At the Frontiers of Integrated Assessment of Climate Change: Distribution, Technology policy, and Land

vorgelegt von
Diplom-Physiker
Anselm Johannes Schultes
geboren in Aachen

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

Promotionsausschuss:

Vorsitzender:	Prof. Dr. Dieter Scherer
Gutachter :	Prof. Dr. Ottmar Edenhofer
Gutachter:	Prof. Massimo Tavoni, Ph.D.
Gutachter:	Prof. Dr. Christian von Hirschhausen

Tag der wissenschaftlichen Aussprache: 11. Juli 2016

Berlin 2017

Abstract

Integrated Assessment Modeling is the prevailing paradigm for the assessment of climate change impacts, mitigation policies, and transformation pathways. Model results were a decisive impulse for the international community to commit itself to stabilize global warming at well below 2°C temperature rise. However, climate policies in place or pledged as of 2015 fall short of what science finds as cost-effective transformation pathways for the 2°C target.

The recurring themes of this thesis are the distributional impacts and the distributional conflicts that are at the heart of climate change, but often hidden in Integrated Assessment Models (IAM). Along these lines, I extend and complement current IAMs, covering the topics of international technology policy, distributional implications of mitigation for developing countries, and the role of land in climate impacts.

In a first contribution, I develop a solution methodology for a global IAM with high technological detail in the energy system that allows for finer regional resolution and the inclusion of non-cooperative regional interactions. Based on this methodology, I derive optimal climate and technology policy for the 2°C target in another contribution, including spillover effects from global learning-by-doing in low-carbon technologies: While carbon pricing is by far the most important policy instrument, global learning effects in low-carbon technologies may provide an economic rationale for significant low-carbon subsidies for solar technologies and advanced vehicles under an international technology protocol.

In another contribution, I focus on the non-environmental incentives for Sub-Saharan Africa as an aggregate region to join a global climate stabilization agreement: I find that while there are significant costs from a reduction in economic growth, those cost may in some scenarios be overcompensated by increased revenue from selling emissions permits and biomass on international markets.

I argue that climate damages on agricultural land are not fully reflected in current IAMs. Land-biased damages may have large economic impacts of due to distortionary land rents, as I demonstrate in a small IAM that considers the intergenerational distribution of wealth explicitly. In addition, I find that land-biased climate damages decrease the incentive for generations to enact climate policy – potentially aggravating the intergenerational distributional conflict that climate change is.

A final contribution on fiscal policy for wealth inequality reduction in rich countries holds that distinguishing life-cycle and bequest savings motives, as well as different types of wealth is crucial: Taxes on capital returns, land rents, and bequests have very different

redistributive power and efficiency costs, and in sum leave room for governments to reduce wealth inequality without sacrificing economic output.

In conclusion, this thesis tries to bring the issue of distribution into the focus of Integrated Assessment Modeling, and asserts that understanding distributional conflicts will be key to strengthen climate policy further.

Zusammenfassung

Die vorherrschende Methodik zur Beurteilung von Klimawandelschäden sowie Klimapolitik und Transformationspfaden beruht auf sogenannten Integrated Assessment Models (IAM). Solche Modellresultate haben entscheidend dazu beigetragen, dass sich die internationale Gemeinschaft dazu verpflichtet hat, den globalen Temperaturanstieg auf deutlich unter 2°C zu begrenzen. Allerdings reichen die im Jahr 2015 existierenden und angekündigten Klimapolitiken bei weitem nicht aus um kosteneffiziente Transformationspfade zu erreichen.

Die Leitmotive dieser Dissertation sind Verteilungseffekte und Verteilungskonflikte, welche entscheidend für die Bewertung von Klimawandel und die Anreize für Klimapolitik, hingegen in IAMs aber oft verdeckt sind. Diesem Motiv folgend erweitere und ergänze ich IAMs um die Themen internationale Technologiepolitik, Verteilungsimplikationen von stringenter Klimapolitik für Länder in Subsahara-Afrika und dem Produktionsfaktor Land zu behandeln.

Im ersten Kapitel entwickle ich ein neuartiges Lösungskonzept für ein globales IAM mit hoher Technologieauflösung, welches eine feinere regionale Auflösung und die Modellierung von nicht-kooperativem Verhalten zwischen Regionen ermöglicht. Darauf basierend berechne ich optimale Klima- und Technologiepolitik für das 2°C Ziel unter Berücksichtigung von Spillover-Effekten bei neuartigen Niedrigkarbontechnologien: Ein Preis auf Kohlenstoffemissionen ist mit Abstand das wichtigste Instrument von Klimapolitik, aber Spillover-Effekte könnten beachtliche Subventionen für solare Energietechnologien und Fahrzeuge ohne fossile Antriebe rechtfertigen.

In einem weiteren Kapitel beschreibe ich die Anreize der Modellregion Subsahara-Afrika einem globalen Abkommen zur Klimastabilisierung beizutreten: Die erheblichen direkten Kosten von Klimapolitik durch vermindertes Wirtschaftswachstum werden in einigen Szenarien durch Erlöse aus dem Handel mit Biomasse und Emissionszertifikaten sogar überkompensiert. Der Nutzen aus vermiedenen Klimawandelschäden ist in dieser Studie noch gar nicht mit einberechnet.

Ich behaupte dass Klimaschäden auf Agrarland in heutigen Modellen nicht ausreichend berücksichtigt sind: In einem Kapitel demonstriere ich anhand eines einfachen IAMs wie Schäden auf Land einen besonders starken ökonomischen Schaden anrichten, da durch die Klimaschäden steigende Renten die Kapitalakkumulation verzerren. Des weiteren verringern Klimaschäden auf Land die Anreize Klimapolitik zu betreiben und könnten damit den Konflikt zwischen Generationen verschärfen, als der sich der Klimawandel verstehen lässt.

In einem letzten Beitrag behaupte ich, dass die Unterscheidung von verschiedenen Motiven im Sparverhalten und von Kapital und Land als verschiedenen Vermögenswerten entscheidend ist für die Beurteilung von fiskalpolitischen Instrumenten zur Reduktion von Vermögensungleichheit: Steuern auf Erträge aus Kapital, Land oder Erbschaften unterscheiden sich stark in Ihren Effizienzkosten und in Ihrem Potential zur Umverteilung. Regierungen in reichen Ländern hätten somit einen gewissen Spielraum zur Umverteilung von Vermögen ohne volkswirtschaftliche Effizienzeinbußen hinnehmen zu müssen.

In dieser Dissertation versuche ich das Thema Verteilung in den Fokus von IAMs zu rücken. Abschließend argumentiere ich, dass das Verständnis von Verteilungskonflikten entscheidend dafür seinen wird stringentere Klimapolitik zu etablieren, und mache einige Anregungen für weitere Forschung in diesem Bereich.

Inhaltsverzeichnis

Kapitel 1

Introduction

Climate change cannot be studied within the traditional boundaries between academic disciplines – to assess climate impacts and climate policy, Integrated Assessment Models of Climate Change (IAM) have been used extensively in the recent decades. Based on a macro-economic core, IAMs include a representation of the climate system, and the frontiers of these models have been pushed back to cover the energy and the land-use system. The great detail on the technological side helped to form the understanding that ambitious climate change mitigation is feasible. This understanding was a decisive input for the international community to commit itself to stabilize global warming at well below 2°C temperature rise (UNFCCC Conference of the Parties 2015).

This thesis does not try to push the frontiers of Integrated Assessment further out into other fields, but is rather concerned with the frontiers *within* IAMs: Climate change impacts and mitigation redistribute income between income factors, between countries, generations, and individuals – distributional conflicts ensue, which are often hidden by construction in IAMs. Understanding these distributional conflicts is crucial for the actual implementation of the policies that eventually have to deliver on the nations' commitment to climate stabilization.

Distributional conflicts are at the heart of climate change: Climate impacts and climate policies redistribute income between generations, as most of the climate damages from emitting greenhouse gases today will be borne by future generations. Among countries, understanding the incentives to mitigate climate change are crucial to foster international cooperation. Within countries, income classes are differently affected by climate impacts, and the political feasibility and acceptance of climate policy often hinges on its distributional implications. Finally, climate impacts and policies change and redistribute income from natural rents and climate policy creates new rents – and while economists often distinguish rent income as special among other incomes, most IAMs do not make that distinction.

My point of departure for this thesis is the current state of IAMs, and their more complex twins with extensive detail in the energy system – Energy-Economy-Climate Models (EECMs). I extend and complement current models and underlying concepts to contribute to the economics of the impacts and the mitigation of climate change. The distribution of income is a recurrent theme in this thesis, along the lines of contributions on international technology policy and the role of land in integrated assessment. In the remainder of this section, I briefly outline the five contributions of this thesis, which I refer to by the short names of the respective chapters printed in SMALL CAPS.

In the methodological contribution of chapter NASH REMIND, I extend an EECM by a solution algorithm that enables non-cooperative interactions between countries, such as, for example, global learning effects in energy technologies. International technology cooperation can target external effects from global learning, and may increase the effectiveness of climate stabilization policy, but studies so far lack in technology detail. I study optimal international technology policy using a technology-rich global EECM in chapter TECHNOLOGY POLICY, and find that while carbon pricing is the essential ingredient of climate policy, a significant amount of subsidies – mostly to solar power, and electric and hydrogen cars – may be justified by global learning effects.

Climate policy redistributes income across regions, which is particularly relevant for developing nations in regions such as Sub-Saharan Africa. Chapter MITIGATION IN SUB-SAHARAN AFRICA is a study on the non-environmental incentives for Sub-Saharan Africa as a model region to join a climate stabilization agreement from an EECM perspective. One result is that the costs of climate policy – mainly due to reduced economic growth – may in some cases even be overcompensated by revenue from the sale of carbon permits and biomass on international markets.

Climate change will likely increase the importance of land, as a result of climate impacts on agricultural land and land-based mitigation options: Land is very prone to climate impacts, and agricultural yields are expected to be reduced strongly in many developing regions. Moreover, land-based mitigation options such as bioenergy with carbon capture and storage (BECCS) are of high value for low climate stabilization targets, and may change the regional distribution of mitigation efforts and costs significantly.

I claim that land is not adequately reflected in current models, and in particular that increases in land rents may lead to detrimental distortions in the economy. I account for such effects in the case of climate impacts in chapter LAND IMPACTS, and differentiate between productive capital investments and unproductive land holdings. I find that land-biased climate damages distort investment decisions through increasing scarcity rents, and consequently enlarge the economic impacts of the physical damages. Furthermore, land-biased damages may decrease the incentive to mitigate climate change for non-altruistic motives, as mitigation would decrease future scarcity rents and thus devalue land assets. In effect, land-biased damages may aggravate the intergenerational conflict that climate change is – a conflict that is hidden by construction in the infinitely-lived agent (ILA) models commonly used.

Recent literature also hints at an important role of land in the formation of wealth in rich countries – a proposition the contribution on fiscal policy and inequality in chapter FISCAL POLICY is based on. Wealth inequality currently is of great concern in many rich countries. Chapter FISCAL POLICY differentiates wealth into land and capital holdings and analyzes fiscal policy options to reduce inequality in a detailed model of households' savings and bequest motives. Taxes targeting different components of wealth have widely different efficiency costs and redistributive potential, and in effect, there is significant room for the reduction of inequality without sacrificing economic output.

The remainder of this introduction provides the relevant background for the contributions in this thesis. In particular, the following sections introduce climate change itself, the welfare analysis of climate policy, the model class of EECMs, technology policy, the implications of climate policy for least-developed countries, the role of land, and inequality and fiscal policy. During the introduction, I explain the rationale of each chapter in this thesis in a short paragraph, visually distinguished from the rest of the text by a wider margin.

1.1 Climate change

For most of history, the vast majority of humans were poor and living standards stagnated (Maddison 2007). Around 200 years ago economic activity and living standards began to grow rapidly in some nations during the industrial revolution (Acemoglu 2009; Jones und Romer 2010). Towards the end of the 18th century, advances in technology fueled the industrial revolution: Innovation in energy technologies – such as the steam engine – allowed for the use of fossil fuels where society was previously constrained by land-intensive sources of energy such as firewood or wind power (Hansen und Prescott 2002; Galor u. a. 2009; Kümmel 2011). Since then, exponential growth of economic activity has generated unprecedented amounts of material wealth.

Growth in per capita income and in population are the main drivers of the dramatic increase in greenhouse gas (GHG) emissions since the industrial revolution (Pachauri und Meyer 2014). Together with emissions from deforestation and other changes in the land-use intensity, carbon dioxide (CO_2) from fossil fuel combustion makes up most of anthropogenic GHG emissions (Stocker u. a. 2013b).

In the remainder of this subsection, I briefly describe the physical side of climate change, the impacts of climate change, climate change as an external effect in the economy, and the role of rents in the economics of climate change.

The physics of climate change

The concentration of CO_2 in the atmosphere has increased dramatically since the industrial revolution, and GHG concentration levels today are unprecedented in at least the last 800,000 years (Stocker u. a. 2013b). Atmospheric concentrations in the future are of course highly uncertain and crucially depend on the pathways of socio-economic and technological development. A commonly used set of possible future concentration scenarios are described by the Representative Concentrations Pathways (RCPs).

Emissions in the past, as well as future emission trajectories compatible with two of the RCP scenarios are shown in Fig. 1.1: Baseline scenarios, without emissions restrictions over those in place today, are expected to lead to emissions pathways along the RCP8.5 scenarios (Edenhofer u. a. 2014). Ambitious climate stabilization policy may achieve emission reductions along the RCP2.6 scenario, which requires a drastic cut, with net zero, or below zero emissions towards the end of the 21st century (Edenhofer u. a. 2014).

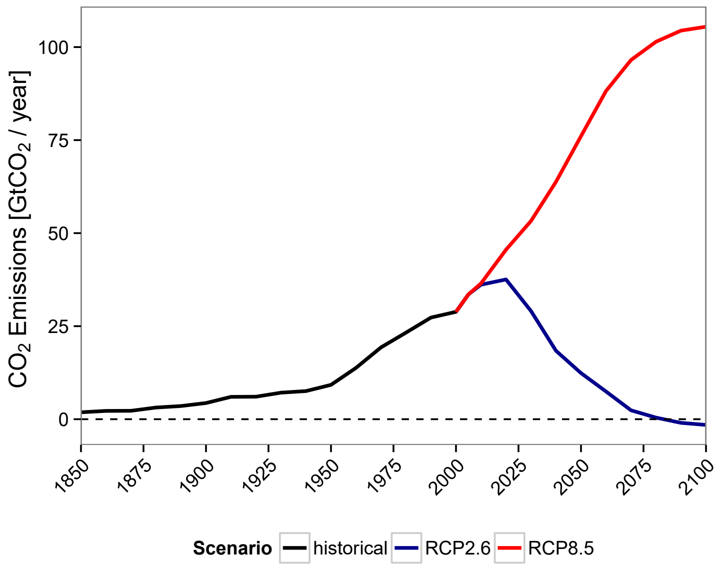


Abbildung 1.1: Global CO_2 emissions from fossil fuels and land-use change: Historical emissions, and emission scenarios for business-as-usual (RCP8.5), and ambitious climate mitigation (RCP2.6). Historical emissions, and exemplary emissions scenarios compatible with the RCPs generated by IAMs (van Vuuren u. a. 2011). Scenario and historical data accessed at IIASA RCP database (`http://tntcat.iiasa.ac.at/RcpDb`) (van Vuuren u. a. 2007; Riahi u. a. 2007; van der Werf u. a. 2006; Schultz u. a. 2008; Mieville u. a. 2010).

GHGs are active in the infrared part of the electromagnetic spectrum, and as the atmospheric temperature declines with altitude, this leads to a net positive radiative forcing (Stocker u. a. 2013b) – the greenhouse effect. The enhanced greenhouse effect is then the excess radiative forcing and temperature increase through the anthropogenic rise in GHGs concentrations – global warming.

Global mean surface temperature rise is the hallmark observation of climate change, having risen around 0.8°C above pre-industrial levels to date already (Stocker u. a. 2013b). Climate change is manifest in many other observations, for example ocean acidification, an increase in climate extremes, rising sea levels, changes in the cryosphere, the carbon cycle, and the water cycle (Stocker u. a. 2013b). Projections of the long-term temperature rise for the RCP scenarios are shown in Fig. 1.2: The RCP2.6 scenario stabilizes the global mean temperature increase above pre-industrial temperatures levels below 2°C with a high probability – I refer to this scenario as the 2°C scenario throughout this thesis[1]. Unmitigated climate change along the RCP8.5 scenario may lead to warming far beyond the around 4°C temperature increase projected for the year 2100, with a large uncertainty range (Stocker u. a. 2013b).

[1] More precisely, the RCP2.6 scenario has a probability >66% of staying below 2°C temperature until 2100 (Stocker u. a. 2013b). Scenarios compatible with RCP2.6 allow for mean cumulative emissions of 990 $GtCO_2$ from 2012 until 2100 (Stocker u. a. 2013b), and show GHGs concentrations of 430-480 ppm CO_2 equivalents in 2100 (Edenhofer u. a. 2014).

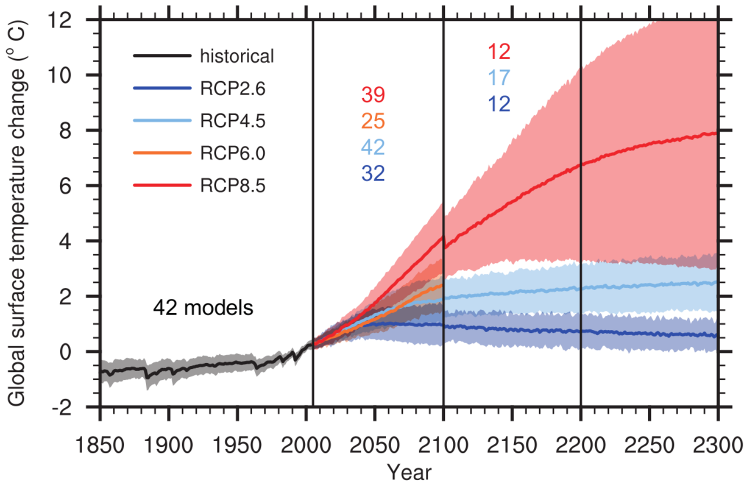


Abbildung 1.2: Global mean temperature change from 1850 to 2300. Historical data in black, colored lines are RCP scenarios. The temperature is the change with respect to the mean from 1986-2005, which is 0.61°C above the pre-industrial temperature. The numbers in the graph refer to the number of model runs, and are of no further concern here. Reproduced from Fig. TS.15 in Stocker u. a. (2013a).

Climate impacts

Climate change is threatening natural systems and human well-being in many different ways. The Fifth Assessment Report of the IPCC (AR5) highlights the risk from climate change in five "areas of concern", sorted by increasing risk with rising temperature (Fig. 1.3): Unique natural and cultural systems are endangered, extreme weather events increase, the distribution of climate risk is biased towards the poor, impacts matter even for the aggregate global economy, and large-scale singular events, such as tipping points in natural systems may be triggered (Field u. a. 2014).

A recent report published by the World Bank (World Bank 2013) emphasizes the impacts of climate change in major developing regions, and concludes that climate change is a serious threat to the eradication of poverty and economic development: Climate change negatively affects human health and productivity through heat extremes, endangers ecosystems, increases the pressure on water supplies, puts at risk agricultural yields and marine ecosystems, endangers food production, and threatens coastal areas by sea-level rise.

Knowledge about future climate damages and impacts is far from complete, such that another report published by the World Bank gives the dire warning: "...given that uncertainty remains about the full nature and scale of impacts, there is also no certainty that adaptation to a 4°C world is possible. A 4°C world is likely to be one in which communities, cities and countries would experience severe disruptions, damage, and dislocation, with many of these risks spread unequally" (World Bank 2012).

Climate change as an externality

The causes and effects of climate change are widely dispersed in location and time (Gardiner 2006). The global effect of emissions, and the long time over which emissions cause

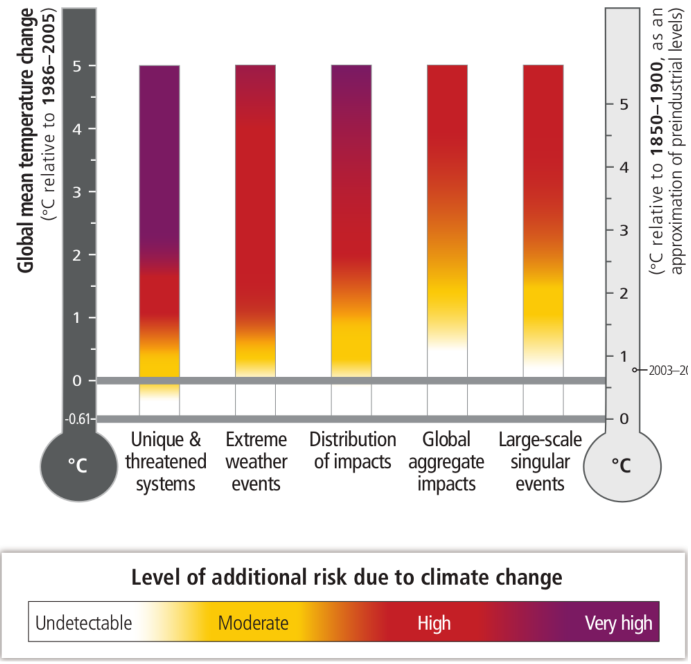


Abbildung 1.3: Risks associated with reasons for concern for climate impacts for varying level of temperature increase (relative to pre-industrial temperature on the scale on the right). Reproduced from Fig. SPM.1 from Field u. a. (2014).

damages require a global appraisal of climate change and climate policy over at least this century. Accordingly, there is a fragmentation of agency, that can be seen in two complimentary ways (Gardiner 2006): Between individuals alive today across the globe, and across time, between individuals alive at different times. Agency is fragmented across geography: As emissions cause damages around the globe, the costs of emissions in the form of climate damages are not fully borne by the individual benefiting from the GHG emitting process – an externality. It can thus be rational for individuals to emit more GHGs than it would be rational to emit collectively. There is also the fragmentation of agency across time: The climate damages from emissions by generations today mainly affect future generations, due to the long time lag between emissions and rising temperatures. From this perspective, GHG emissions can also be understood as an intergenerational externality.

Maintaining an intact climate system is a non-excludable and non-rivalrous benefit for all humans, and can be understood as an intergenerational and global public good (Sandler 1978; John und Pecchenino 1997). Averting the worst of climate change – by limiting the temperature increase to below 2°C – implies that there is only a finite budget of GHGs left that may be deposited in the atmosphere throughout the 21st century (Edenhofer u. a. 2014). The atmosphere as a finite disposal space for GHG emissions is thus a non-excludable, but rivalrous good (Paavola 2011; Ostrom 1990) – a global and intergenerational common good. Common goods are often overexploited, this is the so called 'tragedy of the commons' (Hardin 1968).

