \frac{\partial Z}{\partial L} = a_1 Z^{\sigma_1 - \sigma_2} Y^{1-\sigma_1} (1 - a_2) L^{\sigma_2 - 1} A_L^{\sigma_2} \tag{149}$$

Second Derivative

$$\frac{\partial^2 Y}{\partial E^2} = (\sigma_1 - 1) a_1 Z^{\sigma_1} (1 - a_1) E^{\sigma_1 - 2} Y^{1 - 2\sigma_1} A_E^{\sigma_1} \tag{150}$$

In the case of absence of technological change, $A_L = A_{L,0}$ and $A_E = A_{E,0}$ constant.

B.3 CES Production Function of Fossil Energy Sector

Production Technology

$$E_{fos} = (a K_E^{\sigma} + (1 - a) R^{\sigma})^{(1/\sigma)} \tag{151}$$

First Derivatives

$$\frac{\partial E_{fos}}{\partial R} = (1-a)E_{fos}^{1-\sigma}R^{\sigma-1} \tag{152}$$

$$\frac{\partial E_{fos}}{\partial K_E} = aE_{fos}^{1-\sigma}K_E^{\sigma-1} \tag{153}$$

Second Derivative

$$\frac{\partial^2 E_{fos}}{\partial R^2} = (\sigma-1)aK_E^{\sigma}(1-a)R^{\sigma-2}E^{1-2\sigma} \tag{154}$$

B.4 Capital Productivity of Resource Extraction

Production Technology

$$\kappa = \frac{\chi_1}{\chi_1 + \chi_2\left(\frac{S_0-S}{\chi_3}\right)^{\chi_4}} \tag{155}$$

First Derivative

$$\frac{\partial \kappa}{\partial S} = \frac{\kappa^2\chi_2\chi_4}{\chi_1\chi_3}\left(\frac{S_0-S}{\chi_3}\right)^{\chi_4-1} \tag{156}$$

B.5 Renewable Energy Sector

Production Technology

$$E_{ren} = \kappa_{ren}A_{E_2}K_{E_2}^{\nu} \tag{157}$$

First Derivative

$$\frac{\partial E_{ren}}{\partial K_{E_2}} = \nu\frac{E_{ren}}{K_{E_2}} \tag{158}$$

C The Stackelberg Leader Optimization Problem

Objective:

$$\max_{\{\tau_i,\varsigma_R,\Gamma,R_L,R_E,R_{E_2}\}} \int_0^\infty u(C,L)e^{-\rho_G t}dt$$

with $i \in \{K, K_Y, K_E, K_R, E, R, E_2, L\}$

Subject to:

Mitigation target

$$S \geq \underline{S} \tag{159}$$

Household sector

$$\begin{align} u &= \ln(C) + \ln(L_{max} - L) \tag{160}\\ C &= wL + \bar{r}K - I + \Pi + \Gamma \tag{161}\\ K &= K_Y + K_E + K_R + K_{E_2} \tag{162}\\ I &= I_Y + I_E + I_R + I_{E_2} \tag{163}\\ \Pi &= \Pi_Y + \Pi_E + \Pi_R + \Pi_{E_2} \tag{164}\\ \dot{K} &= I - \delta K \tag{165}\\ u'_C &= \lambda_H \tag{166}\\ u'_L &= -\lambda_H w \tag{167}\\ \dot{\lambda}_H &= \lambda_H(\rho + \delta - \bar{r}). \tag{168}\\ 0 &= \lim_{t\to\infty} \lambda_H K e^{-\rho t} \tag{169} \end{align}$$

Good producing sector

$$\begin{align} \Pi_Y &= Y - r(1+\tau_{K_Y})K_Y - \bar{w}L - \bar{p_E}E \tag{170}\\ Y &= (a_1 Z^{\sigma_1} + (1-a_1)(A_E E)^{\sigma_1})^{(1/\sigma_1)} \tag{171}\\ Z &= (a_2 K_Y^{\sigma_2} + (1-a_2)(A_L L)^{\sigma_2})^{(1/\sigma_2)} \tag{172}\\ E &= E_{fos} + E_{ren} \tag{173}\\ \dot{K}_Y &= I_Y - \delta K_Y \tag{174}\\ r(1+\tau_{K_Y}) &= \frac{\partial Y}{\partial K_Y} \tag{175}\\ \bar{w} &= \frac{\partial Y}{\partial L} \tag{176}\\ \bar{p}_E &= \frac{\partial Y}{\partial E} \tag{177} \end{align}$$