Governing the climate commons requires enforcing a scarcity in emissions throughout the 21st century. The public good nature of mitigation, and resulting incentives to free ride, are key in explaining the failure of the international community so far to establish an effective international agreement for climate stabilization in many studies (Barrett 1994; Finus 2008; Lessmann u. a. 2014).

Natural rents

Governing the common good of the climate is a huge challenge also because the monetary values at stake are so large: Establishing a scarcity of future emissions creates an economic rent (Cramton und Kerr 2002; Kalkuhl und Brecha 2013). This climate rent can be estimated using IAMs[2]: From own calculations based on the scenarios used in the AR5, I estimate the climate rent associated with the 2°C target to be above US$45 trillion – see Fig. 1.4.

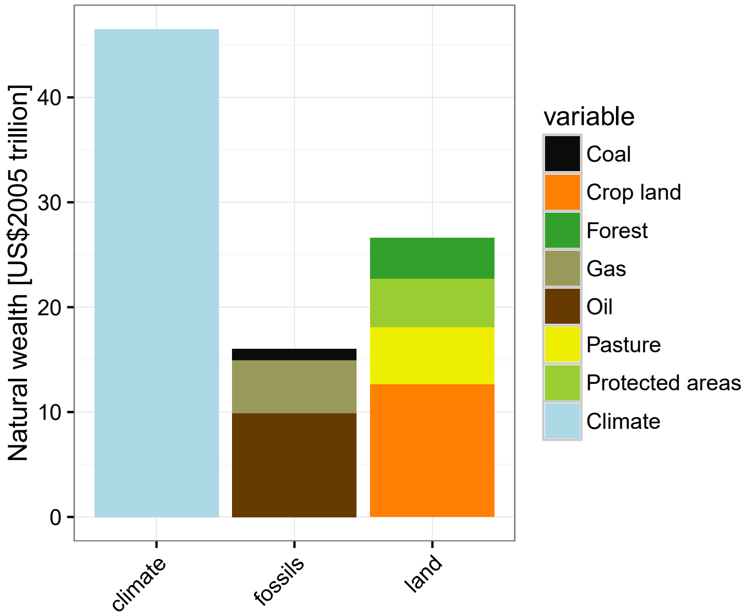


Abbildung 1.4: Natural wealth, calculated as the net present value of natural resource rents. The climate wealth is the fossil fuel CO_2 rent for 2°C scenarios, aggregated at 5% annual discount rate. I show the mean of the climate wealth numbers within the 25th to 75th percentiles for Climate Category 1 scenarios from the AR5 (Edenhofer u. a. 2014), calculated as the integral over CO_2 emissions times the carbon price. Numbers for all other rents are from World Bank (2010), and some aggregation by the author.

The climate rent is similar in value to other forms of natural wealth. Land and fossil fuel make up most of the non-climate natural wealth, which a report by the World Bank (World Bank 2010) estimates based on the net present value of annual resource rents[3] – see Fig. 1.4. Globally, natural wealth – excluding the climate rent – made up only 5% of total wealth in 2005. The largest amounts of wealth are intangible wealth, mostly in rich nations – but in low income countries, natural wealth was 30% of total wealth in 2005 (World Bank 2010).

[2] IAMs are described in detail in section 1.2

[3] Natural capital is included in other wealth accounting exercises lately (Hamilton und Hepburn 2014; Arrow u. a. 2012), and has been connected to the idea of sustainable development (Helm 2014; Hamilton und Hartwick 2014).

Climate damages and mitigation will impact wealth, and especially natural wealth, considerably: Impacts of climate change may particularly affect land rents, as I argue in a later section (1.6). Mitigation creates the climate rent, may eliminate the coal rent while somewhat lowering total fossil rents (Bauer u. a. 2013). Additionally, the demand for land-based mitigation options may drive up land rents (Hertel 2011).

What is special about rent income, as compared to other factor income? First of all, I define a rent as a payment to a factor above the opportunity costs of its owner[4]. Examples for rents are land rents, natural resource rents, monopoly rents, or rents created by public policy, be it environmental policy (Helm 2010), urban planning, or trade restrictions (Krueger 1974). Rent income is special for reasons of equity, and efficiency. First, the creation of new rents, for example from the introduction of climate policy, is a question of equity: Who should have the property rights in the factor that pays the rents?

Second, rents have efficiency effects: For the case of the climate rent, Fullerton und Metcalf (2001) argue that privately retained rents may exacerbate existing distortions in the labor market, and consequently reduce welfare. Beyond that, Krueger (1974) describes rent-seeking as the effort people invest in competing for rents created by government intervention. These efforts crowd out productive activities, rendering them wasteful on a societal level. Murphy u. a. (1993) and Krusell und Rios-Rull (1996) assert that rent-seeking reduces economic growth by discouraging innovative activities.

Rent-seeking behavior is part of the explanation for the resource curse, which is the finding that countries with high shares of primary exports in output show poor economic growth, especially when the quality of institutions is bad: "The political economy of massive resource rents combined with badly defined property rights, imperfect markets, and poorly functioning legal systems provide ideal opportunities for rent seeking behavior of producers, thus diverting resources away from more productive activities"(van der Ploeg 2011).

While rent curses are most relevant in developing countries, rents have efficiency effects in advanced economies too. In advanced economies a large share of wealth is in housing, and rising housing wealth explains most of the increase in the wealth-income ratio in the last decades brought to attention by Piketty und Zucman (2014). Knoll u. a. (2014) assert that the increase in housing wealth is mostly a result of rising land prices due to increasing scarcity of urban land. Stiglitz (2015a) holds that neoclassical theory fails to explain recent trends in the wealth-income ratio, the returns to capital, and inequality – because, among other reasons, rents are commonly disregarded in neoclassical economics. He argues that rents most importantly stem from positional goods, market power, intellectual property, and land. Land wealth is prone to price bubbles, and Stiglitz (2015d) claims that the current regulations of the financial system exacerbate the effect of land rents in the economy. Consequently, Stiglitz asserts that the inclusion of rents, and the modeling of heterogeneous savings behavior are crucial to explain trends in wealth, and wealth inequality (Stiglitz 2015a; Stiglitz 2015b; Stiglitz 2015c).

Taxes on land are often regarded as very effective: A tax on a fixed factor such as land would not change the supply in any factor, there would thus be no deadweight loss of

[4] This is not the only definition of a rent. For a thorough discussion of economic rents and rent taxation, see Dwyer (2014).

the tax – a tax on land should be neutral, and only have distributive, but no distortionary effects in the economy[5] (Dwyer 2014). Feldstein (1977), by contrast, demonstrates that if land is one among other assets in the portfolio of investors, taxes on land are not neutral, but distort capital accumulation[6], and affect the supply of other factors – a Portfolio effect. Along these lines, Petrucci (2006) shows that this distortion of capital accumulation may be beneficial if capital was previously underaccumulated. Edenhofer u. a. (2015) demonstrate that depending on the recycling schemes for revenue from land rent taxation the social optimum can be reached: savings can be redirected from buying land into productive capital investments, thereby increasing growth and welfare. Through a similar Portfolio effect, climate policy may indirectly tax scarcity rents of fossil resources, and redirect investments into productive capital, lowering the costs of climate policy (Siegmeier u. a. 2015b).

In this thesis, I model distortionary effects from rents in chapters LAND IMPACTS and FISCAL POLICY.

1.2 Welfare analysis of climate policy

In this section I introduce concepts and models commonly used in the welfare analysis of climate policy. After briefly introducing IAMs, I discuss the underlying concepts of cost-benefit and cost-effectiveness analysis, and the role of income distribution for climate policy. Furthermore, I elaborate on the choice of overlapping generations versus infinitely-lived agent models, and the notions of socially optimal and Pareto-improving climate policy.

Integrated Assessment Models

The costs and benefits of climate change mitigation, as well as climate policies with corresponding transformation pathways, are commonly evaluated or optimized in IAMs (Weyant u. a. 1996; Schneider 1997). Kelly und Kolstad (1999) define an IAM as a model "which combines scientific and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control". IAMs typically combine a stylized model of the climate system with a model of the macro economy, as well as representations of varying detail of the energy and land-use sector. IAMs have informed the debate on, and the implementation of climate policies for some decades now.

Cost-benefit and cost-effectiveness analysis

Two commonly used methods of policy optimization in IAMs are cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA). In CBA, the optimal mitigation target is found by weighing the costs of mitigating GHGs in terms of consumption foregone

[5] Dwyer (2014) and Stiglitz (2015d) both maintain that bubbles in the price of land make it imperative to tax land for efficiency reasons.

[6] Calvo u. a. (1979) notes that that whether a land rent tax is neutral crucially depends on the assumption on intergenerational altruism: For perfect altruism, the tax is neutral.

against the benefits from avoided climate damages (Arrow u. a. 1997; Pearce 2003). In CEA, on the other hand, only the costs of reaching an exogenous climate target, specified for example as a stabilization temperature or a concentration target, are computed. CEA models thus calculate the gross cost of climate policy, that is, the policy costs without considering the benefits from avoided climate impacts.

Quantifying the costs, but the benefits especially, is riddled with fundamental problems, and subject to troublesome value judgements: Fundamental problems are the inherent uncertainties in the climate and social systems, possible extreme outcomes of climate change, and impacts that are hard to express in monetary terms (Ackerman u. a. 2009; Weitzman 2009).

Beside the fundamental problems in specifying climate damages, the overly simple specification of climate damages is the main criticism of current IAMs used for CBA (Pindyck 2013): Climate damage functions are missing solid empirical foundations in many cases, and the economic impact of climate damages is usually specified in a simplistic way: as temporary reductions in final economic output only (Kopp u. a. 2012; Stern 2013).

There is evidence that climate damages rather decrease the growth rate, and not the level of output (Dell u. a. 2009; Dell u. a. 2012). Damages on the growth rates of output or total factor productivity have been shown to increase the economic impact of damages substantially (Moyer u. a. 2014; Burke u. a. 2015; Moore und Diaz 2015). Chapter LAND IMPACTS contributes to the literature on climate impacts by spelling out some macroeconomic impact channels of climate damages on the production factor land.

CEA analyses have risen to prominence in the light of the developments in international climate policy: The international community has pledged in the 2009 Copenhagen Accord under the United National Framework Convention on Climate Change (UNFCCC) to limit the temperature increase to below 2°C above pre-industrial level, in order to avoid "dangerous anthropogenic interference with the climate system" (UNFCCC Conference of the Parties 2009). In 2015, the Paris Agreement strengthened the commitment to limit the temperature increase to *well below* 2°C, and to pursue efforts to limit the increase to 1.5°C. Furthermore, the Paris Agreement noted with serious concern the gap between the emissions reductions by 2030 pledged by the nations under the UNFCCC, and cost-effective emissions pathways consistent with the 2°C target[7].

Income distribution in models of climate policy

Climate policy internalizes the climate change externality, and thus is fundamentally about the redistribution of income between individuals (Schelling 1995). Models of climate policy commonly aggregate individuals into income classes, countries or regions, generational cohorts, or even into a single global representative agent. Aggregation increases tractability, but may hide frictions and conflicts that come with the redistribution of income caused by climate impacts and climate policy – a recurring theme in this thesis.

[7] There is broad agreement in the literature as well that the pledges as of 2015 are far not be sufficient to reach climate stabilization below 2°C (UNEP 2012; Riahi u. a. 2013; Spencer u. a. 2015).

While regions or countries are commonly represented as distinct actors in IAMs, the heterogeneity of individuals in time is often not modeled explicitly: The core of many IAMs is the Ramsey growth model (Ramsey 1928), a model in which generations are aggregated into a single representative ILA under the assumption of perfect altruism for the succeeding generation. By contrast, overlapping generations (OLG) models contain distinct generations that are not perfectly altruistic. In the popular Diamond-Samuelson model (Samuelson 1958; Diamond 1965), generations face a finite and certain life-time, adjust savings during their life-cycle accordingly, and do not show altruism for future generations.

There are other types of OLG models: Similar to the Diamond-Samuelson model, there are models with a continuum of households with finite life-times (Schneider u. a. 2012), models in which generations are constantly born into the economy and either face a constant probability of death (Blanchard 1985), or live infinitely (Weil 1989). Weil (2008) notes that the common driving force for the many shared properties of these models is the constant arrival of newly born individuals into the economy, who were "not included in the economic calculus of pre-existing agents" (Weil 2008). OLG models have found widespread use in the analysis of intergenerational problems such as social security, public debt, education, but also environmental economics, development economics, and growth theory (Rangel 1993; John u. a. 1995; De La Croix und Michel 2002).

In OLG economies, the competitive market outcome is not necessarily Pareto-efficient, that is, the first welfare theorem does not hold (Weil 2008): There may be an overaccumulation of capital such that the economy is dynamically inefficient. Furthermore, while public debt is usually neutral in ILA models, it is not in OLGs. Public debt neutrality, also know as Ricardian equivalence, holds if households anticipate that public debt has to be refinanced by future tax increases (Seater 1993). Consequently, private savings exactly offset the effect of the increase in public debt on the growth path, which means that it does not matter whether a government finances public expenditures via tax hikes or public debt (Barro 1974; Michel u. a. 2006).

In some cases though, the first welfare theorem or the neutrality of public debt may hold in an OLG model: Homburg (2014b) argues that if land is included as an productive asset in the model, the resulting equilibrium is dynamically efficient as long as there is no confiscatory taxation of land rents (Homburg 1991; Rhee 1991; Homburg 2014b). The inclusion of land also implies the neutrality of public debt (Homburg 2014a).

ILA and OLG models can be seen as polar choices on intergenerational altruism: Barro (1974) shows that for perfect altruism between generations and an operational bequest motive, the distinct generations in a Diamond-Samuelson OLG can be aggregated into an ILA model (Barro 1974; Michel u. a. 2006). Empirical studies show, however, that intergenerational altruism is far from perfect (Laitner und Ohlsson 2001; Kopczuk und Lupton 2007; Jacquet u. a. 2013) – it is thus questionable whether ILA models can be used in appraisal of climate policy.

In ILA models, future consumption is traded off against present consumption at the social discount rate by the single representative agent in the model, who can be interpreted as the social planner of a centralized economy. In an ILA model, the social discount rate is determined by the Ramsey equation as the rate of pure time preference plus the product of the growth rate of consumption and the marginal consumption elasticity of utility

(Karp und Traeger 2013; Heijdra und van der Ploeg 2002). The social discount rate is most decisive in the determination of optimal climate policy using CBA (Weitzman 2007; Anthoff und Yohe 2009; Karp und Traeger 2013).

It is known that private savings decisions are motivated primarily by the desires to smooth consumption over the own life-cycle and to leave bequests to successive generations, but not by pure altruism (Gale und Scholz 1994; de Nardi 2004). OLG models necessarily model the distinction between such private decisions and preferences, and social preferences for intergenerational equity. Private decisions on life-cycle saving, bequest motives and possibly impure altruism of households can be modeled in detail. The utilities of individual generations may then be aggregated using some intergenerational social discount rate for the evaluation of socially optimal policies (Calvo und Obstfeld 1988; Schneider u. a. 2012).

Infinitely-lived agent or overlapping generations models for climate policy?

Schneider u. a. (2012) sum up the shortcomings of ILA models in appraisal of climate policy: First, calibrating ILA models using the so called 'positive' approach to match market interest rates does involve normative assumptions of little cogency, and consequently overestimates the social discount rate. This approach is often referred to as positive in the literature – I use quotes, as any approach on social discounting clearly involves value judgements (Dasgupta 2008; Sterner und Persson 2008). Second, ILA models do not capture the income distribution between individual generations, and hide an equity trade-off between present and future generations. The socially optimal solution found in an ILA model may not be implementable in an OLG economy, as it involves redistribution of income between generations, which may require age-specific fiscal policy instruments.

A prominent controversy in the climate economics literature revolved around social discounting: The studies by Nordhaus (Nordhaus 1993; Nordhaus 2008) and the Stern Report (Stern 2007) both use an ILA model, but arrive at optimal carbon taxes that differ by an order of magnitude. Nordhaus follows a 'positive' approach to social discounting: The rate of pure time preference of the ILA is adjusted for the social discount rate to match observed market interests rates (Nordhaus 1993; Nordhaus 2008). This is problematic for two reasons: First, because it wrongly attributes life-cycle savings behavior, which is not explicitly modeled in the ILA, to the resulting rate of pure time preference of the underlying generations (Schneider u. a. 2012). Further, comparing this ILA economy to an observationally equivalent OLG economy under a social planner reveals the implicit normative assumptions of the 'positive' approach, as the generational welfare weights of the social planner in the OLG economy are determined by a seemingly 'positive' approach. A second problem with the 'positive' method of social discounting in an ILA is that the individual decisions of market participants that are expressed in market interest rates may not reflect preferences on public good problems and market failures such as climate change (Karp und Traeger 2013; Stern 2013).

The Stern Report, on the other hand, is explicit on the normative assumptions on social discounting in the ILA model employed, and argues for a very low social discount rate based on intergenerational equity considerations (Stern 2007). Basing social discounting on equity considerations is endorsed by many others (Ramsey 1928; Schelling 1995; Broome 2010; Karp und Traeger 2013). The optimal carbon price resulting from a normative approach is usually higher than the one in 'positive' approaches: the carbon tax found by Stern (2007) is around ten times higher than the one found by Nordhaus. The social discount rate in the Stern Report is much below the average market rate, and closer to the risk free interest rate – which is the main point of criticism of the Stern Report, as some argue that the market rate should be used as the social discount rate in the evaluation of the costs and benefits of public projects, such as climate change mitigation (Nordhaus 2007). However, Weitzman (2007) clarifies that there is a large uncertainty in the social discount rate to be used for discounting. Furthermore, he suggests that climate impacts on non-market goods – which are not explicitly included in neither Stern's nor Nordhaus' model – should be evaluated at a discount rate lower than the market rate. Given these shortcomings, Weitzman (2007) concludes that "the nature of the impacts of climate change determine whether we should end up closer to using the risk-free rate or the economywide return on capital", and argues that "the risk free interest rate, which is close to the Stern interest rate, then may well end up being more right than wrong."(Weitzman 2007). Sterner und Persson (2008) emphasize the role of relative prices, and argue that climate impacts will increase prices of some goods significantly, effectively lowering the social discount rate, and warranting stringent climate policy. The use of OLG instead of ILA models may also shed light on this controversy, as private time preference and life-cycle saving are naturally separated from the social preferences on intergenerational equity.

Beyond the issue of social discounting, the implementation of climate policies in OLG economies is very sensitive to intergenerational distribution. After early calls for the use of OLG models in environmental economics (Howarth 1991; John u. a. 1995), some demonstrated that OLG and ILA models calibrated to the same growth path do result in very similar outcomes on optimal climate policy (Stephan und Mueller-Fuerstenberger 1997; Manne 1999). Furthermore, Stephan und Mueller-Fuerstenberger (1997) found that the implementation of climate policy is very sensitive to the redistribution of revenue from climate policy among the generations. Howarth (2000) notes that climate policy based on social preferences for intergenerational equity may require large transfers between generations currently alive, and if those age-specific transfers are not available, second-best climate policy differs significantly (Howarth 1998). All these intergenerational distributional conflicts are hidden in an ILA model, as there are no separate generations in the first place.

The modeling of intergenerational heterogeneity in an OLG can be complemented by heterogeneity *within* generational cohorts. Some literature include intragenerational heterogeneity in OLGs (Guruswamy Babu u. a. 1997; Rausch und Rutherford 2010), and chapter FISCAL POLICY differentiates households within one generation by their preferences for bequests.

Pareto-improving and socially optimal policy

It is useful to distinguish the notion of Pareto-improving climate policy from socially optimal climate policy: Pareto-improving climate policy raises the welfare of at least one generation over the business-as-usual (BAU) scenario, without reducing the welfare of any other generation. This concept is illustrated, and contrasted with socially optimal climate policy, in Fig. 1.5. This approach relies on the Pareto criterion, but not on judgements on intergenerational equity; the resulting climate policy is usually less stringent than socially optimal policy.

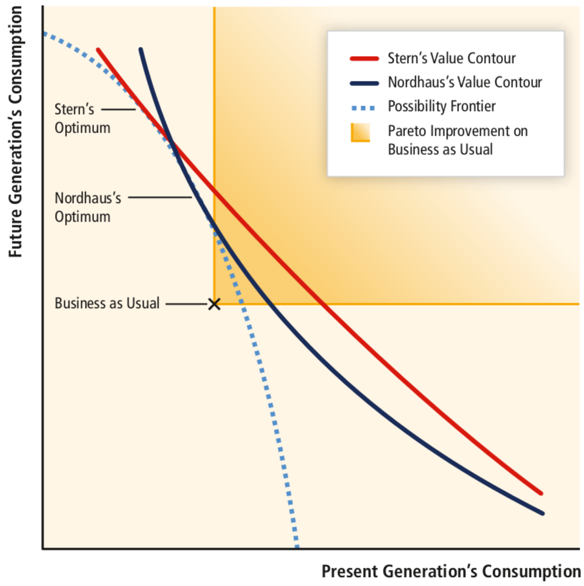


Abbildung 1.5: Socially optimal and Pareto-improving climate policy and the intertemporal production possibility frontier. Reproduced from Fig 3.2 of the WG3 part of the AR5 (Edenhofer u. a. 2014).

The idea behind Pareto-improving climate policy is: As climate change is an externality, the economy works inefficiently, and investing into mitigation brings the economy closer to the intertemporal production possibility frontier (Foley 2009; Rezai 2011). For this climate policy to be Pareto-improving, a mechanism is required to transfer some of the benefits from avoided damages accruing to future generations to present generations, who bear most of the costs of emission abatement. The concept of Pareto-improving climate policy is especially compelling in OLG models, as the welfare changes can be attributed to distinct generations, but the concept may also be useful in ILA models (Rezai u. a. 2012), if the ILA is understood as a succession of perfectly altruistic generations.

Siegmeier u. a. (2015a) review some of the intergenerational transfer mechanisms proposed in the literature: Bovenberg und Heijdra (2002) use public debt as an instrument to redistribute wealth, which is possible because the Ricardian equivalence does not hold in their OLG model (Michel u. a. 2006). Below u. a. (2014) show that a transfer scheme akin to pay-as-you-go pensions can support some Pareto-improving climate policy. Karp und Rezai (2014) argue that the price of a long-lived asset may provide a market-based transfer mechanism incentivizing some climate policy – a line of thought that chapter LAND IMPACTS builds on.

Chapters NASH REMIND, TECHNOLOGY POLICY, and MITIGATION IN SUB-SAHARAN AFRICA focus on the regional redistribution of income and technology diffusion through climate stabilization policies, and I use an ILA model for tractability. By contrast, chapters LAND IMPACTS and FISCAL POLICY revolve around the investment decisions of households under climate change policies, the distribution of wealth, and fiscal policy instruments, which is why OLG models are used.

1.3 Energy-Economy-Climate Models

In this section, I introduce a class of complex IAMs called Energy-Economy-Climate Models, and in particular, the Regional Model of Investments and Development (REMIND). In light of the climate stabilization target the international community committed to, IAMs of the CEA type with very detailed representations of the energy system have been developed: I refer to these models as EECMs, to distinguish them from simpler IAMs that lack a detailed energy system model.

EECMs sidestep the problem of valuating the benefits from avoided damages that CBA models have, as the climate target is set exogenously. Being CEAs, EECMs usually do not represent climate impacts at all (Edenhofer u. a. 2014). Consequently, while the avoided climate damages may be very similar between scenarios reaching a given climate target, differences in residual climate impacts between alternative mitigation pathways for the same climate target are not reflected in the resulting costs. Furthermore, differences in co-benefits for non-climate policy objectives between alternative mitigation pathways are not considered either, because other policy objectives are usually not included endogenously (von Stechow u. a. 2015).

In addition, the influence of social discounting on the outcome of a CEA is not as dramatic as in CBA, as the climate target itself is not influenced, and most of the costs of climate policy occur much earlier than the benefits from avoided damages (Ackerman u. a. 2009). In this light, it may be more defensible to use ILA models for CEA, as many EECMs do.

EECMs have widely been used to explore the feasibility of mitigation targets, as well as the technological, economic, and institutional requirements, and the costs of associated mitigation pathways (Clarke u. a. 2009; Kriegler u. a. 2013; Kriegler u. a. 2015). Specifically, the AR5 of the IPCC makes extensive use of EECMs, and establishes some key facts about mitigation pathways compatible with the 2°C target: Substantial cuts in GHG emissions to 40%-70% of their 2010 levels in 2050, and near zero or negative emissions near the end of the century are necessary, which require massive changes in the energy system and potentially the land-use system (Edenhofer u. a. 2014). Renewable energy deployment is scaled up drastically in most 2°C scenarios, and is a key mitigation technology alongside land-based mitigation options such as BECCS. Still, models indicate moderate aggregate gross policy costs (excluding benefits from avoided damages) for the 2°C target: The median annualized reduction in the growth rate of consumption until 2100 is 0.06 percentage points only (Edenhofer u. a. 2014). The AR5 also finds that current pledges are by far not sufficient to reach the 2°C target, and that delaying mitigation action will increase costs substantially.

The REMIND model

The Regional Model of Investments and Development (REMIND), an EECM, is used in three chapters of this thesis. In REMIND, the energy and climate system are integrated into an intertemporal general equilibrium growth framework (Leimbach u. a. 2010; Bauer u. a. 2012a); the model is described in full detail in Luderer u. a. (2015). It is a Ramsey-type growth model spanning the years from 2005 to 2100 where welfare is maximized in a social planner approach under perfect foresight. Inertia and path-dependencies in the energy system are represented by including more than 50 energy-conversion technologies as capital stocks, subject to adjustment costs. Energy prices reflect resource scarcities, final energy taxes, and potentially, GHG pricing.

Greenhouse gas emissions from the energy system and land-use system are translated into radiative forcing and global mean temperature changes using the MAGICC6 climate model (Meinshausen u. a. 2011). Emissions from land-use and agriculture, as well as bioenergy supply and other land-based mitigation options are represented via reduced-form emulators derived from the detailed land-use and agricultural model MAgPIE (Klein u. a. 2014). Climate targets can be specified by their radiative forcing levels, GHG concentrations, or emissions budgets, and implemented through GHG pricing by taxation or cap and trade. The world is divided into eleven regions that are connected by trade in five primary energy resources, a generic final good, and carbon permits.

As most intertemporally optimizing EECM, REMIND uses a global joint-welfare maximization algorithm to solve for trade between regions, following the Negishi approach (Negishi 1960). In the absence of non-internalized externalities between regions, the Negishi solution is equal to the competitive equilibrium in trade between regions. However, climate change itself is an inter-regional externality, and in technological change (Weyant und Olavson 1999; Jaffe u. a. 2005) spillover externalities are common as well.

In the presence of interregional externalities, model regions can behave cooperatively or non-cooperatively with respect to externalities. In a Negishi solution algorithm, all inter-regional externalities are implicitly internalized – which corresponds to a cooperative solution concept. However, non-cooperative behavior with respect to interregional externalities is common in international relations, and modeling it requires a different solution concept. Nordhaus und Yang (1996), for example, implement a non-cooperative solution concept with respect to the climate problem using a Nash algorithm. Bosetti u. a. (2008) compute the non-cooperative solution in a more complex IAM. The solution algorithms, however, are not well described in the literature, and the trade structure in REMIND is complex, including capital trade and current accounts. The methodological contribution of chapter NASH REMIND is a decentralized solution algorithm of the REMIND model, dubbed Nash algorithm, which allows for the meaningful inclusion of interregional externalities.

Objective of chapter NASH REMIND

Global IAMs rely on algorithms for solving trade interactions between regions that are not well described in the literature. This chapter is a methodological contribution to the literature on solution algorithms and solution concepts for complex global IAMs.

I describe two solution algorithms of the REMIND model in detail, the well known joint-welfare-maximizing Negishi approach, and a newly developed decentralized Nash approach. The Nash algorithm is computationally much more effective, allows for the parallelization of the regional optimization problems, and reduces the solution time by an order of magnitude over the Negishi algorithm. Additionally, the Nash algorithm scales favorably with the number of regions in the problem, and allows for the meaningful inclusion of externalities between regions. I demonstrate that in the presence of global technology spillovers, the Nash algorithm corresponds to the non-cooperative solution concept, while the Negishi algorithm gives the cooperative solution.

This chapter lays the foundation for chapter TECHNOLOGY POLICY on optimal technology policy, where I extend the Nash solution algorithm of REMIND to internalize a global technology spillover, reproducing the cooperative solution.

1.4 Technology policy

Many of the real world imperfections and market failures are not taken into account by current EECMs (Staub-Kaminski u. a. 2014), which may lead to a flawed appraisal of the cost and the effectiveness of climate policies. While the technological detail of these models is high, the representation of fiscal policy, pre-existing distortions, and distribution of income is much less detailed (Siegmeier u. a. 2015a).

Some of the additional market failures most relevant to climate policy are arguably in the development and deployment of emerging energy technologies (Jaffe u. a. 2005): Firms are unable to appropriate the full benefits of their investments in technological innovation. The appropriation failure is usually described as an external effect in the mechanism of endogenous technological change, research and development (R&D) and learning-by-doing (LbD): R&D describes the deliberate search for new knowledge that may then be employed in production processes. By contrast, LbD describes the generation of new knowledge as a byproduct of conventional economic activity (Romer 2001), also called experience effects (Arrow 1962). In both cases, other firms, sectors, or countries can often benefit from the newly available knowledge at little or no cost – knowledge is a public good to some degree. As a result, there is an underinvestment into R&D and learning technologies, and accordingly a social rate of return above the private rate of return: There is evidence for large social returns on R&D across many sectors

(Jaffe 1986), and for LbD in energy technologies (Zimmerman 1982; McDonald und Schrattenholzer 2001; Bollinger und Gillingham 2014).

The attribution of price reductions in emerging technologies to either R&D or LbD is difficult, and mixed forms such as two-factor learning curves exist (Jamasb 2007; Witajewski-Baltvilks u. a. 2015). Some argue though that the dynamics of LbD are similar to R&D under a finite patent lifetime (Gerlagh u. a. 2009).

Both of these mechanisms for induced technological change, R&D and LbD, have been included in IAMs (Goulder und Mathai 2000; Sijm 2004; Rosendahl 2004), and were shown to have a substantial effect on the cost of climate policy. Climate policy thus needs to take market failures in technological change into account; many argue that optimal climate policy should include technology policy in the form of some kind of support for emerging energy technologies or R&D activity as a complement to carbon pricing (Jaffe u. a. 2005; Gerlagh u. a. 2009). Optimal technology policy for LbD externalities has been described in stylized models (Fischer und Newell 2008), or IAMs (Kverndokk und Rosendahl 2007; Kalkuhl u. a. 2012): Optimal policy mandates subsidies to emerging energy technologies that decline quickly after the widespread adoption. Andor und Voss (2014) show that for externalities associated with the capacity of the respective technology, investment cost subsidies are the first-best response.

The literature does not agree on the relative importance of subsidies for renewable energy and carbon pricing in climate stabilization: In the model of Acemoglu u. a. (2012), temporary policy interventions, including subsidies, are very effective in redirecting investment towards clean technologies, and pushing the economy on a clean development path[8]. However, most other studies conclude that subsidies are much less important than carbon pricing in climate stabilization, and that subsidies have a sizable, but not a dramatic effect on the effectiveness of climate policy (Van Der Zwaan u. a. 2002; Popp 2006; Kverndokk und Rosendahl 2007; Kalkuhl u. a. 2012; Rezai und van der Ploeg 2014). These models, however, include very few stylized energy technologies only, and the results are strongly driven by the assumptions on available technologies.

Appraisal of technology policy for climate stabilization thus crucially depends on modeling detail in energy technologies, making EECMs the models of choice. Induced technological change is represented in various forms in EECMs (Edenhofer u. a. 2006), but studies so far relied on exogenously specified technology policies instead of calculating optimal policies: Rao u. a. (2006) emphasizes the need for coordinated policy that takes spillovers into account. Kypreos und Turton (2011) exogenously specify some technology-specific transfer protocols to finance investments into learning energy technologies in developing countries, and find moderate cost reductions on a global level compared to a policy relying on carbon pricing only. Bauer u. a. (2012b), Marcucci und Turton (2013), and Bertram u. a. (2015) find that increases in near-term renewable energy deployment can reduce the cost increase resulting from delayed carbon pricing – but again, do not calculate *optimal* technology policies.

Knowing the optimal subsidies for low-carbon energy technologies is relevant to the design of climate policy. While there is agreement that carbon pricing is the single most

[8] Mattauch u. a. (2015) clarify the role of the elasticity of substitution between dirty and clean technologies and infrastructure for path dependencies and the effectiveness of policy intervention.

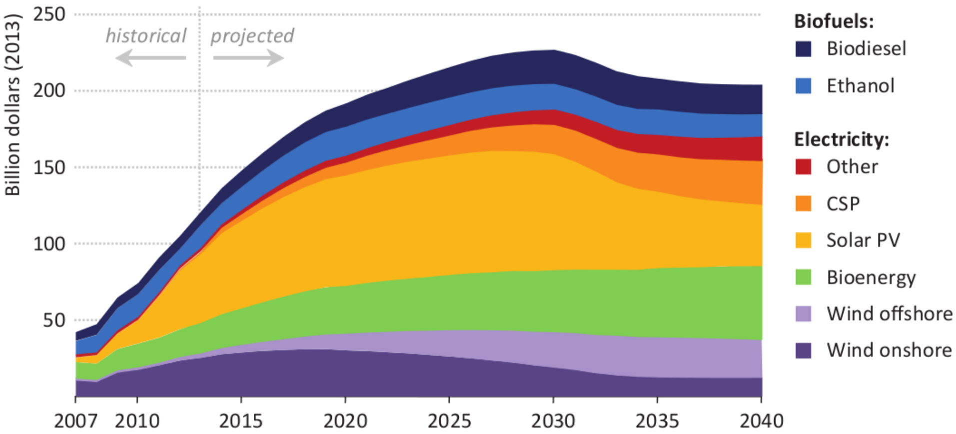


Abbildung 1.6: Global renewable energy subsidies by technology, including projections according to the IEA's 'New Policies Scenario'. Source: World Energy Outlook 2014, Copyright: (International Energy Agency 2014); license: `https://www.iea.org/t&c/termsandconditions/`

important element of climate stabilization policy (Aldy u. a. 2010; Edenhofer u. a. 2014), only 12% of global GHG emissions in 2014 were priced (World Bank 2015a). On the other hand, policies supporting renewable energy had been enacted in 138 countries (International Energy Agency 2014), including subsidies of more than US$100 billion globally – much more than the value of priced carbon of US$50 billion in 2014 (World Bank 2015a). Renewable energy subsidies have risen sharply in the last decade, and are projected to increase further (Fig. 1.6). I set out to understand whether these subsidies may in part be justified by spillovers from global learning, and what optimal subsidies for climate stabilization look like.

Objective of chapter TECHNOLOGY POLICY

It is commonly accepted that carbon pricing is the most important element of effective climate stabilization policy, and that complementary technology subsidies can be used to target market failures in technology development and deployment. However, it is not clear what the optimal extent of technology subsidies for climate stabilization is, and which technologies should be supported the most.

Chapter TECHNOLOGY POLICY is the first study to calculate optimal cooperative technology policy for the 2°C target in a technology rich EECM. I include a spillover externality from global LbD in emerging low-carbon technologies in REMIND, and extend the Nash algorithm developed in NASH REMIND by the optimal policy instruments for the cooperative internalization of the spillover. Optimal international climate policy for the 2°C target mandates technology subsidies alongside carbon pricing of around 6% of the value of priced carbon – a cumulative value of more than US$ 1 trillion from 2020 until 2100. Most of the subsidies support solar technologies, and advanced car technologies that accelerate the decarbonization of the transport sector. Climate stabilization relying exclusively on carbon pricing policies increases the welfare costs only very little above the optimal policy cost, confirming the paramount importance of carbon pricing. The cost increase due to a delay in full carbon pricing can only be reduced somewhat by stepping up subsidies in the near term.

1.5 Climate policy for least-developed countries

Technology policy as part of international climate policy is particularly relevant for the least-developed countries today, as they may profit from increasing access to new technologies (Collier u. a. 2008). As least-developed countries face enormous tasks in alleviating poverty and fostering economic growth, stringent mitigation action is particularly challenging for those countries (Tavoni u. a. 2014). The AR5 notes that the literature on the distributional consequences of climate policy for least-developed countries from an Integrated Assessment Model of Climate Change perspective is weak (Edenhofer u. a. 2014). Chapter MITIGATION IN SUB-SAHARAN AFRICA spells out the growth effects and distributional consequences of a climate stabilization agreement for one of the poorest regions, Sub-Saharan Africa[9], from the perspective of an EECM.

Energy demand is projected to grow rapidly in Africa in the coming decades (Calvin u. a. 2013), especially in Sub-Saharan Africa (Lucas u. a. 2015) – which will increase GHG emissions drastically if, in the absence of stringent climate policy, the energy is supplied mostly by fossil fuels (Lucas u. a. 2015). For the countries in Sub-Saharan Africa, entering a cooperative climate stabilization agreement would deny them a carbon-intensive development path, and may endanger their economic growth prospects. There are also concerns about the potentially regressive effect of climate policies in developing countries (Jakob und Steckel 2014). On the other hand, Africa in aggregate has great renewable energy potential, and most African countries do not yet suffer from a lock-in into carbon-intensive infrastructure[10] (Collier und Venables 2012) – which could be a factor driving down the costs of climate policy in African countries.

Furthermore, burden sharing schemes based on historical responsibility or equity concerns imply allocating most of the emissions permits under a climate stabilization agreement to developing countries (Edenhofer u. a. 2014). The proceedings from sale of excess permits on international carbon markets may provide a significant source of revenue for developing countries (Jakob u. a. 2015), and form an incentive to join climate stabilization

[9] In the REMIND model, the region Sub-Saharan Africa includes all nations on the African continent except Algeria, Egypt, Libya, Morocco, South Africa, Tunisia, and Western Sahara.

[10] Many African countries are increasingly at risk of locking into a carbon-based energy system, driven by low coal prices (Steckel u. a. 2015).

regimes.

Objective of chapter MITIGATION IN SUB-SAHARAN AFRICA

This contribution quantifies the non-environmental incentives for Sub-Saharan Africa as an aggregate region to join climate stabilization regimes. Using the EECM REMIND, I account for fossil fuel prices reflecting scarcities and resource trade, international technology diffusion, possible lock-ins in the energy sector, detailed renewable energy potentials, and the distributional implications of burden sharing schemes in climate agreements. I use the methodology described in NASH REMIND to describe spillover effects in emerging low-carbon technologies in scenarios with immediate or delayed cooperation.

Sub-Saharan Africa faces significant gross costs in a cooperative climate and technology policy regime, mainly due to a reduction in economic growth, and increasing investment costs in the energy system. These gross costs are partly offset by increasing revenue from the export of biomass and carbon permits. Under some equity-based allocation of carbon permits, the net costs of climate policy may even be negative. Delayed cooperation on carbon pricing in combination with no international technology policy decreases the policy costs for Sub-Saharan Africa against the global trend of strongly increasing policy costs. Furthermore, the energy system undergoes a massive transformation, and requires significantly higher investment flows. Revenue from the sale of biomass on international markets is a significant factor in reducing the costs of climate policy, but may put additional pressure on the land use system. Finally, the poorest income groups often excessively rely on liquid fuels, which may result in climate policy being regressive. Liquid fuel prices increase strongly through climate policy, but electricity prices do not.

1.6 Land and climate change

In this section, I discuss the special role of land for the economics of climate change in two subsections on the role of land in mitigation, and in the impacts of climate change.

The role of land in mitigation

Land-based mitigation options are of crucial importance for climate stabilization. The Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC 2012) estimates the technical potential of biomass supply in the year 2050 at 50-500 EJ yr^{-1}, and finds that bioenergy is the most used renewable primary energy source in scenarios compatible with the 2°C target. Specifically, most of the potential bioenergy potential is in dedicated crop production on agricultural land (IPCC 2012; Creutzig u. a. 2015).

Bioenergy, especially in combination with carbon capture and storage, is of high value for reaching low climate stabilization targets, such as the 2°C target, mainly because of its potential in providing negative emissions (Klein u. a. 2014). Mitigation costs increase strongly if the availability of bioenergy if limited (Edenhofer u. a. 2014), making it likely that bioenergy will be used to some extent. The land requirements for bioenergy with carbon capture and storage are significant in scenarios compatible with the 2°C target: Smith u. a. (2015) estimate the required area for biomass production in 2100 at 7-25% of today's agricultural land, and point to the water requirements of bioenergy crops as well. The required area for the alternative land-based mitigation strategy of afforestation are on a similar scale.

The AR5 indicates that the vast majority of bioenergy production is projected to occur in developing and transitional economies (Edenhofer u. a. 2014). There are positive and negative consequences of large-scale biomass production: Creutzig u. a. (2015) give an overview, and note that "For any bioenergy system to deliver net climate benefits with few negative environmental or socio-economic impacts, will require attention to a range of factors that influence land-use change related GHG emissions and biogeophysical perturbations; displacement of other land and water uses; other livelihood aspects such as employment, land access and social assets; and biodiversity"(Creutzig u. a. 2015).

By contrast, IAMs and EECMs rely on rather simple representation of biomass production and deployment that is very close to first-best conditions: detrimental effects of biomass use are often excluded by construction, and non-market subsistence farming or non-market environmental goods are ignored (Creutzig u. a. 2012). On top of the aforementioned detrimental effects, rising food prices and land rents in developing countries are adverse side-effects expected from biomass deployment that are not adequately reflected in current EECMs.

The analysis in chapter MITIGATION IN SUB-SAHARAN AFRICA finds significant non-environmental benefits of climate stabilization policy for Sub-Saharan Africa from increased revenues from exports of biomass, and possibly emission permits. These export revenues are up to 10% of cumulative discounted consumption over the 21st century, and are thus decisive for the net costs of climate policy in Sub-Saharan Africa. This implies a sizable transformation in the economic structure towards more dependence on resource and permit exports. In the light of the aforementioned effects of large-scale biomass production, one may doubt that the revenue from biomass exports will translate into welfare improvements without large losses.

In fact, while increasing resource exports may be a huge economic opportunity, developing economies often fail to translate revenue from primary exports into lasting economic growth – a phenomenon known as the resource curse: "The best available empirical evidence suggests that countries with a large share of primary exports in GNP have bad growth records and high inequality, especially if quality of institutions, rule of law, and corruption are bad"(van der Ploeg 2011). Specifically, the most important mechanisms behind the resource curse are increased exposure to volatile resource prices, intensified rent-grabbing and detrimental effects on institutions and policy making.

In effect, many countries fail to fully reinvest their natural resource wealth into reproducible assets that are decisive for long term prosperity (van der Ploeg 2011). While the literature on the resource curse identifies high value point resources such as minerals as particularly detrimental, it is plausible that increasing land rents may as well distort the economy. One example is costly rent-seeking in political economy models (Hvid 2015).

The role of land in impacts

Climate impacts also increase the pressure on the land use system. Agricultural land is particularly prone to climate damages: the impacts of climate change on crop yields were significant in the last decades already (Lobell u. a. 2011). Impacts are highly dependent on the region, but negative impacts on crop yields are expected to outweigh the positive impacts globally in the long term (Pachauri und Meyer 2014), and are concentrated in the developing regions (Rosenzweig u. a. 2013; World Bank 2013).

The microeconomic literature on distortionary effects of increasing land rents, similar to resource curses, is weak. Consequently, I use a generic so called Portfolio effect to model the efficiency impacts of changes in land rents in an IAM in Land Impacts. The Portfolio effect here describes how the increase in land rents makes owning land more profitable than investing into productive capital, consequently affecting the relative price of land and capital, and capital accumulation.

Current EECM do not capture this effect: State of the art EECMs have been coupled to spatially explicit land-use models with high biophysical detail. This coupling typically includes bioenergy demand and prices, GHG prices, and emissions from land use and land use change (Klein 2014). These coupled models, however, are not general equilibrium models (Klein 2014); there are no explicit markets in these models for the stock of land, and thus no competition between land and capital assets for households' savings.

Objective of chapter Land Impacts

I claim that current IAMs and EECMs do not capture the full impacts of land-biased climate damages on investment, economic growth, and the incentives for mitigation. To clarify the economic impacts of land-biased damage, I use a simple IAM based on an OLG structure, and include land and capital as separate assets.

I find two impact channels of land-biased climate damages that go unobserved in the previous literature: First, future land-biased climate damages may raise land rents, and consequently the price of land today. The higher price of land reduces investments into productive capital formation, and consequently increases the impact of land-biased damages on economic growth. Second, confirming previous results for aggregate damage specifications, there is some room for Pareto-improving climate policy, as avoided damages on factor returns in the near future provide some incentive to mitigate. However, as avoiding future damages would also decrease future scarcity rents and today's price of land, the incentive for climate policy decreases when damages are biased towards land. In effect, land-biased damages reduce the incentive for climate policy, and may lead to climate policy further away from the social optimum – aggravating the intergenerational conflict that climate change is.

This chapter is a step towards understanding the macroeconomic impacts of climate damages, and focuses on the mechanisms, not on a quantitative appraisal. Our results underline the importance of disaggregating climate damages in cost-benefit analyses of climate change.

1.7 Inequality and fiscal policy

Chapter FISCAL POLICY analyzes fiscal policy instruments targeting wealth inequality in rich countries. This contribution does not include climate change, but is still in the light of it: Inequality matters for climate change first and foremost from an intergenerational perspective, as climate damages are an externality imposed on future generations. Additionally, inequality among people alive at the same time matters, as climate damages are expected to hit the poor hardest, while most historic GHGs were emitted by today's developed countries (Pachauri und Meyer 2014).