Fossil energy sector

$$\Pi_E = p_E E_{fos} - r(1+\tau_{K_E})K_E - \bar{p}_R R \tag{178}$$

$$E_{fos} = (aK_E^{\sigma} + (1-a)R^{\sigma})^{(1/\sigma)} \tag{179}$$

$$\dot{K}_E = I_E - \delta K_E \tag{180}$$

$$\bar{p}_R = p_E \frac{\partial E}{\partial R} \tag{181}$$

$$r(1+\tau_{K_E}) = p_E \frac{\partial E_{fos}}{\partial K_E} \tag{182}$$

$$\tag{183}$$

Resource extracting sector

$$\Pi_R = (p_R - \varsigma_R)R - r(1+\tau_{K_R})K_R \tag{184}$$

$$R = \kappa K_R \tag{185}$$

$$\dot{S} = -R \tag{186}$$

$$\dot{K}_R = I_R - \delta K_R \tag{187}$$

$$S \geq 0 \tag{188}$$

$$\kappa = \frac{\chi_1}{\chi_1 + \chi_2 \left(\frac{S_0 - S}{\chi_3}\right)^{\chi_4}} \tag{189}$$

$$\tilde{r} = \bar{r} - \delta = r(1-\tau_K) - \delta \tag{190}$$

$$\dot{\lambda}_R = \tilde{r}\lambda_R - (p_R + \frac{\partial p_R}{\partial R}R - \varsigma_R - \lambda_R)K_R \frac{\partial \kappa}{\partial S} \tag{191}$$

$$r(1+\tau_{K_E}) = (p_R + \frac{\partial p_R}{\partial R}R - \varsigma_R - \lambda_R)\kappa \tag{192}$$

$$0 = \lim_{t\to\infty} \lambda_R (S - S_c) e^{\int_0^t -\tilde{r}\ ds} \tag{193}$$

$$\frac{\partial p_R}{\partial R} = \theta_1 \frac{1}{1+\tau_R}\left(p_E E_R'' + \theta_2 \frac{1}{1+\tau_E} Y_E''(E_R')^2\right) \tag{194}$$

Renewable energy sector

$$\Pi_{E_2} = p_E(1-\tau_{E_2})E_{ren} - rK_{E_2} \tag{195}$$

$$E_{ren} = \kappa_{ren} A_{E_2} K_{E_2}^{\nu} \tag{196}$$

$$\dot{K}_{E_2} = I_{E_2} - \delta K_{E_2} \tag{197}$$

$$r = p_E(1-\tau_{E_2})\frac{\partial E_{ren}}{\partial K_{E_2}} \tag{198}$$

Government

$$\begin{aligned}C_{gov} =& \Gamma + \tau_K rK + \tau_L wL + \tau_E p_E E + \tau_R p_R R + \tau_{E_{ren}} p_E E_{ren} \\ &+ \tau_{K_Y} rK_Y + \tau_{K_R} rK_R + \tau_{K_R} rK_R + \varsigma_R R \\ &- R_L - R_E - R_{E_2}\end{aligned} \tag{199}$$

$$\bar{r} = r(1 - \tau_K) \tag{200}$$

$$\bar{w} = w(1 + \tau_L) \tag{201}$$

$$\bar{p}_E = p_E(1 + \tau_E) \tag{202}$$

$$\bar{p}_R = p_R(1 + \tau_R) \tag{203}$$

Endogenous technological change

$$A_L = A_{L,0} + \xi_L K_Y^{\varsigma_L} + H_L \tag{204}$$

$$\dot{H}_L = h_L R_L^{b_L} H_L^{\phi_L} - \delta_H H_L \tag{205}$$

$$A_E = A_{E,0} + \xi_E K_Y^{\varsigma_E} + H_E \tag{206}$$

$$\dot{H}_E = h_E R_E^{b_E} H_E^{\phi_E} - \delta_H H_E \tag{207}$$

$$A_{E_2} = A_{E_2,0} + \xi_{E_2} K_{E_2}^{\varsigma_{E_2}} + H_{E_2} \tag{208}$$

$$\dot{H}_{E_2} = h_{E_2} R_{E_2}^{b_{E_2}} H_{E_2}^{\phi_{E_2}} - \delta_H H_{E_2} \tag{209}$$