Climate change mitigation may well be significant for fiscal policy: The climate rent implied by the 2°C target is estimated by Bauer u. a. (2013) to around 2% of cumulative Gross Domestic Product (GDP) over the 21st century. Depending on the instrument choice, some share of the climate rent may be appropriated by governments (Fullerton und Metcalf 2001). As governments currently levy taxes of 14% of GDP on world average (World Bank 2015b), climate policy is thus potentially significant for fiscal policy. Siegmeier u. a. (2015a) provide an overview on climate policy in the light of public finance, and review and classify interactions of climate and fiscal policy.

Wealth inequality is a concern in many rich countries today, and has been on the rise in the last decades in some countries, for example in the United States (Saez und Zucman 2015). Some authors recommend capital taxation to reduce inequality (Benhabib u. a.

2011) – but capital taxes are inefficient, as they depress productive investments (Judd 1985; Chamley 1986).

Another trend in the last decades are rising wealth-income ratios in most rich countries, as highlighted by the work of Piketty und Zucman (2014), who connect rising wealth-income ratios to increases in wealth inequality. Consequently, the taxation of capital as a remedy for high inequality is brought forward by Piketty (2014)[11]. Even though the work of Piketty und Zucman shows that housing prices are the major driver for the rising wealth-income ratio, they do not consider the composition of wealth as crucial in explaining the rising wealth-income ratio, or the rising wealth inequality (Piketty und Zucman 2014; Piketty 2014). Others disagree, and maintain that differentiating capital and housing as different forms of wealth is pivotal in understanding wealth accumulation (Bonnet u. a. 2014; Rognlie 2015). Knoll u. a. (2014) find that rising land rents are the main driver for housing prices, and similarly, Homburg (2015) attributes the increase in the wealth-to-income ratio to the rising value of land.

Stiglitz (2015a) argues that rents from fixed factors – such as land – are crucial in explaining trends in wealth and wealth inequality. The analysis of Stiglitz (2015a), however, is based on a very stylized class model of heterogeneity, distinguishing workers and capitalists only. In chapter FISCAL POLICY, households are differentiated by heterogeneity in their preferences for bequests, as bequests are a key driver of wealth inequality (Cagetti und De Nardi 2008). This chapter combines a more detailed model of the heterogeneity in the savings motives of households, and distinguishes capital and land as distinct assets.

Objective of chapter FISCAL POLICY

High wealth inequality is a concern in many rich countries, but research on fiscal policy options to reduce wealth inequality is inconclusive.

This chapter relies on a general equilibrium OLG model with heterogeneous preferences, differentiates wealth into land and capital wealth, and disentangles the life-cycle saving from the bequest motive. The effects of three different wealth taxes is very different: Taxing land rents increases investment into capital and output through a Portfolio effect, and reduces inequality slightly. By contrast, a tax on bequests reduces inequality strongly with only moderate reductions in output. Lastly, taxing capital returns decreases output strongly – confirming this standard result – with only moderate decreases in inequality. Furthermore, tax revenue recycling is not neutral, and revenue recycling biased towards the young generation increases efficiency and equality. In summary, this study implies that a through a tax reform,

[11] Piketty uses the term capital synonymously with wealth.

governments have considerable freedom to reduce inequality without sacrificing economic output.

This last contribution on fiscal policy is followed by Chapter 7, which concludes this thesis. In the concluding chapter I summarize the main results and point to gaps and limitations. Furthermore, I attempt to evaluate one of the main propositions of this thesis, that is, the importance of distributional conflicts due to climate change, and their representation in IAMs.

Literatur

Acemoglu, D (2009). *Introduction To Modern Economic Growth*. Princeton University Press.

Acemoglu, D., P. Aghion und D. Hemous (2012). "The environment and directed technical change". *American Economic Review* 102.1, S. 131–166. DOI: 10.1093/oxrep/gru031.

Ackerman, F., S. J. DeCanio, R. B. Howarth und K. Sheeran (2009). "Limitations of integrated assessment models of climate change". *Climatic Change* 95.3-4, S. 297–315. DOI: 10.1007/s10584-009-9570-x.

Aldy, J. E., A. J. Krupnick, R. G. Newell, I. W. H. Parry und W. A. Pizer (2010). "Designing Climate Mitigation Policy". *Journal of Economic Literature* 48.4, S. 903–934.

Andor, M. und A. Voss (2014). "Optimal Renewable Energy Subsidies". *Ruhr Economic Papers* 473. DOI: 10.4419/86788533.

Anthoff, D. und G. W. Yohe (2009). "Discounting for Climate Change". *Economics* 3.24.

Arrow, K. J. (1962). "The Economic Learning Implications of by Doing". *Review of Economic Studies* 29.3, S. 155–173.

Arrow, K. J., M. L. Cropper, G. C. Eads, R. W. Hahn, L. B. Lave, R. G. Noll, P. R. Portney, M. Russell, R. Schmalensee, V. K. Smith und R. N. Stavins (1997). "Is there a role for benefit-cost analysis in environmental, health, and safety regulation?" *Environment and Development Economics* 2.2, S1355770X97220164. DOI: 10.1017/S1355770X97220164.

Arrow, K. J., P. Dasgupta, L. H. Goulder, K. J. Mumford und K. Oleson (2012). "Sustainability and the measurement of wealth". *Environment and Development Economics* 17.03, S. 315–316. DOI: 10.1017/S1355770X12000186.

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

Barro, R. J. (1974). "Are Government Bonds Net Wealth?" *Journal of Political Economy* 82.6, S. 1095. DOI: 10.1086/260266.

Bauer, N., R. J. Brecha und G. Luderer (2012a). "Economics of nuclear power and climate change mitigation policies". *Proceedings of the National Academy of Sciences* 109, S. 16805–16810. DOI: 10.1073/pnas.1201264109.

Bauer, N., L. Baumstark und M. Leimbach (2012b). "The REMIND-R model: The role of renewables in the low-carbon transformation-first-best vs. second-best worlds". *Climatic Change* 114.1, S. 145–168. DOI: 10.1007/s10584-011-0129-2.

Bauer, N., I. Mouratiadou, G. Luderer, L. Baumstark, R. J. Brecha, O. Edenhofer und E. Kriegler (2013). "Global fossil energy markets and climate change mitigation - an analysis with REMIND". *Climatic Change*. DOI: 10.1007/s10584-013-0901-6.

Below, D. V., F. Dennig und N. Jaakkola (2014). "The climate debt deal: an intergenerational bargain". *mimeo*.

Benhabib, J., A. Bisi und S. Zhu (2011). "The Distribution of Wealth and Fiscal Policy in Economies With Finitely Lived Agents". *Econometrica* 79.1, S. 123–157. DOI: 10.3982/ECTA8416.

Bertram, C., G. Luderer, R. C. Pietzcker, E. Schmid und E. Kriegler (2015). "Complementing carbon prices with technology policies to keep climate targets within reach". *Nature Climate Change* 5, S. 235–239. DOI: 10.1038/NCLIMATE2514.

Blanchard, O. J. (1985). "Debt, Deficits, and Finite Horizons". *The Journal of Political Economy* 93.2, S. 223–247.

Bollinger, B. und K. Gillingham (2014). "Learning-by-Doing in Solar Photovoltaic Installations". *SSRN Electronic Journal* 2342406.

Bonnet, O., P.-h. Bono, G. Chapelle und E. Wasmer (2014). "Does housing capital contribute to inequality? A comment on Thomas Piketty's Capital in the 21st Century". *Sciences Po Economics Discussion Papers*.

Bosetti, V., C. Carraro, E. Massetti und M. Tavoni (2008). "International energy R\&D spillovers and the economics of greenhouse gas atmospheric stabilization". *Energy Economics* 30.6, S. 2912–2929. DOI: 10.1016/j.eneco.2008.04.008.

Bovenberg, A. L. und B. J. Heijdra (2002). "Environmental Abatement and Intergenerational Distribution". *Environmental and Resource Economics* 23, S. 45–84.

Broome, J. (2010). "The most important thing about climate change". *Public Policy: Why Ethics Matters*. Hrsg. von J. Boston, A. Bradstock und D. Eng. Canberra: ANU E Press. Kap. 6, S. 101–116.

Burke, M., S. M. Hsiang und E. Miguel (2015). "Global non-linear effect of temperature on economic production". *Nature* 527, S. 235–239. DOI: 10.1038/nature15725.

Cagetti, M. und M. De Nardi (2008). "Wealth inequality: data and models". *Macroeconomic Dynamics* 12.Supplement S2, S. 285–313. DOI: 10.1017/S1365100507070150.

Calvin, K., S. Pachauri, E. De Cian und I. Mouratiadou (2013). "The effect of African growth on future global energy, emissions, and regional development". *Climatic Change* Cmcc, S. 1–17. DOI: 10.1007/s10584-013-0964-4.

Calvo, G. A. und M. Obstfeld (1988). "Optimal Time-Consistent Fiscal Policy with Finite Lifetimes". *Econometrica* 56.2, S. 411–432.

Calvo, G. A., L. J. Kotlikoff und C. A. Rodriguez (1979). "The Incidence of a Tax on Pure Rent: A New (?) Reason for an Old Answer". *Journal of Political Economy* 87.4, S. 869. DOI: 10.1086/260798.

Chamley, C. (1986). "Optimal Taxation of Capital Income in General Equilibrium with Infinite Lives". *Econometrica* 54.3, S. 607–622. DOI: 10.2307/1911310.

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose und M. Tavoni (2009). "International climate policy architectures: Overview of the EMF 22 International Scenarios". *Energy Economics* 31.SUPPL. 2, S64–S81. DOI: 10.1016/j.eneco.2009.10.013.

Collier, P., G. Conway und T. Venables (2008). "Climate change and Africa". *Oxford Review of Economic Policy* 24.2, S. 337–353. DOI: 10.1093/oxrep/grn019.

Collier, P. und A. J. Venables (2012). "Greening Africa? Technologies, endowments and the latecomer effect". *Energy Economics* 34, S75–S84. DOI: 10.1016/j.eneco.2012.08.035.

Cramton, P. und S. Kerr (2002). "Tradeable carbon permit auctions". *Energy Policy* 30.4, S. 333–345. DOI: 10.1016/S0301-4215(01)00100-8.

Creutzig, F., A. Popp, R. Plevin, G. Luderer, J. Minx und O. Edenhofer (2012). "Reconciling top-down and bottom-up modelling on future bioenergy deployment". *Nature Climate Change* 2.5, S. 320–327. DOI: 10.1038/nclimate1416.

Creutzig, F., N. H. Ravindranath, G. Berndes, S. Bolwig, R. Bright, F. Cherubini, H. Chum, E. Corbera, M. Delucchi, A. Faaij, J. Fargione, H. Haberl, G. Heath, O. Lucon, R. Plevin, A. Popp, C. Robledo-Abad, S. Rose, P. Smith, A. Stromman, S. Suh und O. Masera (2015). "Bioenergy and climate change mitigation: an assessment". *GCB Bioenergy* 7.5, S. 916–944. DOI: 10.1111/gcbb.12205.

Dasgupta, P. (2008). "Discounting climate change". *Journal of Risk and Uncertainty* 37.2-3, S. 141–169. DOI: 10.1007/s11166-008-9049-6.

De Nardi, M (2004). "Wealth inequality and Intergenerational Links". *Review of Economic Studies* 71.3, S. 743–768.

De La Croix, D. und P. Michel (2002). *A theory of economic growth: dynamics and policy in overlapping generations*. Cambridge University Press.

Dell, M., B. F. Jones und B. a. Olken (2009). "Temperature and Income: Reconciling New Cross-Sectional and Panel Estimates". *American Economic Review* 99.2, S. 198–204. DOI: 10.1257/aer.99.2.198.

– (2012). "Temperature Shocks and Economic Growth: Evidence from the Last Half Century". *American Economic Journal: Macroeconomics* 4.3, S. 66–95. DOI: 10.1257/mac.4.3.66.

Diamond, P. (1965). "National debt in a neoclassical growth model". *The American Economic Review* 55.5, S. 1126–1150.

Dwyer, T. (2014). "Taxation: The Lost History". *American Journal of Economics and Sociology* 73.4, S. 627–637. DOI: 10.1111/ajes.12082.

Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel und J. C. Minx, Hrsg. (2014). *Climate Change 2014: Mitigation of Climate Change*. Cambridge, United Kingdom und New York, NY, USA: Cambridge University Press.

Edenhofer, O., K. Lessman, C. Kemfert, M. Grubb und J. Köhler (2006). "Induced technological change: Exploring its implications for the economics of atmospheric stabilization: Synthesis report from the innovation modeling comparison project". *Energy Journal* 27.SPEC. ISS. MAR. S. 57–107. DOI: 10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI1-3.

Edenhofer, O., L. Mattauch und J. Siegmeier (2015). "Hypergeorgism : When is Rent Taxation as a Remedy for Insufficient Capital Accumulation Socially Optimal ?" *FinanzArchiv: Public Finance Analysis* fast track. DOI: 10.1628/001522115X14425626525128.

Feldstein, M. (1977). "The Surprising Incidence of a Tax on Pure Rent : A New Answer to an Old Question". *Journal of Political Economy* 85.2, S. 349–360.

Field, C., V. Barros, D. Dokken, K. Mach, M. Mastrandrea, T. Bilir, M. Chatterjee, K. Ebi, Y. Estrada, R. Genova, B. Girma, E. Kissel, A. Levy, S. MacCracken, P. Mastrandrea und L.L.White, Hrsg. (2014). *IPCC, 2014: Summary for policymakers in Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom und New York,USA: Cambridge University Press.

Finus, M. (2008). "Game Theoretic Research on the Design of International Environmental Agreements: Insights, Critical Remarks, and Future Challenges". *International Review of Environmental and Resource Economics* 2.1, S. 29–67. DOI: 10.1561/101.00000011.

Fischer, C. und R. G. Newell (2008). "Environmental and technology policies for climate mitigation". *Journal of Environmental Economics and Management* 55.2, S. 142–162. DOI: 10.1016/j.jeem.2007.11.001.

Foley, D. K. (2009). "The Economic Fundamentals of Global Warming". *Twenty-first century macroeconomics: Responding to environmental challenges*. Hrsg. von J. M. Harris und N. R. Goodwin, S. 115.

Franks, M., D. Klenert, A. Schultes, K. Lessmann und O. Edenhofer (2015). "Is Capital Back? The Role of Land Ownership and Savings Behavior". *mimeo*.

Fullerton, D. und G. E. Metcalf (2001). "Environmental controls, scarcity rents, and pre-existing distortions". *Journal of Public Economics* 80.2, S. 249–267. DOI: 10.1016/S0047-2727(00)00087-6.

Gale, W. G. und J. K. Scholz (1994). "Intergenerational Transfers and the Accumulation of Wealth". *Journal of Economic Perspectives* 8.4, S. 145–160.

Galor, O., O. Moav und D. Vollrath (2009). "Inequality in Land Ownership, the Emergence of Human Capital Promoting Institutions and the Great Divergence". *Review of Economic Studies* 76, S. 143–179.

Gardiner, S. M. (2006). "A Perfect Moral Storm : Climate Change , Intergenerational Ethics and the Problem of Moral Corruption". 15.3, S. 397–413.

Gerlagh, R., S. Kverndokk und K. E. Rosendahl (2009). “Optimal Timing of Climate Change Policy: Interaction Between Carbon Taxes and Innovation Externalities”. *Environmental and Resource Economics* 43.3, S. 369–390. DOI: 10.1007/s10640-009-9271-y.

Goulder, L. H. und K. Mathai (2000). “Optimal CO2 Abatement in the Presence of Induced Technological Change”. *Journal of Environmental Economics and Management* 39.1, S. 1–38. DOI: 10.1006/jeem.1999.1089.

Guruswamy Babu, P., K. Kavi Kumar und N. Murthy (1997). “An overlapping generations model with exhaustible resources and stock pollution”. *Ecological Economics* 21.1, S. 35–43. DOI: 10.1016/S0921-8009(96)00089-4.

Hamilton, K. und J. Hartwick (2014). “Wealth and sustainability”. *Oxford Review of Economic Policy* 30.1, S. 170–187. DOI: 10.1093/oxrep/gru006.

Hamilton, K. und C. Hepburn (2014). “Wealth”. *Oxford Review of Economic Policy* 30.1, S. 1–20. DOI: 10.1093/oxrep/gru010.

Hansen, G. D. und E. C. Prescott (2002). “Malthus to Solow.” *American Economic Review* 92.4, S. 1205–1217.

Hardin, G. (1968). “The Tragedy of the Commons”. *Science* 162.3859, S. 1243–1248. DOI: 10.1126/science.162.3859.1243.

Heijdra, B. J. und F. van der Ploeg (2002). *The Foundations of Modern Macroeconomics*. Oxford University Press, USA.

Helm, D. (2010). “Government failure, rent-seeking, and capture: The design of climate change policy”. *Oxford Review of Economic Policy* 26.2, S. 182–196. DOI: 10.1093/oxrep/grq006.

– (2014). “Taking natural capital seriously”. *Oxford Review of Economic Policy* 30.1, S. 109–125. DOI: 10.1093/oxrep/gru005.

Hertel, T. W. (2011). “The global supply and demand for agricultural land in 2050: A perfect storm in the making?” *American Journal of Agricultural Economics* 93.2, S. 259–275. DOI: 10.1093/ajae/aaq189.

Homburg, S. (1991). “Interest and growth in an economy with land”. *The Canadian Journal of Economics* 24.2, S. 450–459.

– (2014a). “Overaccumulation, Public Debt and the Importance of Land”. *German Economic Review* 15.4, S. 411–435. DOI: 10.1111/geer.12053.

– (2014b). “Property taxes and dynamic efficiency: A correction”. *Economics Letters* 123.3, S. 327–328. DOI: 10.1016/j.econlet.2014.03.013.

– (2015). “Critical remarks on Piketty’s Capital in the Twenty-first Century”. *Applied Economics* 47.14, S. 1401–1406. DOI: 10.1080/00036846.2014.997927.

Howarth, R. B. (1991). "Intertemporal equilibria and exhaustible resources: an overlapping generations approach". *Ecological Economics* 4.3, S. 237–252. DOI: 10.1016/0921-8009(91)90053-H.

– (1998). "Model of Generations An Overlapping Interactions Climate-Economy". *The Scandinavian Journal of Economics* 100.3, S. 575–591.

– (2000). "Climate Change and the Representative Agent". *Environmental and Resource Economics* 1928, S. 135–148.

Hvid, A. (2015). "Increasing Natural Resource Rents from Farmland: A Curse or a Blessing for the Rural Poor?" *Peace Economics, Peace Science and Public Policy* 21.1, S. 59–78. DOI: 10.1515/peps-2014-0004.

International Energy Agency (2014). *World Energy Outlook 2014*. World Energy Outlook. Paris. DOI: 10.1787/weo-2014-en.

IPCC (2012). *Special Report on Renewable Energy Sources and Climate Change Mitigation*. Hrsg. von O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer und C. von Stechow. United Kingdom und New York, NY, USA: Cambridge University Press.

Jacquet, J., K. Hagel, C. Hauert, J. Marotzke, T. Röhl und M. Milinski (2013). "Intra- and intergenerational discounting in the climate game". *Nature Climate Change* 3.11, S. 1–5. DOI: 10.1038/nclimate2024.

Jaffe, A. B. (1986). "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value". *American Economic Review* 76.5, S. 984–1001.

Jaffe, A. B., R. G. Newell und R. N. Stavins (2005). "A tale of two market failures: Technology and environmental policy". *Ecological Economics* 54.2-3, S. 164–174. DOI: 10.1016/j.ecolecon.2004.12.027.

Jakob, M. und J. C. Steckel (2014). "How climate change mitigation could harm development in poor countries". *WIREs Climate Change* 5.2, S. 161–168.

Jakob, M., J. C. Steckel, C. Flachsland und L. Baumstark (2015). "Climate finance for developing country mitigation: blessing or curse?" *Climate and Development* 7.1, S. 1–15. DOI: 10.1080/17565529.2014.934768.

Jamasb, T. (2007). "Technical Change Theory and Learning Curves: Patterns of Progress in Electricity Generation Technologies". *The Energy Journal* 28.3, S. 51–72. DOI: 10.5547/ISSN0195-6574-EJ-Vol28-No3-4.

John, A, R Pecchenino, Schimmelpfennig und Schreft (1995). "Short-lived agents and the long-lived environment". *Journal of Public Economics* 50.94.

John, A. und R. Pecchenino (1997). "International and intergenerational environmental externalities". *The Scandinavian Journal of ...* 99.3, S. 371–387.

Jones, C. I. und P. M. Romer (2010). "The New Kaldor Facts: Ideas, Institutions, Population, and Human Capital". *American Economic Journal: Macroeconomics* 2.1, S. 224–245. DOI: 10.1257/mac.2.1.224.

Judd, K. L. (1985). "Redistributive taxation in a simple perfect foresight model". *Journal of Public Economics* 28.1, S. 59–83. DOI: 10.1016/0047-2727(85)90020-9.

Kalkuhl, M. und R. J. Brecha (2013). "The carbon rent economics of climate policy". *Energy Economics* 39, S. 89–99. DOI: 10.1016/j.eneco.2013.04.008.

Kalkuhl, M., O. Edenhofer und K. Lessmann (2012). "Learning or lock-in: Optimal technology policies to support mitigation". *Resource and Energy Economics* 34.1, S. 1–23. DOI: 10.1016/j.reseneeco.2011.08.001.

Karp, L und C Traeger (2013). "Discounting". *Encyclopedia of Energy, Natural Resource, and Environmental Economics*. Hrsg. von J. F. Shogren. Bd. 2. Amsterdam: Elsevier, S. 286–292. DOI: 10.1016/B978-0-12-375067-9.00150-9.

Karp, L. und A. Rezai (2014). "The political economy of environmental policy with overlapping generations". *International Economic Review* 55.3, S. 711–733.

Kelly, D. und C. Kolstad (1999). "Integrated assessment models for climate change control". *International yearbook of environmental and Resource Economics 1999/2000: A Survey of Current Issues*, S. 1–34.

Klein, D. (2014). "Bioenergy markets in a climate constrained world". Diss. Technical University of Berlin. DOI: 10.14279/depositonce-4307.

Klein, D., G. Luderer, E. Kriegler, J. Strefler, N. Bauer, M. Leimbach, A. Popp, J. P. Dietrich, F. Humpenöder, H. Lotze-Campen und O. Edenhofer (2014). "The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE". *Climatic Change* 123.3, S. 705–718. DOI: 10.1007/s10584-013-0940-z.

Knoll, K., M. Schularick und M. Steger (2014). "No Price Like Home : Global House Prices , 1870 - 2012". *CESifo Working Papers* 2006.

Kopczuk, W. und J. P. Lupton (2007). "To leave or not to leave: The distribution of bequest motives". *Review of Economic Studies* 74.1, S. 207–235. DOI: 10.1111/j.1467-937X.2007.00419.x.

Kopp, R. E., A. Golub, N. O. Keohane und C. Onda (2012). "The Influence of the Specification of Climate Change Damages on the Social Cost of Carbon". *Economics: The Open-Access, Open-Assessment E-Journal* 6.2012-13. DOI: 10.5018/economics-ejournal.ja.2012-13.

Kriegler, E., M. Tavoni, K. Riahi und D. P. Van Vuuren (2013). "Introducing the Limits Special Issue". *Climate Change Economics* 04.04, S. 1302002. DOI: 10.1142/S2010007813020028.

Kriegler, E., K. Riahi, V. Bosetti, P. Capros, N. Petermann, D. P. van Vuuren, J. P. Weyant und O. Edenhofer (2015). "Introduction to the AMPERE model intercomparison studies on the economics of climate stabilization". *Technological Forecasting and Social Change* 90.PA, S. 1–7. DOI: 10.1016/j.techfore.2014.10.012.

Krueger, A. O. (1974). "The Political Economy Seeking of the Society". *The American Economic Review* 64.3, S. 291–303.

Krusell, P. und J.-V. Rios-Rull (1996). "Vested Interests in a Positive Theory of Stagnation and Growth". *The Review of Economic Studies* 63.2, S. 301. DOI: 10.2307/2297854.

Kümmel, R. (2011). *The second law of economics: Energy, entropy, and the origins of wealth*. Springer Science & Business Media.

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

Kypreos, S. und H. Turton (2011). "Climate change scenarios and Technology Transfer Protocols". *Energy Policy* 39.2, S. 844–853. DOI: 10.1016/j.enpol.2010.11.003.

Laitner, J. und H. Ohlsson (2001). "Bequest motives: a comparison of Sweden and the United States". *Journal of Public Economics* 79.1, S. 205–236. DOI: 10.1016/S0047-2727(00)00101-8.

Leimbach, M., N. Bauer, L. Baumstark und O. Edenhofer (2010). "Mitigation costs in a globalized world: Climate policy analysis with REMIND-R". *Environmental Modeling and Assessment* 15, S. 155–173. DOI: 10.1007/s10666-009-9204-8.

Leimbach, M., N. Roming, A. Schultes und G. Schwerhoff (2015). "Development perspectives of Sub-Saharan Africa under climate policies". *mimeo*.

Leimbach, M., A. Schultes, L. Baumstark, A. Giannousakis und G. Luderer (2016). "Solution algorithms for regional interactions in large-scale integrated assessment models of climate change". *Annals of Operations Research*, S. 1–17. DOI: 10.1007/s10479-016-2340-z.

Lessmann, K., U. Kornek, V. Bosetti, R. Dellink, H.-P. Weikard, J. Emmerling, J. Eyckmans, M. Nagashima und Z. Yang (2014). "The Stability and Effectiveness of Climate Coalitions: A Comparative Analysis of Multiple Integrated Assessment Models". DOI: 10.1007/s10640-015-9886-0.

Lobell, D. B., W Schlenker und J Costa-Roberts (2011). "Climate Trends and Global Crop Production Since 1980". *Science* 333, S. 1186–1189.

Lucas, P. L., J. Nielsen, K. Calvin, D. L. McCollum, G. Marangoni, J. Strefler, B. C. van der Zwaan und D. P. van Vuuren (2015). "Future energy system challenges for Africa: Insights from Integrated Assessment Models". *Energy Policy* 86, S. 705–717. DOI: 10.1016/j.enpol.2015.08.017.

Luderer, G., M. Leimbach, N. Bauer, E. Kriegler, L. Baumstark, C. Bertram, A. Giannousakis, J. Hilaire, D. Klein, A. Levesque, I. Mouratiadou, M. Pehl, R. Pietzcker, F.

Piontek, N. Roming, A. Schultes, V. J. Schwanitz und J. Strefler (2015). “Description of the REMIND model (Version 1.6)”. *SSRN Electronic Journal* 2697070.

Maddison, A. (2007). *Contours of the world economy 1-2030 AD: Essays in macro-economic history*. Oxford University Press.

Manne, A. S. (1999). “Equity, Efficiency, and Discounting”. *Discounting and Intergenerational Equity*. Hrsg. von P. R. Portney und J. P. Weyant. Resources for the Future, S. 111.

Marcucci, A. und H. Turton (2013). “Induced technological change in moderate and fragmented climate change mitigation regimes”. *Technological Forecasting and Social Change* 90.A, S. 230–242. DOI: 10.1016/j.techfore.2013.10.027.

Mattauch, L., F. Creutzig und O. Edenhofer (2015). “Avoiding carbon lock-in: Policy options for advancing structural change”. *Economic Modelling* 50.1, S. 49–63. DOI: 10.1016/j.econmod.2015.06.002.

McDonald, A. und L. Schrattenholzer (2001). “Learning rates for energy technologies”. *Energy Policy* 29, S. 255–261. DOI: 10.1016/S0301-4215(00)00122-1.

Meinshausen, M., T. M. L. Wigley und S. C. B. Raper (2011). “Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications”. *Atmospheric Chemistry and Physics* 11.4, S. 1457–1471. DOI: 10.5194/acp-11-1457-2011.

Michel, P., E. Thibault und J. P. Vidal (2006). “Intergenerational altruism and neoclassical growth models”. *Handbook of the Economics of Giving, Altruism and Reciprocity*. Bd. 2. 06, S. 1055–1106. DOI: 10.1016/S1574-0714(06)02015-X.

Mieville, A., C. Granier, C. Liousse, B. Guillaume, F. Mouillot, J.-F. Lamarque, J.-M. Grégoire und G. Pétron (2010). “Emissions of gases and particles from biomass burning during the 20th century using satellite data and an historical reconstruction”. *Atmospheric Environment* 44.11, S. 1469–1477. DOI: 10.1016/j.atmosenv.2010.01.011.

Moore, F. C. und D. B. Diaz (2015). “Temperature impacts on economic growth warrant stringent mitigation policy”. *Nature Climate Change* 5.2, S. 127–131. DOI: 10.1038/nclimate2481.

Moyer, E., M. Woolley, N. Matteson, M. Glotter und D. A. Weisbach (2014). “Climate Impacts on Economic Growth as Drivers of Uncertainty in the Social Cost of Carbon”. *The Journal of Legel Studies* 43.2, S. 401–425.

Murphy, K. M., A. Shleifer und R. W. Vishny (1993). “Why Is Rent-Seeking So Costly to Growth?” *The American Economic Review* 83.2, S. 409–413.

Negishi, T (1960). “Welfare Economics and existence of an equilibrium for a competitive economy”. *Metroeconomica* 12.2-3, S. 92–97.

Nordhaus, W. D. (1993). “Optimal Greenhouse-Gas Reductions and Tax Policy in the "DICE "Model”. *American Economic Review* 83.2.

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

Nordhaus, W. D. (2007). "A Review of the Stern Review Economics of Climate Change". *Journal of Economic Literature* 45.3, S. 686–702.

Nordhaus, W. D. und Z. Yang (1996). "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies". *American Economic Review* 86.4, S. 741–765. DOI: 10.2307/2118303.

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge university press.

Paavola, J. (2011). "Climate change: the ultimate 'tragedy of the commons'?" *Centre for Climate Change Economics and Policy Working Paper* 53.March.

"IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" (2014). Hrsg. von R. Pachauri und L. Meyer.

Pearce, D. (2003). "The Social Cost of Carbon and its Policy Implications". *Oxford Review of Economic Policy* 19.3, S. 362–384. DOI: 10.1093/oxrep/19.3.362.

Petrucci, A. (2006). "The incidence of a tax on pure rent in a small open economy". *Journal of Public Economics* 90.4-5, S. 921–933. DOI: 10.1016/j.jpubeco.2005.05.005.

Piketty, T. (2014). *Capital in the Twenty-First Century*. Belknap Press.

Piketty, T. und G. Zucman (2014). "CAPITAL IS BACK: WEALTH-INCOME RATIOS IN RICH COUNTRIES 1700-2010". *Quarterly Journal of Economics* 129.3, S. 1255–1310. DOI: 10.1093/qje/qju018.

Pindyck, R. S. (2013). "Climate Change Policy : What Do the Models Tell Us ?" *Journal of Economic Literature* 51.3, S. 860–872. DOI: 10.1257/jel.51.3.860.

Popp, D. (2006). "R&D subsidies and climate policy: Is there a "free lunch"?" *Climatic Change* 77.2002, S. 311–341. DOI: 10.1007/s10584-006-9056-z.

Ramsey, F. P. (1928). "A Mathematical Theory of Saving". *The Economic Journal* 38.152, S. 543–559. DOI: 10.1017/CBO9781107415324.004.

Rangel, A. (1993). "Forward and Backward Intergenerational Goods : Why Is Social Security Good for the Environment ?" *American Economic Review* 93.3, S. 813–834.

Rao, S., I. Keppo und K. Riahi (2006). "Importance of Technological Change and Spillovers in Long-Term Climate Policy". *The Energy Journal* 27, S. 123–139.

Rausch, S. und T. F. Rutherford (2010). "Computation of Equilibria in OLG Models with Many Heterogeneous Households". *Computational Economics* 36.2, S. 171–189. DOI: 10.1007/s10614-010-9229-8.

Rezai, A. (2011). "The Opportunity Cost of Climate Policy: A Question of Reference*". *The Scandinavian Journal of Economics* 113.4, S. 885–903. DOI: 10.1111/j.1467-9442.2011.01681.x.

Rezai, A. und F. van der Ploeg (2014). "Abandoning Fossil Fuel : How fast and how much?" *OxCarre Research Paper* 44.

Rezai, A., D. K. Foley und L. Taylor (2012). "Global warming and economic externalities". *Economic Theory* 49, S. 329–351. DOI: 10.1007/s00199-010-0592-4.

Rhee, C. (1991). "Dynamic Inefficiency with in an Economy". *The Review of Economic Studies* 58.4, S. 791–797.

Riahi, K., A. Grübler und N. Nakicenovic (2007). "Scenarios of long-term socio-economic and environmental development under climate stabilization". *Technological Forecasting and Social Change* 74.7, S. 887–935. DOI: 10.1016/j.techfore.2006.05.026.

Riahi, K., E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, T. Longden, G. Luderer, A. Méjean, D. L. McCollum, S. Mima, H. Turton, D. P. van Vuuren, K. Wada, V. Bosetti, P. Capros, P. Criqui, M. Hamdi-Cherif, M. Kainuma und O. Edenhofer (2013). "Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals". *Technological Forecasting and Social Change* 90, S. 8–23. DOI: 10.1016/j.techfore.2013.09.016.

Rognlie, M. (2015). "Deciphering the fall and rise in the net capital share". *Brookings Papers on economic activity.*

Romer, D (2001). *Advanced Macroeconomics*. Economics series. McGraw-Hill.

Rosendahl, K. E. (2004). "Cost-effective environmental policy: implications of induced technological change". *Journal of Environmental Economics and Management* 48.3, S. 1099–1121. DOI: 10.1016/j.jeem.2003.12.007.

Rosenzweig, C., J. Elliott, D. Deryng, A. C. Ruane, C. Müller und A. Arneth (2013). "Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison". *Proceedings of the National Academy of Sciences* 14, S. 1–6. DOI: 10.1073/pnas.1222463110.

Saez, E. und G. Zucman (2015). "Wealth Inequality in the United States since 1913: Evidence from Capitalized Income Tax Data". *Quarterly Journal of Economics* forthcomin. DOI: 10.3386/w20625.

Samuelson, P. A. (1958). "An exact consumption-loan model of interest with or without the social contrivance of money". *The Journal of Political Economy* 66.6, S. 467–482.

Sandler, T. (1978). "Interregional and Intergenerational Spillover Awareness". *Scottish Journal of Political Economy* 25.3.

Schelling, T. C. (1995). "Intergenerational discounting". *Energy Policy* 23.4-5, S. 395–401. DOI: 10.1016/0301-4215(95)90164-3.

Schneider, M. T., C. P. Traeger und R. Winkler (2012). "Trading off generations: Equity, discounting, and climate change". *European Economic Review* 56.8, S. 1621–1644. DOI: 10.1016/j.euroecorev.2012.08.006.

Schneider, S. H. (1997). "Integrated assessment modeling of global climate change : Transparent rational tool for policy making or opaque screen hiding value-laden assumptions ?" *Environmental Modeling and Assessment* 2, S. 229–249.

Schultes, A., O. Edenhofer und M. Leimbach (2015a). "Biased Climate Damages and their Intergenerational Impacts". *mimeo*.

Schultes, A., M. Leimbach, G. Luderer, R. Pietzcker, L. Baumstark, N. Bauer, E. Kriegler und O. Edenhofer (2015b). "Optimal international technology policy for the low-carbon transformation". *mimeo*.

Schultz, M. G., A. Heil, J. J. Hoelzemann, A. Spessa, K. Thonicke, J. G. Goldammer, A. C. Held, J. M. C. Pereira und M. van het Bolscher (2008). "Global wildland fire emissions from 1960 to 2000". *Global Biogeochemical Cycles* 22.2, n/a–n/a. DOI: 10.1029/2007GB003031.

Seater, J. (1993). "Ricardian Equivalence". *Journal of Economic Literature* 31, S. 142–190.

Siegmeier, J., L. Mattauch, M. Franks, D. Klenert, A. Schultes und O. Edenhofer (2015a). "A Public Finance Perspective on Climate Policy: Six Interactions That May Enhance Welfare". *FEEM working paper series* 031.2015. DOI: 10.2139/ssrn.2596604.

Siegmeier, J., L. Mattauch und O. Edenhofer (2015b). "Climate Policy Enhances Efficiency : A Macroeconomic Portfolio Effect". *CESifo Working Papers* 5161.

Sijm, J. P. M. (2004). *Induced Technological Change and Spillovers in Climate Policy Modeling - An assessment*.

Smith, P., S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R. B. Jackson, A. Cowie, E. Kriegler, D. P. van Vuuren, J. Rogelj, P. Ciais, J. Milne, J. G. Canadell, D. McCollum, G. Peters, R. Andrew, V. Krey, G. Shrestha, P. Friedlingstein, T. Gasser, A. Grübler, W. K. Heidug, M. Jonas, C. D. Jones, F. Kraxner, E. Littleton, J. Lowe, J. R. Moreira, N. Nakicenovic, M. Obersteiner, A. Patwardhan, M. Rogner, E. Rubin, A. Sharifi, A. Torvanger, Y. Yamagata, J. Edmonds und C. Yongsung (2015). "Biophysical and economic limits to negative CO2 emissions". *Nature Climate Change* December. DOI: 10.1038/nclimate2870.

Spencer, T., R Pierfederici, H. Waisman und M. Colombier (2015). *Beyond the numbers: understanding the transformation induced by INDCs. A Report of the MILES Project Consortium*.

Staub-Kaminski, I., A. Zimmer, M. Jakob und R. Marschinski (2014). "Climate Policy in Practive: A Typology Of Obstacles And Implications For Integrated Assessment Modeling". *Climate Change Economics* 5.1. DOI: 10.1142/S2010007814400041.

Steckel, J. C., O. Edenhofer und M. Jakob (2015). “Drivers for the renaissance of coal”. *Proceedings of the National Academy of Sciences* 112.29, E3775–E3781. DOI: 10.1073/pnas.1422722112.

Stephan, G. und G. Mueller-Fuerstenberger (1997). “Overlapping Generations or Infinitely-Lived Agents”. *Environmental and Resource Economics* 10, S. 27–40.

Stern, N. (2013). “The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models”. *Journal of Economic Literature* 51, S. 838–859. DOI: 10.1257/jel.51.3.838.

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

Sterner, T. und U. M. Persson (2008). “An Even Sterner Review: Introducing Relative Prices into the Discounting Debate”. *Review of Environmental Economics and Policy* 2.1, S. 61–76. DOI: 10.1093/reep/rem024.

Stiglitz, J. E. (2015a). “New Theoretical Perspectives on the Distribution and Wealth among Individuals: Part I. The Wealth Residual”. *NBER Working Paper* 21189. DOI: 10.3386/w21189.

– (2015b). “New Theoretical Perspectives on the Distribution and Wealth among Individuals: Part II: Equilibrium Wealth Distributions”. *NBER Working Paper* 21190. DOI: 10.3386/w21190.

– (2015c). “New Theoretical Perspectives on the Distribution and Wealth among Individuals: Part III: Life Cycle Savings Vs. Inherited Savings”. *NBER Working Paper* 21191. DOI: 10.3386/w21191.

– (2015d). “New Theoretical Perspectives on the Distribution and Wealth among Individuals: Part IV: Land and Credit”. *NBER Working Paper* 21192. DOI: 10.3386/w21192.

Stocker, T. F., D Qin, G.-K. Plattner, L. V. Alexander, S. K. Allen, N. L. Bindoff, F.-M. Bréon, J. A. Church, U Cubasch, S Emori und Others (2013a). “Technical summary”. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Hrsg. von T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex und P. Midgley. Cambridge, United Kingdom und New York, NY, USA.: Cambridge University Press.

Stocker, T., D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex und P. Midgley, Hrsg. (2013b). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom und New York, NY, USA: Cambridge University Press.

Tavoni, M., E. Kriegler, K. Riahi, D. P. van Vuuren, T. Aboumahboub, A. Bowen, K. Calvin, E. Campiglio, T. Kober, J. Jewell, G. Luderer, G. Marangoni, D. McCollum,

M. van Sluisveld, A. Zimmer und B. van der Zwaan (2014). “Post-2020 climate agreements in the major economies assessed in the light of global models”. *Nature Climate Change* 5.2, S. 119–126. DOI: 10.1038/nclimate2475.

UNEP (2012). “The Emissions Gap Report - Technical Summary”.

UNFCCC Conference of the Parties (2009). *Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009. Addendum. Part Two: Action taken by the Conference of the Parties at its fifteenth session.*

– (2015). *Adoption of the Paris Agreement. Proposal by the President.*

Van Vuuren, D. P., M. G. J. den Elzen, P. L. Lucas, B. Eickhout, B. J. Strengers, B. van Ruijven, S. Wonink und R. van Houdt (2007). “Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs”. *Climatic Change* 81.2, S. 119–159. DOI: 10.1007/s10584-006-9172-9.

Van Vuuren, D. P., J. a. Edmonds, M. Kainuma, K. Riahi und J. Weyant (2011). “A special issue on the RCPs”. *Climatic Change* 109.1, S. 1–4. DOI: 10.1007/s10584-011-0157-y.

Van der Ploeg, F. (2011). “Natural Resources: Curse or Blessing?” *Journal of Economic Literature* 49.2, S. 366–420. DOI: 10.1257/jel.49.2.366.

Van der Werf, G. R., J. T. Randerson, L. Giglio, G. J. Collatz, P. S. Kasibhatla und A. F. Arellano (2006). “Interannual variability in global biomass burning emissions from 1997 to 2004”. *Atmospheric Chemistry and Physics* 6.11, S. 3423–3441. DOI: 10.5194/acp-6-3423-2006.

Van Der Zwaan, B. C. C., R Gerlagh, G Klaassen und L. Schrattenholzer (2002). “Endogenous technological change in climate change modelling”. *Energy Economics* 24, S. 1–19.

Von Stechow, C., D. McCollum, K. Riahi, J. C. Minx, E. Kriegler, D. P. van Vuuren, J. Jewell, C. Robledo-Abad, E. Hertwich, M. Tavoni, S. Mirasgedis, O. Lah, J. Roy, Y. Mulugetta, N. K. Dubash, J. Bollen, D. Ürge-Vorsatz und O. Edenhofer (2015). “Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis”. *Annual Review of Environment and Resources* 40.1, S. 363–394. DOI: 10.1146/annurev-environ-021113-095626.

Weil, P. (1989). “Overlapping families of infinitely-lived agents”. *Journal of public economics* 38, S. 183–198.

– (2008). “Overlapping Generations: The First Jubilee”. *Journal of Economic Perspectives* 22.4, S. 115–134. DOI: 10.1257/jep.22.4.115.

Weitzman, M. L. (2007). “A Review of the SStern Review on the Economics of Climate Change”. *Journal of Economic Literature* 45, S. 703–724. DOI: 10.1257/jel.45.3.703.

Weitzman, M. L. (2009). "On Modeling and Interpreting the Economics of Catastrophic Climate Change". *Review of Economics and Statistics* 91.1, S. 1–19. DOI: 10.1162/rest.91.1.1.

Weyant, J, O. Davidson, H. Dowlatabadi, J Edmonds, M. Grubb, E. A. Parson, R Richels, J Rotmans, P. R. Skukla, R. S. J. Tol, W. R. Cline und S. Fankhauser (1996). "Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results". *Climate Change 1995: Economic and Social Dimensions of Climate Change*. December 2015. Cambridge, United Kingdom und New York, NY, USA.: Cambridge University Press.

Weyant, J. P. und T. Olavson (1999). "Issues in modeling induced technological change in energy , environmental , and climate policy". *Environmental Modeling and Assessment* 4, S. 67–85.

Witajewski-Baltvilks, J., E. Verdolini und M. Tavoni (2015). "Bending the Learning Curve". *Energy Economics*. DOI: 10.1016/j.eneco.2015.09.007.

World Bank (2010). *The Changing Wealth of Nations*. The World Bank. DOI: 10.1596/978-0-8213-8488-6.

– (2012). *Turn Down the Heat: Why a 4C warmer world must be avoided*. Washington, DC.

– (2013). *Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience*. Washington, DC.

– (2015a). *State and Trends of Carbon Pricing*.

– (2015b). *World Development Indicators 2015*. Washington, DC: The World Bank. DOI: 10.1596/978-1-4648-0440-3.

Zimmerman, M. B. (1982). "Learning effects and the commercialization of new energy technologies: The case of nuclear power". *The Bell Journal of Economics* 13.2, S. 297–310.

Kapitel 2

Nash REMIND

–

Solution algorithms for regional interactions in large-scale integrated assessment models of climate change[1]

Marian Leimbach
Anselm Schultes
Lavinia Baumstark
Anastasis Giannousakis
Gunnar Luderer

[1] submitted and accepted in Annals of Operations Research as 'Solution algorithms for regional interactions in large-scale integrated assessment models of climate change', 2016, p1-17. Final version at doi:10.1007/s10479-016-2340-z. With permission of Springer.

Noname manuscript No.
(will be inserted by the editor)

Solution algorithms for regional interactions in large-scale Integrated Assessment models of climate change

Marian Leimbach* · Anselm Schultes* · Lavinia Baumstark · Anastasis Giannousakis · Gunnar Luderer

the date of receipt and acceptance should be inserted later

Abstract We present two solution algorithms for a large-scale integrated assessment model of climate change mitigation: the well known Negishi algorithm and a newly developed Nash algorithm. The algorithms are used to calculate the Pareto-optimum and competitive equilibrium, respectively, for the global model that includes trade in a number of goods as an interaction between regions. We demonstrate that in the absence of externalities both algorithms deliver the same solution. The Nash algorithm is computationally much more effective, and scales more favorably with the number of regions. In the presence of externalities between regions the two solutions differ, which we demonstrate by the inclusion of global spillovers from learning-by-doing in the energy sector. The non-cooperative treatment of the spillover externality in the Nash algorithm leads to a delay in the expansion of renewable energy installations compared to the cooperative solution derived using the Negishi algorithm.