D Decomposition Analysis

The goal of the decomposition analysis is to decompose (additively) the change of a specific variable into changes of other variables related to macroeconomic key variables. Here, I want to decompose the change of resource extraction ΔR into the changes of output production Y, energy intensity $\varepsilon = E/Y$ and carbon intensity $\gamma = R/E$ to analyze, what are the driving forces of the modified resource extraction. The change of these variables refers to a baseline case $Y_0, \varepsilon_0, \gamma_0$ instead of a time instant (this baseline case is a specific model version or policy scenario).

I use Laspeyres index method with equally distributed residual terms. For detailed information about decomposition analysis and proof of the following identity see Gerlinger (2004, ch. 7) and Sun (1998). The symbol Δ refers to the difference of a variable respect to the baseline case, i.e. $\Delta X = X - X_0$.

$$\begin{aligned}\Delta R =& R - R_0 = Y\frac{E}{Y}\frac{R}{E} - Y_0\frac{E_0}{Y_0}\frac{R_0}{E_0} && (210)\\ =& Y\varepsilon\gamma - Y_0\varepsilon_0\gamma_0 && (211)\\ =& \Delta\varepsilon Y_0\gamma_0 + \Delta\gamma Y_0\varepsilon_0 + \Delta Y\gamma_0\varepsilon_0 + \\ & \underbrace{\Delta Y\Delta\gamma\Delta\varepsilon + \Delta\varepsilon\Delta Y\gamma_0 + \Delta Y\Delta\gamma\varepsilon_0 + \Delta\varepsilon\Delta\gamma Y_0}_{\text{residual term}} && (212)\end{aligned}$$

Equal distribution of residual terms to effective factor changes leads to:

$$\begin{aligned}\Delta R =& Y_{\text{eff}} + \varepsilon_{\text{eff}} + \gamma_{\text{eff}} && (213)\\ Y_{\text{eff}} =& \Delta Y\gamma_0\varepsilon_0 + \underbrace{\frac{1}{3}\Delta Y\Delta\gamma\Delta\varepsilon + \frac{1}{2}\Delta Y(\Delta\varepsilon\gamma_0 + \Delta\gamma\varepsilon_0)}_{\text{residual term}} && (214)\\ \varepsilon_{\text{eff}} =& \Delta\varepsilon Y_0\gamma_0 + \underbrace{\frac{1}{3}\Delta Y\Delta\gamma\Delta\varepsilon + \frac{1}{2}\Delta\varepsilon(\Delta Y\gamma_0 + \Delta\gamma Y_0)}_{\text{residual term}} && (215)\\ \gamma_{\text{eff}} =& \Delta\gamma Y_0\varepsilon_0 + \underbrace{\frac{1}{3}\Delta Y\Delta\gamma\Delta\varepsilon + \frac{1}{2}\Delta\gamma(\Delta Y\varepsilon_0 + \Delta\varepsilon Y_0)}_{\text{residual term}} && (216)\end{aligned}$$

E List of Variables and Parameters

E.1 Variables

Production & consumption	
C	consumption
Y	produced final output (GDP)
Z	capital-labor intermediate product
L	labor
R	resource flow (resource extraction)
E_{fos}	fossil energy
E_{ren}	renewable energy
E	total energy
Stocks	
K_Y	capital stock in production sector
K_E	capital stock in fossil energy sector
K_{E_2}	capital stock in renewable energy sector
K_R	capital stock in resource extracting sector
K	total capital stock
S	resource stock
Costate variables	
λ_H	costate variable for total capital stock (household)
λ_R	costate variable for resource stock (resource sector)
Investments	
I_Y	investments in production sector
I_E	investments in fossil energy sector
I_{E_2}	investments in renewable energy sector
I_R	investments in resource extracting sector
I	total investments
R_L	R&D expenditures in labor productivity
R_E	R&D expenditures in energy productivity
R_{E_2}	R&D expenditures for renewable energy
Productivities	
A_L	labor productivity
A_E	energy productivity
A_{E_2}	capital productivity in renewable sector
H_L	labor efficiency augmenting human capital
H_E	energy efficiency augmenting human capital
H_{E_2}	human capital in renewable energy sector