Keywords climate change mitigation · general equilibrium · non-cooperative solution · non-linear programming · trade interaction · energy system modeling

Acknowledgements Funding from the German Federal Ministry of Education and Research (BMBF) in the Call Economics of Climate Change (funding code 01LA1105A CliPoN) is gratefully acknowledged.

Marian Leimbach · Anselm Schultes · Lavinia Baumstark · Anastasis Giannousakis · Gunnar Luderer
Potsdam Institute for Climate Impact Research, P.O.Box 601203, 14412 Potsdam, Germany.
E-mail: leimbach@pik-potsdam.de

Anselm Schultes
Technische Universitaet Berlin, Secretariat EB 4-1, Strasse des 17. Juni 145, 10623 Berlin, Germany.

* Both first authors contributed equally to this work.

1 Introduction

Climate change is a complex global phenomenon involving long time scales. The assessment of climate change mitigation policies requires specialized tools to deal with the long-term impacts and the interactions between different environmental and socio-economic systems. Over the last three decades, Integrated Assessment (IA) models have increasingly been used for analyzing climate change mitigation and adaptation strategies. IA models describe the complex relations between macro-economic, energy, climate, and land use systems. Yet, the solution algorithms used to solve these large-scale models are hardly ever discussed in the literature (Nordhaus and Yang 1996). The choice and specification of the solution algorithm determine, on the one hand, the numerical effectiveness of the solution process. On the other hand, the type of regional interactions covered in IA model places requirements on the solution algorithms.

In this paper we discuss different solution algorithms of an IA model that can be classified as a policy optimization model (Weyant et al. 1996). We present a new implementation of an algorithm that is commonly used to compute a competitive equilibrium solution in less complex models. This new algorithm is computationally more effective than previously used algorithms and allows for integration of real-world externalities that are usually not covered by existing IA models.

In the discussion of the solution algorithms, we are not interested in the details of the underlying mathematical optimization procedures. Instead, we describe the algorithms with emphasis on economic mechanisms, asking how to reconcile actions and decisions of different actors. Our model does not capture regional interaction due to climate change damages. Therefore, we do not contribute to the literature addressing climate policies and the stability of climate coalitions based on the climate externality (Finus et al. 2014). The new algorithm developed in this contribution primarily captures international trade. Recent literature increasingly focuses on the interaction of trade and climate policies (e.g. Copeland and Taylor 2005, Weber and Peters 2009). Trade is relevant to climate policy, as, for example, climate policies may put revenues of fossil fuel exporters at risk. Models including trade interactions are useful to assess viable mitigation strategies of regions or countries and provide insights into terms-of-trade effects.

The paper is structured in the following way: Referring to the existing literature, we discuss in Section 2 the representation of regional interactions and extrernalities in IA models, and relevant solution algorithms. In Section 3, we introduce the IA model REMIND. Two different algorithms to find a general equilibrium solution are presented in Section 4, highlighting advantages of the new algorithm. The application of the model for the evaluation of a climate change mitigation scenario in Section 5 highlights differences in the solution of the two algorithms due to the inclusion of an externality. This indicates the potential of the newly developed algorithm in analyzing other policy questions. We end with conclusions in Section 6.

2 Regional interactions in Integrated Assessment models

IA models simulate long-term dynamics of the socio-economic system, often including the energy sector and parts of the environmental system, in particular the climate system. IA models of the policy optimization type, for example MERGE (Manne et al. 1995), DICE (Nordhaus and Boyer 2000), and MESSAGE (Messner and Schrattenholzer 2000), derive a solution in form of mitigation strategies by cost minimization or welfare maximization. The solution algorithms for these models either treat the interaction of decentralized regional actors explicitly, or assume a global social planner – this differences is most important in the presence of externalities. While a global social planner internalizes external effects between regions, decentralized actors do usually not anticipate and internalize them. In IA models, these actors commonly are world regions. We distinguish four types of regional interactions:

(I) For trade interactions, the synchronization of trade decisions is the modeling challenge in a decentralized decision framework, as is the redistribution of wealth in a social planner framework. Trade relations are therefore commonly considered in a restricted way in IA models only, for example excluding capital trade and changes in the current accounts (Bosetti 2006).

(II) Technological learning in energy technologies is included in some IA models with great detail in the energy system. Learning effects decrease investment costs driven by cumulative investments in modern energy conversion technologies (i.e. learning-by-doing) (Manne and Richels 2004, Rao et al. 2006, Magne et al. 2010). Learning effects are partly external, as some investment costs decrease independently of where and by whom the new capacities are built.

(III) Technological spillovers affecting the productivity of production factors are taken into account just by few IA models (Crassous et al. 2006, Bosetti et al. 2008, Leimbach and Baumstark 2010, Huebler et al. 2012). They depend on R&D investments and may represent externalities in a way similar to learning spillovers.

(IV) The climate externality is caused by the global impact of GHG emissions of each country. If the climate externality is included in the form of a damage function or a global climate target, it is fully internalized by a social planner. In a decentralized setting, however, depending on whether or not the actors internalize this externality, a cooperative solution or a non-cooperative solution can be obtained (Brechet et al. 2014). Nordhaus and Yang (1996) prominently discuss the difference of the cooperative and non-cooperative solution, including algorithmic implications. Their results show that non-cooperative policy, with selfishly acting nations ignoring spillovers and damages imposed on others, leads to much smaller emission reductions than cooperative policy.

The representation of these regional interactions in IA models varies, and so does the specification of the solution algorithm. A complete overview is beyond the scope of the paper – we focus on a particular IA model, the REMIND model. Regarding the four regional interactions discussed above, REMIND includes trade on different markets. Interactions through global technological learning are covered by the model as well. By contrast, R&D spillover externalities and the climate externality are not represented in REMIND. While the Nash and Negishi algorithm, as presented in the next section, compute the same solution with respect to the trade interaction, they compute a non-cooperative (Nash) and cooperative (Negishi) solution with respect to the learning externality.

REMIND belongs to the class of intertemporal optimization models which are computationally expensive (Pan 1992), and is formulated as a non-linear optimization problem. The computation time of such problems rises strongly with the number of variables in the problem. The main challenge in solving the REMIND model is the large number of different markets that have to be cleared simultaneously. We apply two different algorithms to compute a competitive equlibrium. One follows a proven approach for finding a Pareto-optimal solution that corresponds to a competitive equilibrium: Negishi (1972) demonstrated that this market equilibrium can be computed by global welfare optimization with a particular adjustment of the regional welfare weights (see Section 4). The other algorithm in this paper – the Nash algorithm – follows a Walrasian type price adjustment approach. The basic idea of this type of algorithm dates back to the tatonement process of the Walrasian auctionneer, as described by Arrow and Hahn (1971). By iterative price adjustments, this algorithm searches for a fixed point where the aggregated excess demand equals zero. Numerical determination of the equilibrium of a Walrasian system was first provided by Scarf (1967). Other essential contributions to the computation of equilibria in large-scale models are, for example, Dixon (1975) and Manne and Rutherford (1994).

The Negishi algorithm used in REMIND to find a Pareto-optimal solution is similar to that in RICE (Nordhaus and Yang 1996) and MERGE (Manne et al. 1995). The Nash algorithm we implement does not have direct antecedents in IA models: While Nordhaus and Young (1996) implemented a Nash algorithm[1] in order to find a non-cooperative solution with respect to the climate externality, we develop an algorithm for a competitive equilibrium solution with respect to the trade interaction.

3 REMIND Model

REMIND is a global energy-economy-climate model spanning the time from 2005 to 2100 (Leimbach et al. 2010). Its general structure is illustrated in Fig. 1. A comprehensive description of REMIND can be found in Luderer et al. (2015).

The macro-economic core of REMIND is a Ramsey-type optimal growth model where intertemporal welfare is maximized. The world is divided into eleven model regions. Each region is modeled as a representative household with a utility function $U(r)$ that depends only on per-capita consumption:

[1] Within an iterative sequence Nordhaus and Yang (1996) compute a closed-loop Nash equilibrium (Fudenberg and Levine 1988). Technically, this is an outcome of a finite game with perfect information and calculated through backward induction (Mas-Colell 1995, Chapter 9, Kicsiny et al. 2014). A survey on Generalized Nash equilibrium problems is provided by Facchinei and Kanzow (2010). Yang (2003) demonstrated how the closed-loop solution can be found by a computationally more tractable sequence of open-loop equilibria.

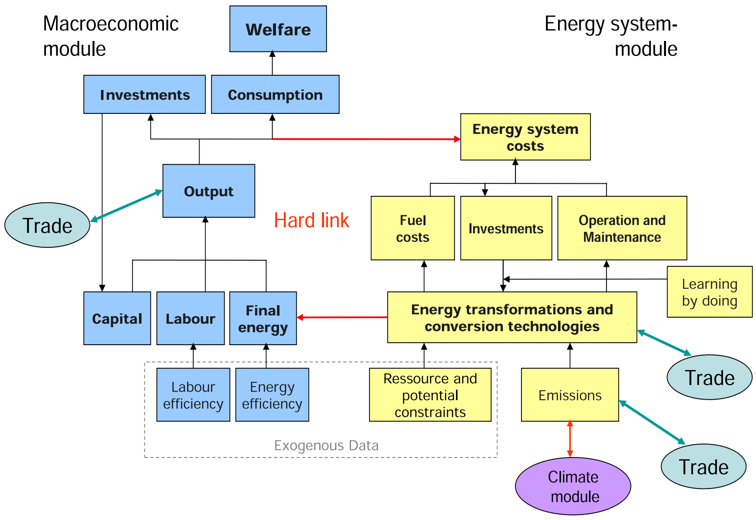


Fig. 1 Structure of REMIND

$$U(r) = \sum_{t=t_0}^{T} (1+\zeta)^{-t} \cdot L(t,r) \cdot \ln\left(\frac{C(t,r)}{L(t,r)}\right) \qquad \forall\ r. \tag{1}$$

The variable $C(t,r)$ is the consumption in time-step t and region r, $L(t,r)$ is population, and ζ is the rate of pure time preference.

Each region generates macro-economic output (GDP) based on a calibrated and nested constant elasticity of substitution (CES) production function with factor inputs labor, capital, and final energy. Final energy is generated through a detailed representation of the energy system in a nested CES tree. The production function reads:

$$V_{out}(t,r) = \left(\sum_{M_{CES}} (\theta_{in} V_{in}(t,r))^{\rho_{out}}\right)^{\dfrac{1}{\rho_{out}}} \qquad \forall t, r, out. \tag{2}$$

$V_{out}(t,r)$ represents CES function output (GDP and intermediate products) and $V_{in}(t,r)$ CES function input. The mapping M_{CES} assigns input types in to each output out. θ and ρ are parameters representing efficiency and elasticity of substitution, respectively. GDP $Y(t,r)$ is available for consumption, investments into the macro-economic capital stock $I(t,r)$, energy system expenditures $E(t,r)$ and for the export of composite goods $X_G(t,r)$, which may instead also be imported as $M_G(t,r)$:

$$Y(t,r) = C(t,r) + I(t,r) + X_G(t,r) - M_G(t,r) + E(t,r) + D(t,r). \tag{3}$$

The term $D(t,r)$, as defined in Eq.(15), is relevant only for technical reasons of the convergence process and does not change the solution point of the model.

Macro-economic investments $I(t,r)$ as control variable enter a common capital stock equation for macro-economic capital $K(t,r)$ with depreciation rate δ:

$$K(t+1,r) = (1-\delta)\cdot K(t,r) + I(t,r) \qquad \forall r,t. \tag{4}$$

Energy system expenditures $E(t,r)$ consist of investment costs $E_{inv}(t,r)$, fuel costs $E_{fc}(t,r)$ as well as operation and maintenance costs $E_{om}(t,r)$:

$$E(t,r) = E_{fc}(t,r) + E_{om}(t,r) + E_{inv}(t,r) \qquad \forall r,t. \tag{5}$$

By means of energy expenditures and final energy input in the production function, the macro-economic core and the energy system module are hard-linked to each other. This ensures simultaneous equilibria on all primary energy carrier and capital markets (Bauer et al. 2008). Around fifty different technologies are represented in REMIND for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy. Technology choice follows implicit cost optimization based on investment costs, operation and maintenance costs, fuel costs, emission costs, efficiencies, lifetimes, and learning rates. Endogenous technological progress is captured by learning-by-doing: Variable investment costs of low-carbon technologies decrease with cumulative installed capacity through global learning curves.

Balance equations ensure that energy demand matches production. One balance equation equals production $P_e(t,r)$ of primary energy type e to extraction $F_e(t,r)$ and net export $X_e - M_e$ of the corresponding primary energy carrier:

$$P_e(t,r) \quad = \quad F_e(t,r) \; - \; X_e(t,r) \; + \; M_e(t,r) \qquad \forall \quad t,r,e \tag{6}$$

Resource scarcity is reflected by extraction cost curves. The model accounts for CO_2 emissions from fossil fuel combustion and land use as well as emissions of other greenhouse gases (GHGs). REMIND is coupled to the MAGICC climate model (Meinshausen et al., 2011) to translate emissions into changes in atmospheric composition, radiative forcing, and temperature increase.

Besides macroeconomic investment, investments into the installation of energy conversion capacities, resource extraction, and the reduction of non-energy related greenhouse gases, trade is another control variable of the regional actors. Trade between regions is induced by differences in factor endowments and technologies. There is trade in five primary energy carriers (oil, coal, gas, biomass, uranium), in a composite good (aggregated output), and in emission permits. Trade is not bilateral, but through exports into and imports from a common pool. Capital mobility is represented by free trade in the composite good and by the possibility of intertemporal trade – resulting in comparatively high capital trade flows. Nordhaus and Yang (1996) and Leimbach et al. (2015) discuss alternatives approaches to intertemporal trade. Capital mobility and intertemporal trade cause price equalization and guarantee an intertemporal and inter-regional equilibrium.

4 Solution algorithms

To find the intertemporal and inter-regional equilibrium, a mechanism of reconciling trade decisions of regions is needed. In the following subsections we describe the Negishi and the Nash algorithms in detail.

4.1 Negishi algorithm

We apply a sequential joint maximization algorithm (Manne and Rutherford, 1994) – also called the Negishi algorithm (Negishi, 1972). In this iterative algorithm, the objective functions of the individual regions $U(r)$, as defined in Eq. (1), are aggregated into a global objective function W by means of welfare weights $w^i(r)$ (index i is the iteration index):

$$W = \sum_r w^i(r) \cdot U(r). \tag{7}$$

Market clearing is included as a constraint to the optimization problem. With $X_j(t,r)$ and $M_j(t,r)$ as export and import of region r in period t, the following clearance condition holds for each market j:

$$\sum_r (X_j(t,r) - M_j(t,r)) = 0 \quad \forall\ t,j. \tag{8}$$

A distinguished Pareto-optimal solution, which in the absence of externalities also corresponds to a competitive market solution, is obtained by iteratively adjusting the welfare weights based on the intertemporal trade balances $B^i(r)$:

$$B^i(r) = \sum_t \sum_j p^i_j(t) \cdot [X^i_j(t,r) - M^i_j(t,r)] \quad \forall\ r,i. \tag{9}$$

Present value world market prices $p^i_j(t)$ are derived iteratively as shadow prices from Eq. 8.

A new set of weights is derived iteratively (Leimbach et al. 2015):

$$w^{i+1}(r) = w^i(r) + \frac{B^i(r)}{\sum_t (1+\zeta)^{-(t-t_0)} L(t,r)} \quad \forall\ r,i. \tag{10}$$

Based on the new weights, a new solution is computed from which we derive $B^{i+1}(r)$. This algorithm has a fixed point in which the intertemporal trade balance of each region converges towards zero. We stop the iteration as soon as the residual deviation from zero is sufficiently small. An exemplary convergence process is shown in Fig. 2.

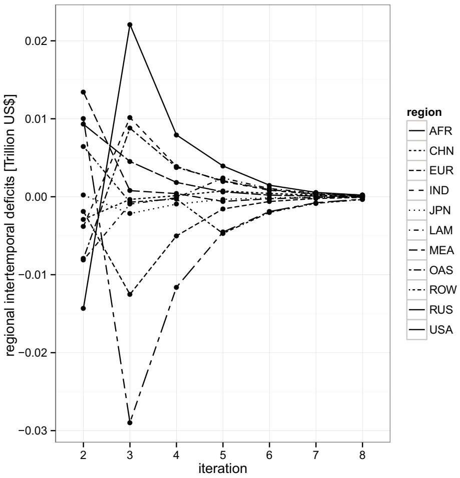


Fig. 2 Exemplary convergence process generated by the Negishi algorithm. Deficits from the intertemporal trade balance (9) for each region approach zero over some 8 iterations.

4.2 Nash algorithm

The Nash algorithm assumes that decisions are taken by decentralized regional actors. In contrast to the Negishi algorithm it neither includes a global welfare function nor explicit market clearing conditions as part of the optimization. Instead, the optimization of each region directly includes its respective intertemporal budget constraint:

$$B(r) = \sum_{t,j} p_j^i(t) \cdot (1 + \chi^i) \cdot [X_j^i(t,r) - M_j^i(t,r)]. \tag{11}$$

The factor χ^i is only of importance for technical aspects of the algorithm, and is explained in Eq. (14).

Market clearing is achieved through a Walrasian-auctioneer type iterative price adjustment. Regional actors start from an initial price vector and choose their trade pattern, acting as price takers. The regional solutions are consequently collected, and the price for the next iteration is adjusted based on the surplus $S_j^i(t)$ on each market:

$$S_j^i(t) = \sum_r \left(X_j^i(t,r) - M_j^i(t,r) \right) \tag{12}$$

$$p_j^{i+1}(t) = p_j^i(t) \left(1 - \eta_j H_j^i(t) \frac{S_j^i(t)}{Z_j^i(t)} \right). \tag{13}$$

Market surpluses are normalized by $Z^i_j(t)$, the global consumption of the respective good, which is a proxy measure for the potential market volume. The parameters η_j^{-1} play the role of price elasticities, and are set from experience as to support convergence and minimize convergence time. An auxiliary parameter $H^i_j(t)$ is used to introduce a time-dependence into the price elasticity η_j^{-1} that is set from experience in order to achieve convergence.

The algorithm converges towards a fixed point where markets clear, as demonstrated exemplarily in Fig. 3. We stop the iteration as soon as the market surplus falls below a certain residual threshold, which typically requires in between 30 and 100 iterations.

The biggest challenge with this formulation of the algorithm is the large number of markets that need to be cleared simultaneously. In our model there is one market for each traded good at each time step. In order to guarantee convergence, we employ two auxiliary mechanisms: Both act as guardrails protecting against a too abrupt change in trade patterns across iterations that may otherwise lead to diverging trade patterns. These mechanisms do not influence the solution point of the iteration. The first one allows regions to anticipate price changes caused by their trade decisions endogenously within the optimization. This is achieved by an additional factor χ^i in the intertemporal budget equation (11):

$$\chi^i(t,r) = \xi^i_j \frac{\left([X^{i-1}_j - M^{i-1}_j] - [X^i_j - M^i_j]\right)}{V^i_j(t,r)} \tag{14}$$

This factor is linear in the differences between the net exports of subsequent iterations (we suppressed the time and region index of the trade variables). An interpretation of the anticipation mechanism from an economic perspective is: Regions are able to anticipate a decline (increase) in the price for a good when increasing their exports (imports), enabling strategic behavior on the markets (Mandel and Gintis 2016). Technically, the mechanism helps the algorithm to converge.

In order to prevent the fixed point of the algorithm to be influenced by this kind of strategic behaviour, we smoothly fade out the anticipation parameter ξ^i to zero as soon as the markets are reasonably close to clearance. We make sure that the influence of the price anticipation helper mechanism on the solution point is negligible: Varying the anticipation parameter in numerical experiments, we observe a robust solution point. The variation in the solution due to the anticipation parameter is much less than the already small variance that is due to residual market surpluses, which not only depend on the length of the convergence process but also on the starting point. As there are non-convexities in the model, multiple equilibria may in principle exist. In the course of our experiments we only observe unique solutions though, disregarding the aforementioned inherent small numerical variance.

The second auxiliary mechanism is a penalty cost $D(t,r)$ depending on the change in the regional trade pattern over iterations, a mechanism sometimes referred to as regularization. The square of the deviation from last iteration's trade pattern is multiplied by a weight parameter Ω_j, and priced into each respective region's budget equation (3) as a penalty:

$$D(t,r) = \sum_j \Omega_j \frac{p^i_j(t)}{V^i_j(t,r)} \left([X^{i-1}_j - M^{i-1}_j] - [X^i_j - M^i_j] \right)^2 \qquad \forall\ t,r \qquad (15)$$

Regions are thus prevented from changing their trade pattern all too abruptly across iterations. As trade patterns converge, this cost penalty goes to zero and does thus not influence the solution point of the algorithm.

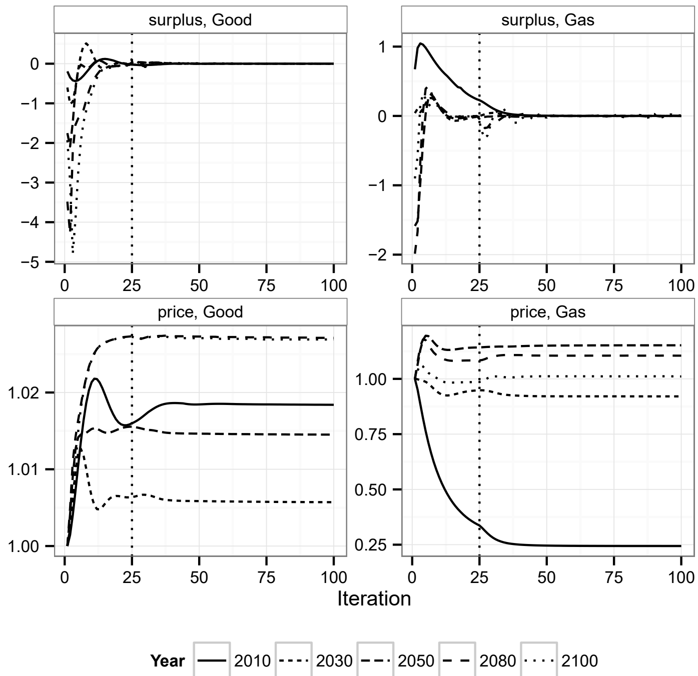


Fig. 3 Exemplary convergence process generated by the Nash algorithm. Residual surplus over iteration are in the first row of panels, and prices over iterations in the second row are shown for two markets (Goods and Gas) at selected time steps. Units for surplus are Trillion US Dollar for goods, and exajoule per year for the gas market. Prices are normalized to their first-iteration value. The begin of the phase-out of the price anticipation mechanism is marked by a dotted vertical line.