κ	capital productivity of resource extraction
Prices	
r	interest rate
w	wages
p_E	energy price
p_R	resource price
$\overline{r}, \overline{w}, \overline{p_E}, \overline{p_R}$	taxed factor prices
$\tilde{r}$	interest rate net of taxes and depreciation $\tilde{r} = r(1 - \tau_K) - \delta$
Taxes	
τ_K	ad-valorem global capital tax
τ_{K_Y}	ad-valorem production sector specific capital tax
τ_{K_E}	ad-valorem fossil energy sector specific capital tax
τ_{K_R}	ad-valorem resource extraction sector specific capital tax
τ_L	ad-valorem labor tax
τ_E	ad-valorem energy tax
τ_{E_2}	ad-valorem renewable energy tax
τ_R	ad-valorem resource tax
ς_R	unit resource tax
Γ	lump-sum tax (household)
Profits	
Π_Y	profits production sector
Π_E	profits fossil energy sector
Π_{E_2}	profits renewable energy sector
Π_R	profits resource extraction sector
Gov	government's share
u	utility function
W	social welfare function

E.2 Parameters

ρ_H	pure time preference rate of household	0.03
ρ_G	pure time preference rate of government	0.03
L_{max}	maximal labor supply	1
C_{gov}	government consumption	0
a_1	share parameter in final good production	0.95
s_1	elasticity of substitution in final good production	0.4
a_2	share parameter in intermediate good production	0.3
s_2	elasticity of substitution in intermediate good production	0.6
a	share parameter in fossil energy production	0.3

s	elasticity of substitution in fossil energy sector	0.3
ν	exponent of renewable energy production function	0.7
κ_{ren}	scaling parameter for renewable energy production	0.15
δ	depreciation rate of physical capital (all sectors)	0.01
θ_1	monopoly power (first-stage)	0
θ_2	monopoly power (second-stage)	0
K_0	initial total capital stock	1
S_0	initial fossil resource stock	250
$\underline{S}$	mitigation target	230
$A_{L,0}$	initial productivity level of labor	1.0
$A_{E,0}$	initial productivity level of energy	1.0
$A_{E_2,0}$	initial productivity level of capital in ren. energy sec.	1.0
$H_{L,0}$	initial human capital (labor)	10^{-3}
$H_{E,0}$	initial human capital (energy)	10^{-3}
$H_{E_2,0}$	initial human capital (ren. energy)	10^{-3}
χ_1	scaling parameter	0.01
χ_2	scaling parameter	0.01
χ_3	resource base parameter	100
χ_4	slope of Rogner's curve	2
ξ_L	spillover factor labor	0.06
ς_L	spillover exponent labor	0.9
h_L	R&D factor labor	0.04
b_L	R&D exponent labor	0.1
ϕ_L	human capital exponent labor	0.1
δ_L	depreciation rate of labor augmenting human capital	0.0
ξ_E	spillover factor energy	0.02
ς_E	spillover exponent energy	0.9
h_E	R&D factor energy	0.01
b_E	R&D exponent energy	0.1
ϕ_E	human capital exponent energy	0.1
δ_E	depreciation rate of energy augmenting human capital	0.0
ξ_{E_2}	spillover factor renewable energy	0.25
ς_{E_2}	spillover exponent capital (ren. en. sec.)	0.1
h_{E_2}	R&D factor renewable energy	0.02
b_{E_2}	R&D exponent renewable energy	0.1
ϕ_{E_2}	human capital exponent renewable energy	0.1
δ_{E_2}	depreciation rate of energy augmenting human capital	0.0

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Ehrenwörtliche Erklärung

Hiermit versichere ich, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.