4.3 Computational effectiveness

Both solution algorithms, Negishi and Nash, are implemented in GAMS (Brooke et al. 1992). We use CONOPT3 (Drud 1994) as the solver for the non-linear programming problem (NLP) of the global social planner maximizing global welfare (Eq. 7) in the Negishi case, and the regional social planners maximizing regional welfare (Eq. 1) in the Nash case, respectively. The two respective NLP problems differ in their number of non-superbasic variables by a factor of $m = 11$, the number of regions in our model. From our experience, the computing time to solve NLP models grows much faster than linear with the number of non-superbasic variables. This can be understood assuming matrix inversion is the most expensive operation within the solver, which scales polynomially with the size of the system (Pan 1992).

Large-scale NLP models (size of more than 100 000 variables and equations) in GAMS often cannot be reliably solved without providing a starting point for the solver in form of a GDX file. The choice of the GDX file from previous model runs significantly influences model run time. In order to compare performance between the Nash and Negishi algorithms, we set up the following model runs: Two exemplary REMIND scenarios, a business-as-usual and a carbon tax scenario are each run in Negishi-, sequential-Nash-, and parallel-Nash-mode. We use six different GDX points as initial starting points for the solver, some known to be closer to the solution, some farther away. Run times of the resulting 36 model realizations are shown in Fig. 4. The median run times are significantly smaller for the Nash algorithm, around an order of magnitude below the Negishi value. Furthermore, the performance of the Nash algorithm is less dependent on the starting point, as seen from the smaller spread of run times in the Nash mode.

Computational effectiveness mainly depends on three factors: First, for NLP problems the time complexity of problems typically rises much faster than linear with the size of the problem. Formulating the model as m independent regional NLP problems thus potentially decreases the total run time, even if the problems are solved sequentially.

Second, the Nash algorithm requires an adjustment of many more parameters in between iterations than the Negishi algorithm – potentially increasing total run time. In the Nash algorithm, prices on markets for all goods and all times (on the order of 100) have to be adjusted in each iteration, while the Negishi algorithm only requires updating the Negishi weight of each region (11 in our case). Consequently, while the Negishi algorithm takes about 10 iterations to converge, the Nash algorithm requires in between 30 and 100 iterations. In our implementation, the first effect outweighs the second one quite drastically. As seen from Fig. 4, the median run time in sequential Nash mode (where all regions are solved on the same CPU core sequentially) is 4.2 hours, much less than the 42.4 hours in Negishi mode.

Third, the separate regional problems can be solved in parallel in the Nash mode, using the GAMS grid computing facilities. Each regional problem then runs as a separate thread, allowing for the distribution of these threads on different CPU cores[2]. This contributes to the reduction in total run time of the model in Nash

[2] We solve the model on a high-performance computer cluster equipped with Intel Xeon E5472 CPUs at 3.0GHz.

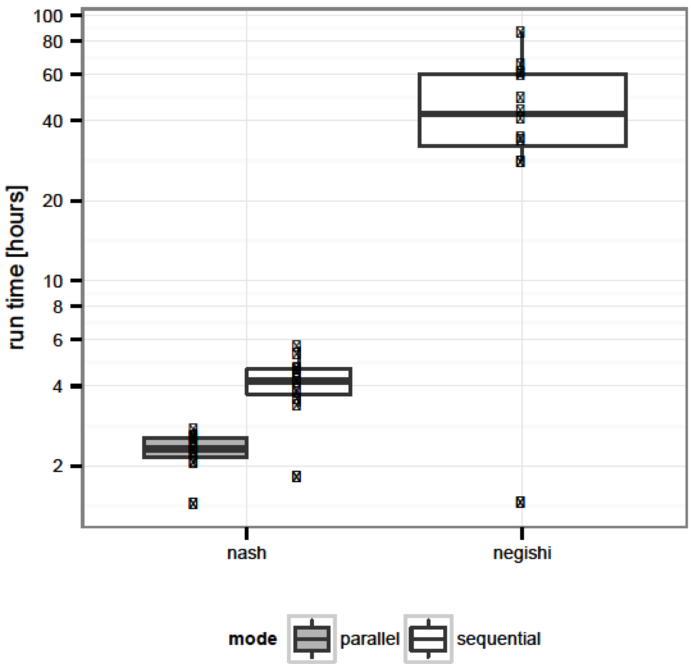


Fig. 4 Comparison of run times (wall clock time) of Nash and Negishi algorithms over a set of different starting points (GDX) and scenarios. In the Nash case, sequential- and parallel-mode results are shown. Boxes indicate interquartile range, the horizontal lines the median value.

mode, reducing the median run time from 4.2 hours in sequential Nash mode to 2.3 hours in the parallel mode.

The separation into regional NLP problems in the Nash algorithm also allows for a very favorable scaling of run time with the number of regions in the model. Given the GAMS grid computing facility has access to as many cores as regions in the problem, total run time should not significantly increase with the number of regions. This is in stark contrast to the scaling behaviour of the Negishi algorithm, where the number of regions is effectively limited by the drastic increase of run time of the single NLP problem with its size.

4.4 Equivalence in the absence of externalities

In the absence of the learning-by-doing externality (i.e. assuming that there are no learning technologies), trade is the only interaction between regions in our model. In this case, the Negishi and Nash solution algorithms converge to the same fixed point – the competitive equilibrium. We demonstrate this by comparing both solutions numerically in detail.

Trade pattern deviation [%]	median	mean	max
Oil	0.05	0.17	2.01
Coal	0.08	0.34	5.31
Gas	0.12	0.40	5.80
Biomass	0.56	0.99	2.82
Uranium	0.09	0.91	12.84
Composite good	0.05	0.11	1.45

Table 1 Deviation of trade patterns between Nash and Negishi solution on different markets in relative terms.

Trade pattern deviation relative to global consumption [%]	median	mean	max
Oil	0.000	0.004	0.069
Coal	0.003	0.020	0.181
Gas	0.003	0.039	0.754
Biomass	0.001	0.013	0.875
Uranium	0.007	0.333	9.033
Composite good	0.000	0.000	0.009

Table 2 Deviation of trade patterns between Negishi and Nash solution on different markets, relative to the global consumption of the respective market good in percent.

To compare the two solutions, statistics on relative deviations in regional trade patterns between the two solution points are shown in Tab. 1. Statistics are based on the relative deviations of net exports at all time periods and regions of an exemplary Nash and Negishi run:

$$\text{Trade pattern deviation} = 100 \cdot \left| \frac{X(t,r)^{\text{nash}} - M(t,r)^{\text{nash}}}{X(t,r)^{\text{negishi}} - M(t,r)^{\text{negishi}}} - 1 \right| \tag{16}$$

We exclude the resource markets with a very small volume of below 0.5 EJ/yr from this analysis, as the resulting high relative deviations would only be an artifact of regions switching from import to export of this specific resource. The deviations are small in general, with median relative deviations of below 0.6% across all markets and all times. The relatively high maximum deviations on the uranium markets of up to 13% are due to the high flexibility (indeterminacy) of uranium deployment across regions in the model as compared to other types of primary energy supply.

We introduce a more aggregated measure for the residual deviations in the trade structure of the two solutions: The deviation of trade patterns between Nash and Negishi solution, divided by to the global consumption of the respective good or primary energy type, as shown in Tab. 2. These normalized deviations in trade patterns are very small, with a median value below 0.007%.

Differences in the regional consumption paths are also small, with a maximum deviation of around 0.07% and a median of 0.02%.

5 Application to climate change mitigation

In this section, we present an exemplary climate change mitigation assessment with REMIND using both solution algorithms discussed previously. REMIND does not model climate change damages, but evaluates mitigation strategies for a given global climate target, that is, the analysis here is a cost-effectiveness, not a cost-benefit analysis. The cost-efficient allocation of mitigation efforts is based on a globally uniform carbon tax imposed on each region. The tax path is iteratively adjusted based on the difference between the simulated radiative forcing and and the forcing level corresponding to the aspired climate stabilization target (see below), ensuring that the given climate target is achieved.

The alternative use of the Nash and Negishi algorithm computes a constrained competitive equilibrium solution and a constrained Pareto-optimum, repectively. The solutions deviate from each other due to a different handling of technological spillovers. In contrast to the experiment in the previous section, we activated the technological learning externality for this application. Due to learning-by-doing, the globally uniform specific investment costs $I_L(t)$ decrease with the cumulative capacities $\mathrm{CC}_L(t,r)$ for emerging low carbon energy conversion technologies of type L:

$$I_L(t) = I_{L,\mathrm{floor}} + I_{L,0}\left(\sum_r \mathrm{CC}_L(t,r)\right)^{-b_L} \tag{17}$$

$I_{L,\mathrm{floor}}$ and $I_{L,0}$ represent the floor costs and the initial variable costs of investments, respectively. The parameter b_L describes the learning rate of technology L. Learning technologies are solar photovoltaics, concentrated solar power, wind power, hydrogen cars, electric cars, and storage technologies.

The global social planner of the Negishi algorithm anticipates that regional investments into learning technologies reduce the respective investment costs worldwide. The respective regional social planners in the Nash algorithm do not take these spillovers to other regions into account in their investment decision, creating a wedge between the Negishi solution and the Nash solution. Regarding the learning externality, a cooperative solution is computed by the Negishi algorithm and a non-cooperative solution by the Nash algorithm. Global technological learning still exists in the decentralized world though. In each iteration of the Nash algorithm, the unanticipated spillover effect is captured through the inclusion of the investment decisions of the decentralized actors from the preceding iteration.

The international community has agreed on the long-term target of limiting global warming to no more than 2°C above pre-industrial levels. Here we consider a climate mitigation scenario with a radiative forcing target of 2.6 W/m^2 by 2100, allowing for temporary overshoot of this target during the century. Such scenarios have been shown to keep global warming below 2°C with a high likelihood (Clarke et al. 2014, Rogelj et al. 2011). This climate target requires a drastic reduction of global greenhouse gas emissions and a sustained transformation of the global energy system. Fig. 5 shows the emission trajectories for both, the Negishi and the Nash solution, for a baseline scenario with no mitigation (scenario names: NE-

BAU, NA-BAU), and a mitigation scenario (NE-450 and NA-450) simulated by REMIND.

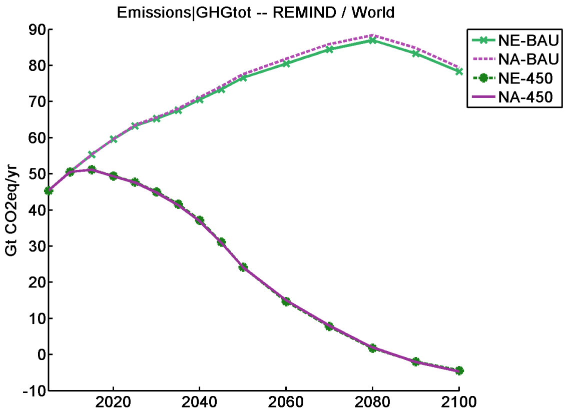


Fig. 5 Total greenhouse gas emissions over time for different scenarios: Baseline scenarios (named "BAU"), and climate policy scenarios in line with the 2°C target ("450"), each for the Nash ("NA-") and Negishi("NE-") algorithm.

While the baseline scenarios show an increase of total GHG emissions until 2080 to a level of around 90 $GtCO_2eq$, emissions peak at 51 $GtCO_2eq$ in 2015 in the mitigation scenarios and decline to below zero over the second half of the century. The emission trajectories differ only slightly between the Nash and Negishi solution. While learning technologies play a minor role in the baseline scenario, they are heavily used in the mitigation scenario, but the optimal emission trajectory is mainly determined by the climate target.

The consumption of primary energy and electricity in 2050, as shown in Fig. 6 and Fig. 7, indicates the marked transformation of the energy system induced by the ambitious mitigation policies. In the baseline scenarios, fossil fuels are still dominating the energy mix in 2050. In the mitigation scenarios, by contrast, the high share of renewables increases constantly until 2100 – modern biomass in the non-electricity sector and solar and wind in the electricity sector. Furthermore, energy efficiency improvements contribute significantly to emissions reduction. Primary energy consumption is reduced by around 20% in 2050 and more than 30% in 2100 compared to the baseline scenario. This reduction is mainly at the expense of the non-electricity sector, while the share of electricity on final energy consumption increases continuously.

Differences between the Nash and Negishi solution are moderate. Within the baseline scenario, the reduced incentive to invest into learning technologies results in hardly any investments in solar technologies until 2050 in the Nash solution. Some investments in solar technologies is found for the Negishi solution (Fig. 8). Differences can be seen in the use of solar energy in the mitigation scenario. A substantial

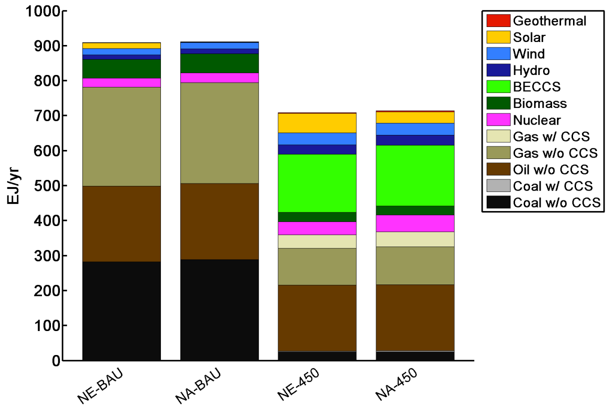


Fig. 6 Primary energy consumption in 2050 for different scenario: Baseline scenarios (named "BAU"), and climate policy scenarios in line with the 2°C target ("450"), each for the Nash ("NA-") and Negishi("NE-") algorithm.

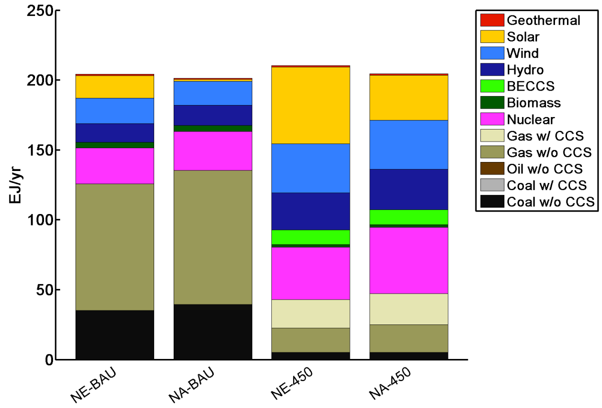


Fig. 7 Electricity consumption in 2050

part of nuclear energy that is used for electricity production in the Nash solution is replaced by solar energy in the Negishi solution (Fig. 7). As a common pattern, the expansion of solar technologies is delayed by around 10-15 years in the non-cooperative Nash solution.

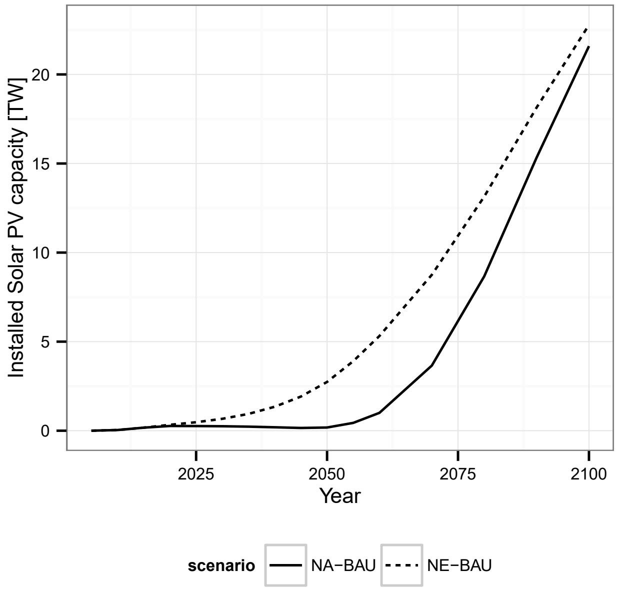


Fig. 8 Solar Photovoltaic (PV) capacity paths in the Nash (NA-BAU) and the Negishi (NE-BAU) solution of the business-as-usual scenario.

6 Conclusions

We present an implementation of a decentralized solution algorithm to find a general equilibrium solution of an IA model of climate change mitigation. The main contribution is a more effective computation of trade interactions. We demonstrate robustness of the solution by comparing it to a solution from an established Negishi solution algorithm. The new algorithm – called Nash algorithm – has two major advantages: first, it is computationally more effective, and allows for an increased number of regions in the problem. The median run time of the model is reduced by more than a factor of 10 with respect to the Negishi algorithm. The new algorithm can also take advantage of parallel computing. Second, the algorithm allows, based on the assumption of decentralized actors, for an extended representation of real-world inter-regional externalities. In an exemplary application of the two algorithms to climate change mitigation, we demonstrate moderate differences in technology choice between a cooperative and non-cooperative solution: internalizing global spillover externalities related to investments into learning technologies accelerates the adoption of emerging low-carbon technologies such as solar power.

Further research could apply the Nash algorithm in model settings including other externalities, as, for example, the climate externality or technological spillover driven by R&D investments. A larger gap between the Nash and the Negishi solution can be expected in both cases. Moreover, the question of how these externalities could be explicitly internalized by policy instruments within the decentralized Nash solution algorithm arises. While corresponding instruments (e.g. carbon tax, technology subsidy) are well-understood conceptually, the design and implementation of solution algorithms of large-scale IA models will likely be challenged by each additional inter-regional externality and policy instrument.

References

1. Arrow, K.J., Hahn, F.H. (1971). General competitive analysis. Mathematical Economic Texts, No. 6. Oliver and Boyd. San Francisco, pp. 452.
2. Bauer, N., Edenhofer, O., Kypreos, S. (2008). Linking Energy System and Macroeconomic Growth Models. Journal of Computational Management Science 5, 95-117.
3. Bosetti, V., Carraro, C., Massetti, E., Tavoni, M. (2006). A World Induced Technical Change Hybrid Model. Energy Journal, Special Issue #2, 13-37.
4. Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M. (2008). International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. Energy Economics 30, 2912-2929.
5. Brechet, T., Camacho, C., Veliov, V.M. (2014). Model predictive control, the economy, and the issue of global warming. Annals of Operations Research 220, 25-48.
6. Brooke, A., Kendrick, D., Meeraus, A. (1992). GAMS - A User's Guide, Release 2.25. The Scientific Press, San Francisco.
7. Clarke, L., Jiang, K. et al. (2014). Assessing transformation pathways. In: Climate Change 2014 - Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, chapter 6.
8. Copeland, B.R., Taylor, M.S. (2005). Free trade and global warming: a trade theory view of the Kyoto protocol. Journal of Environmental Economics and Management 49, 205-234.
9. Crassous, R., Hourcade, J.-C., Sassi, O. (2006). Endogenous Structural Change and Climate Targets, Modelling experiments with Imaclim-R. Energy Journal, Special Issue #1, 259-276.
10. Dixon, P.B. (1975). The Theory of Joint Maximization. Amsterdam: North-Holland Publishing Company.
11. Drud, A. (1994). CONOPT - A large-scale GRG code. ORSA Journal on Computing 6, 207-216.
12. Facchinei, F., Kanzow, C. (2010). Generalized Nash Equilibrium Problems. Annals of Operations Research 175, 177-211.
13. Finus, M., Rundshagen, B., Eyckmans, J. (2014). Simulating a sequential coalition formation process for the climate change problem: first come, but second served? Annals of Operations Research 220, 5-23.
14. Fudenberg, D., Levine, K.L. (1988). Open-Loop and Closed-Loop Equilibria in Dynamic Games with Many Players. Journal of Economic Theory 44, 1-18.
15. Huebler, M., L. Baumstark, M. Leimbach, N.Bauer, O. Edenhofer (2012). An integrated assessment model with endogenous growth. Ecological Economics 83, 118-131.
16. Kicsiny, R., Varga, Z., Scarelli, A. (2014). Backward induction for a class of closed-loop Stackelberg games. European Journal of Operational Research 237, 1021-1036.
17. Leimbach, M., Baumstark, L. (2010). The impact of capital trade and technological spillovers on climate policies. Ecological Economics 69, 2341-2355.
18. Leimbach, M., Bauer, N., Baumstark, L., Edenhofer, O. (2010). Mitigation costs in a globalized world: climate policy analysis with REMIND-R. Environmental Modeling and Assessment 15, 155-173.
19. Leimbach, M., Baumstark, L., Luderer, G. (2015). The role of time prefences in explaining the long-term pattern of international trade. Global Economy Journal 15, 83-106, DOI: 10.1515/gej-2014-0035.
20. Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., Baumstark, L., Bertram, C., Giannousakis, A., Hilaire, J., Klein, D., Levesque, A., Mouratiadou, I., Pehl, M., Pietzcker,

R., Piontek, F., Roming, N., Schultes, A. and Schwanitz, V. J., Strefler, J. (2015). Description of the REMIND Model (Version 1.6) (November 30, 2015). Available at SSRN: http://ssrn.com/abstract=2697070.
21. Magne, B., Kypreos, S., Turton, H. (2010). Technology Options for Low Stabilization Pathways with MERGE. Energy Journal 31, 83-107.
22. Mandel, A., Gintis, H.(2016). Decentralized Pricing and the equivalence between Nash and Walrasian equilibrium. Journal of Mathematical Economics 63, 84-92.
23. Manne, A.S., Mendelsohn, M., Richels, R. (1995). MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies. Energy Policy 23, 17-34.
24. Manne, A.S., Richels, R. (2004). The impact of learning-by-doing on the timing and costs of CO_2 abatement. Energy Economics 26, 603-619.
25. Manne, A. S., Rutherford, T. (1994). International trade, capital flows and sectoral analysis: formulation and solution of intertemporal equilibrium models. In: Cooper, W. W. and Whinston, A. B. (eds.), New directions in computational economics, Kluwer Academic Publishers, Dordrecht, The Netherlands, 191-205.
26. Mas-Colell, A., Whinston, M.D., Green J.R. (1995). Microeconomic Theory. Oxford University Press, New York.
27. Meinshausen, M., Raper, S. C. B., Wigley, T. M. L. (2011). Emulating Coupled Atmosphere-Ocean and Carbon Cycle Models with a Simpler Model, MAGICC6 Part 1: Model Description and Calibration. Atmos. Chem. Phys. 11: 141756, doi:10.5194/acp-11-1417-2011.
28. Messner, S., Schrattenholzer, L. (2000). MESSAGE-MACRO: Linking an energy supply sodel with a macroeconomic module and solving it iteratively. Energy 25, 267-282.
29. Negishi, T. (1972). General Equilibrium Theory and International Trade. North-Holland, Amsterdam.
30. Nordhaus, W.D, Boyer, J. (2000). Warming the World: Economic Models of Global Warming. MIT Press, Cambridge, Massachusetts.
31. Nordhaus, W.D., Yang, Z. (1996). A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies. American Economic Review 86, 741-765.
32. Pan, V. (1992). Complexity of Computation with Matrices and Polynomials. SIAM Review 34, 225-262.
33. Rao, S., Peppo, I., Riahi, K. (2006). Importance of Technological Change and Spillovers in Long-term Climate Policy. Energy Journal, Special Issue #1, 123-139.
34. Rogelj, J., Hare, W., Lowe, J., van Vuuren, D.P. et al. (2011). Emission pathways consistent with a 2°Cglobal temperature limit. Nature Climate Change 1, 413-418.
35. Scarf, H. (1967). On the computation of equilibrium prices. In: W. Fellner (ed.), Ten Economic Studies in the Tradition of Irving Fisher. New York: John Wiley & Sons. pp.207-230.
36. Yang, Z. (2003). Reevaluation and renegotation of climate change coalitions - a sequential closed-loop game. Journal of Economic Dynamics & Control 27, 1563-1594.
37. Weber, C.L., Peters, G.P. (2009). Climate change policy and international trade: Policy considerations in the US. Energy Policy 37, 432-440.
38. Weyant, J., Davidson, O., Dowlabathi, H., Edmonds, J., Grubb, M., Parson, E.A., Richels, R., Rotmans, J., Shukla, P.R., Tol, R.S.J., Cline, W., Fankhauser, S. (1996). Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results. In: J. P. Bruce et al. (eds.), Climate Change 1995: Economic and Social Dimensions of Climate Change. Cambridge University Press, pp. 367-439.

Kapitel 3

Technology Policy
–
Optimal international technology policy for the low-carbon transformation[1]

Anselm Schultes
Marian Leimbach
Gunnar Luderer
Robert C. Pietzcker
Lavinia Baumstark
Nico Bauer
Elmar Kriegler
Ottmar Edenhofer

[1] Submitted to Energy Policy.

Optimal international technology cooperation for the low-carbon transformation

Anselm Schultes*[†], Marian Leimbach[‡], Gunnar Luderer[‡], Robert C. Pietzcker[‡], Lavinia Baumstark[‡], Nico Bauer[‡], Elmar Kriegler[‡], Ottmar Edenhofer[‡†§]

Abstract

Research on low-carbon transformation pathways has focused on carbon pricing as a means for climate stabilization. By contrast, technology policies remain the more prominent national climate policy instruments: renewable energy subsidies amount to more than US$100 billion per year globally – more than twice the value of priced carbon. Given technology spillovers and global learning effects it remains unclear how technology policies can be coordinated internationally as part of climate stabilization policy. Here we show an economic rationale to include an international technology protocol alongside carbon pricing. Cumulative low-carbon subsidies of more than US$1 trillion from 2020 until the end of the century mainly support solar power and advanced car technologies. Higher carbon pricing could replace subsidies at very low cost, but mitigation cost increases from delayed carbon pricing can only somewhat be reduced by stepping up subsidies. Existing low-carbon subsidies must be complemented by full carbon pricing to achieve 2°C cost-efficiently.

The international community agrees that global warming should be limited to well below 2°C above the pre-industrial temperature[1], but negotiations so far have not resulted in commitment to sufficient emissions reduction[2,3]. While the spotlight is on the negotiations about national emission reductions, technology cooperation continues to play an important role in the UNFCCC process. Meanwhile, policies supporting renewable energy have been enacted in 138 countries[4]: Subsidies for renewable energy production were above US$100 billion in 2013[4], much higher than the value of priced carbon at US$50 billion in 2014[5]. Of these subsidies, around US$80 billion supported solar and wind power[4]. Even though these subsidies have multiple objectives, reducing emissions is their primary aim[6]. Coordinating technology policies has the potential to advance climate policy by increasing efficiency and opening up technology support to public funds like the Green Climate Fund[7,8]. It is not clear, however, how large a role technology subsidies can play in cooperative climate policy, and which low-carbon technologies should be supported the most[9].

*Corresponding author: schultes@pik-potsdam.de; Potsdam Institute for Climate Impact Research, P.O.Box 601203, 14412 Potsdam, Germany; Phone +49 331 288 20781

†Technische Universität Berlin, Berlin.

‡Potsdam Institute for Climate Impact Research, Potsdam

§Mercator Research Institute on Global Commons and Climate Change, Berlin

There are market failures in the development and deployment of energy technologies[10]. As a means to correct these market failures, optimal technology policy under carbon pricing has been characterized in stylized models[11]. Subsidizing the dynamically superior technologies can prevent costly lock-ins in the energy system, as shown in single-region growth models with simple technology representation[12–14]. Obviously, the results obtained in these studies depend strongly on the modeling detail in energy technologies. Technology-rich energy-economy-climate models did not include optimal technology policies, but rather relied on guesstimated combinations of technology policies[15–19]. Knowing the optimal policy instrument, however, is a requirement to implement the low-carbon transformation cost-efficiently.

Scenario	Description	Cost increase	Subsidies	Subsidies/Tax	Tax in 2020
NoSub	no subsidies, carbon tax from 2020 only	0.01 pp	0	0	33 US$/tCO2
Optimal	optimal mix of subsidies and tax from 2020	–	1.4 US$ trillion	6.2 %	31 US$/tCO2
LowTax	slightly too low tax from 2020, subsidies close the gap	0.08 pp	5.3 US$ trillion	26 %	28 US$/tCO2
DelayTaxNoSub	full tax from 2035 only, no subsidies	0.40 pp	0	0	7 US$/tCO2
DelayTaxHighSub	full tax from 2035, large subsidies until then	0.31 pp	2.1 US$ trillion	8.2%	7 US$/tCO2

Table 1: Scenarios for climate stabilization at 2°C. Mitigation cost increases are in percentage points above the optimal (first-best) level of 1.62% of discounted consumption losses until from 2015 to 2100. Cumulative values of subsidies and taxes are given in US$2015 net present value terms. Model results are highlighted over scenario assumptions in grey.

Our study is the first to calculate optimal technology policy as part of cooperative climate stabilization using an integrated energy-economy-climate model with high technological and regional resolution. We close a gap in the literature between optimal policy models and technology-rich models – informing policy design about the cost-efficient mix of carbon pricing and subsidies for climate stabilization.

Energy-economy-climate modeling

We use REMIND[20], a global model integrating the energy and the climate system into the macro-economy in a coherent way. The energy system includes more than 50 energy conversion technologies. Some emerging low-carbon technologies are subject to endogenously induced cost reductions. Induced technological progress is usually attributed to either learning-by-doing, research and development, or a combination of both in the literature[21]. It has been argued[22] that research and development with finite patent lifetimes has dynamics similar to learning-by-doing. Consequently, we attribute cost reductions to learning-by-doing only in our model. Investment costs decrease endogenously with cumulative capacity due to global learning-by-doing in: wind power, photovoltaics (PV), concentrated solar power (CSP), energy storage, and electric- and hydrogen-cars in the transport sector[23].

There is evidence that firms fail to appropriate the full learning benefits in emerging low-carbon technologies[10,24,25]. We model a spillover externality in learning-by-doing: An investment in a learning technology by the representative firm in one region causes some unanticipated spillover in the own region, but most of this spillover accrues in other regions. As the firms cannot appropriate the spillovers, an underinvestment in emerging low-carbon technologies results – learning is a global public good.

We identify the set of technology- and region-specific subsidies on investment costs that internalizes the spillover, quantifying the technology support to be mandated by an optimal international technology protocol. The globally uniform per unit subsidy is the sum of the spillovers of a unit of capacity investment across all regions. The per unit subsidy $S_{t,T}$ at time t for technology T is calculated as the sum over regional capitalized marginal benefits of learning $M_{r,t,T}$:

$$S_{t,T} = \sum_{r \in \text{all regions}} M_{r,t,T} \tag{1}$$

After the initial adoption of the technology, the per unit subsidy declines rapidly, reflecting decreasing learning effects with cumulative capacities. Capacity additions $c_{r,t,T}$ in each region r are subsidized with the per unit subsidy, such that the subsidy is $S_{t,T} \cdot c_{r,t,T}$. Each region subsidizes capacity additions, and finances the subsidy by a lump-sum tax on households. We assume here that firms cannot appropriate any of the spillover, but the results are robust in this respect: Assuming instead that at least the spillover in each region due to its own investment is completely internal decreases the aggregate global subsidy by around 15% only, as most of the spillovers accrue to other regions anyway.

In effect, the technology protocol transforms the non-cooperative solution into the one where regions cooperatively internalize the learning spillover alongside the climate externality. The climate externality itself is internalized by a global carbon tax in this cost-effectiveness setting for the 2°C target.

Cost-efficient policy for 2°C

In the cost-efficient policy for limiting the temperature increase to below 2°C with a probability of ∼75% – the Optimal scenario (Tab. 1) – regions agree on a globally uniform carbon price and a technology protocol.

Full carbon pricing starts in 2020 at the global tax rate of US\$31 per tonne of CO_2, realizing a tax revenue of US\$1 trillion in 2020 alone. Subsidy expenditures are much smaller at ∼US\$60 billion in 2020. The subsidy rises to US\$370 billion in 2080 in constant terms (Fig. 1), which is still below 8% of the value of priced carbon in that year. Cumulated from 2020 to 2100, subsidies make up 6% of the value of priced carbon.

The cumulative present value of all subsidies under this protocol is US\$1.4 trillion. Cost-optimization implies that ∼60% of the cumulative present value is spend on solar power, and ∼30% on advanced car technologies.

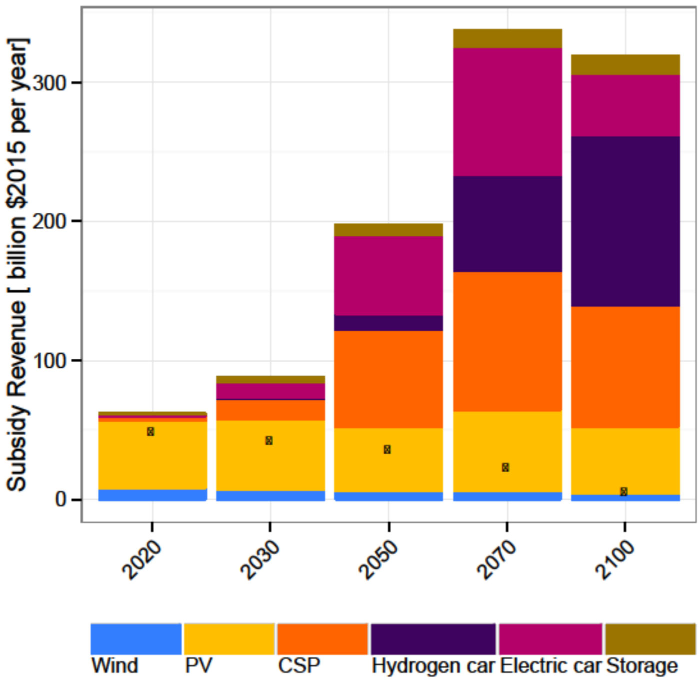


Figure 1: Optimal global subsidy by technology. Stacked bars show subsidy by technology in constant value terms, the black dots indicate the present value in $US\$_{2015}$.

In 2020, PV subsidies are ~US$50 billion; this figure stays roughly the same over the century, as increasing deployment volumes are balanced by decreasing per unit subsidies. For CSP, subsidies grow from ~US$4 billion in 2020. The split between PV and CSP in total solar subsidies is 60% to 40%, but as PV and CSP are good substitutes, this technology split could be varied at low cost. Most of the solar subsidies are payed out in China, the United States, India, and the model region Sub-Saharan Africa, as seen from the regional allocation of subsidies in Fig. 2.

For advanced cars, two thirds of the cumulative subsidies go to electric cars and one third to hydrogen cars – but again, these two car technologies are good substitutes. More than half of the advanced car subsidies until 2030 are carried by Europe.

Wind power subsidies, which decline from US$8 billion in 2020 on, and storage subsidies make up the rest of the bill. For every dollar in subsidies to variable renewables, 6 cent are spend on storage capacities in aggregate.

The effect of the technology protocol

In the scenario NoSub (see Tab. 1), regions do not agree on a technology protocol, and there are no subsidies from 2020 on. Instead, regions cooperatively price carbon at a slightly higher rate to reach the same climate target. Compared to this second-best NoSub scenario, the optimal subsidy protocol speeds up the low-carbon

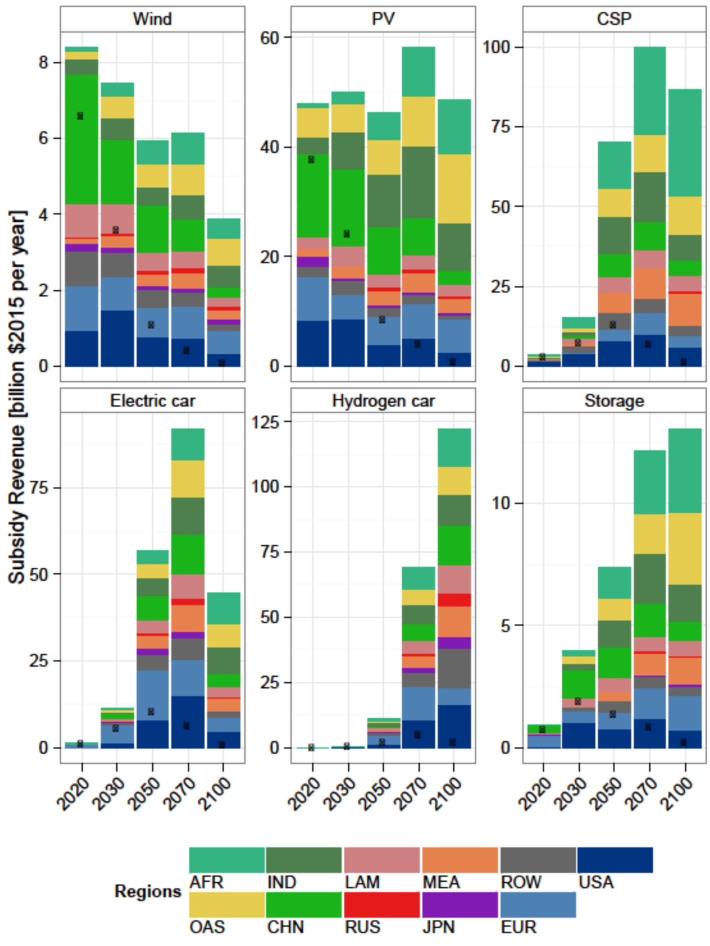


Figure 2: Optimal subsidy by region and technology. Stacked bars show regional distribution of the subsidy in constant value terms. Present values (in US$$_{2015}$) are indicated by black dots. Region definitions are found in the Methods section.

transformation: Variable renewables exceed the 25% share in total electricity generation around a decade earlier, and the adoption of advanced cars is accelerated as well (Fig. 3).

Cumulative use of solar energy until 2100 increases by 15% through the optimal subsidy: This allows to reduce the use of wind power, and the use of low-carbon technologies which face public opposition due to risks and sustainability issues like nuclear power generation, and bio-energy and fossils in combination with carbon capture and storage by 5%.

Therefore, the subsidy protocol increases the efficiency of the low-carbon transformation: The carbon price required for climate stabilization in the Optimal scenario is 6% below the one in the NoSub scenario, but mitigation costs are only reduced marginally (Tab. 1).

Regional differences in the physical and economic potential of low-carbon technologies are reflected in the regional share of subsidies in the carbon rent, which

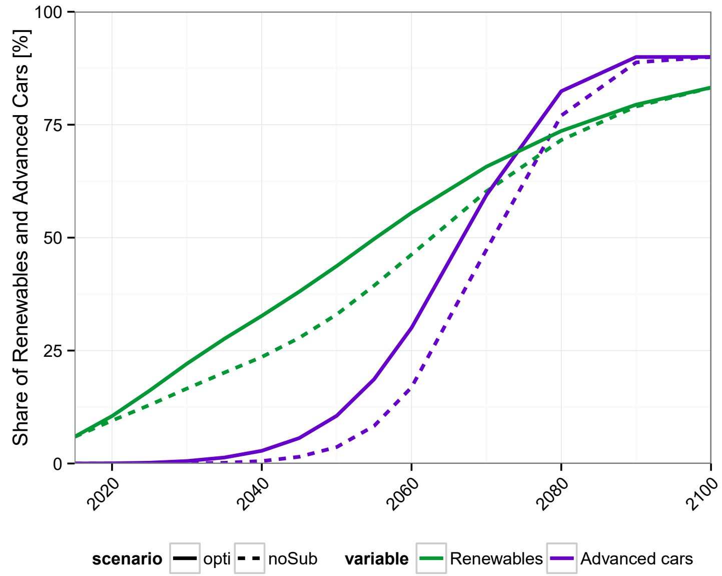


Figure 3: Low-carbon transformation accelerated by subsidies: Share of variable renewables in total electricity generation; share of advanced cars in total cars.

ranges from 3% to 11%.

Agreeing on the protocol, and paying for the subsidies in their own region, optimally provides the global public good of learning. Despite large regional differences in the subsidies, this technology protocol does not result in large income shifts between regions: In aggregate, most of the benefits accrue to the regions that implement most of the subsidies, such that net spillovers between regions due to the subsidy are small, and mostly benefit today's developing regions. Note that no explicit transfer of technology or money is part of our climate policy scenarios: The net spillover caused by the technology protocol is an implicit transfer through a decrease in the investment costs for low-carbon technologies. In effect, the Optimal policy scenario increases welfare over the NoSub scenario for most regions. Explicit transfer schemes may change the incentives such that all regions are better off through the Optimal policy, but this study rather outlines the optimal global agreement in a first step.

Subsidies cannot replace carbon pricing

Beyond internalizing the spillover, subsidies could substitute for too low carbon pricing, but this increases mitigation costs significantly: Higher subsidies still accelerate the adoption of low-carbon technologies, but rebound effects prevent effective emission reductions: If only the carbon tax is permanently 7% below the Optimal level, as in the LowTax scenario (Tab. 1), and large subsides are used to still reach climate stabilization, mitigation costs increase significantly.

If instead full carbon pricing is delayed, mitigation costs increase strongly. In the DelayTaxNoSub scenario, carbon is only weakly priced – on global average at only

US$7 – until full pricing starts in 2035. The resulting lock-in into carbon intensive infrastructure in the near term increases mitigation costs by a hefty 0.40 percentage points (pp) above the first-best level of 1.62% of discounted consumption. Using the method presented here we cannot determine the cost-optimal subsidy protocol when carbon pricing is delayed, but we find that up to some degree an increase in subsidies reduces the costs of the lock-in: Mitigation costs in the DelayTaxHighSub scenario are reduced to 0.31pp above the first-best level by a threefold increase in subsidies until 2030, and total subsidies of ∼US$2 trillion over the century – reducing the cost markup due to the lock-in by only around one-fourth only. Additional policies, like banning the construction of new coal-fired power plants, or an accelerated phase-out of final energy subsidies, have been shown to reduce the cost markup due to delayed carbon pricing further[19].

Technology subsidies need carbon pricing

In summary, we complement the result that carbon pricing is by far the most important single element in cost-efficient cooperative climate stabilization by specifying the optimal subsidies for emerging low-carbon technologies – which in total amount to 6% of the aggregate value of priced carbon.

We note that global solar and wind subsidies realized in 2013 are in sum not much above the optimal value for the year 2020 found in this study under the assumption of fully external spillovers. These subsidies, however, are only part of cost-efficient climate policy given full carbon pricing, starting at US$31 per tonne of CO_2 in 2020.

Our work focused on external effects in learning-by-doing, but there are other external effects associated with emerging technologies, giving rationales for additional policy interventions. In this work we assume that all other external effects are internalized by appropriate policy instruments, including those beyond the ones in emerging technologies, for example local air pollution.

The mitigation cost increase for an international agreement based only on carbon pricing is found to be very small. Including a subsidy protocol has to be weighted against the uncertainties and difficulties in determining and enacting the technology-specific optimal rates. However, if there are external effects in the adoption of emerging technologies beyond learning-by-doing, the mitigation cost markup for climate policy without subsidies would increase compared to our results.

If full carbon pricing is delayed any further, we find that the resulting cost increase can only be somewhat reduced by stepping up subsidies in the near term. Stepping up low-carbon subsidies in the near term, however, must therefore in no case replace efforts to price carbon. International transfers may also be a route to incentivize carbon pricing – cutting back fossil fuel subsidies could free up public funds for that at negative social cost[26].

Methods

To identify optimal climate stabilization policies we use the integrated energy-economy-climate model REMIND, a global intertemporal general equilibrium model spanning the 21st century. Our modelling results are by no means predictions of future developments, but rather a tool to assess the trade-offs between different long-term policy scenarios. The world is divided into eleven regions: The individual countries China (CHN), India (IND), Japan (JPN), The United States of America (USA), and Russia (RUS), as well as the aggregated regions European Union (EUR), Latin America (LAM), Sub-Saharan African countries with the exception of South Africa (AFR), Middle East and North Africa (MEA), Other Asia (OAS), and Rest of the World (ROW). We use the Shared Socio-economic Pathways scenario SSP2 for assumptions on GDP and population growth[27]. The energy system captures inertia and path-dependencies by representing more than 50 technologies energy-conversion technologies as capital stocks, subject to adjustment costs. Energy prices reflect resource scarcities and final energy taxes. Induced technological progress is captured by learning-by-doing (LbD) for some energy technologies with the highest learning rates: the emerging low-carbon technologies. In the literature, induced technological progress is usually attributed to either LbD, research and development (R&D), or a combination of both[21]. It has been argued[22] that R&D with finite patent lifetimes has similar dynamics as LbD - we thus attribute cost reductions to LbD only in our model. Variable investment costs decrease with cumulative capacity through global learning curves in six low-carbon technologies, approaching floor costs. The highest learning rate – the decrease in specific investment cost for every doubling of cumulative capacity – is found for PV at 20%[28], the other technologies learn at rates of around 10%. Firms fail to appropriate the full benefits from LbD caused by their investments[10,24,25]. Investments by the representative firm in one region not only cause an intertemporal spillover by reducing future investment cost in this region, but also a much larger spillover to other regions. We find the non-cooperative solution (NoSub scenario) with respect to this spillover, where regions play a Nash game in choosing their learning investment – the resulting equilibrium shows a Pareto-inefficiently low investment in learning technologies. In effect, this technology subsidy protocol transforms the non-cooperative solution into the one where regions cooperate to internalize the spillover externality alongside the climate externality (Optimal scenario).

Greenhouse gas emissions from the energy system and land-use are translated into radiative forcing levels and global mean temperature using the MAGICC6 climate model[29]. All of our climate policy scenarios stabilize the climate at the same forcing level in 2100 – which corresponds to a temperature increase of below 2°C above pre-industrial levels with a probability of around 75%. Climate stabilization is enforced by a globally uniform tax on greenhouse gas emissions which rises at a rate of 5% p.a., yielding a close to cost-efficient abatement path. The aggregate value of priced carbon is the fossil fuel carbon rent, collected through a carbon tax in our model.

In the first-best Optimal scenario, carbon taxation from 2020 on internalizes the emissions externality and the optimal subsidy protocol internalizes the spillover. All other scenarios are second-best in different respects. With no subsidy protocol in the NoSub scenario instead, a slightly higher carbon tax enforces the same climate target from 2020 on. In the delayTaxNoSub scenario with delayed carbon pricing, emissions in a first phase are priced at US$7 on global average from 2015 on, until full pricing starts from 2035 - which is unanticipated during the first phase. On top of this, the delayTaxHighSub scenario has a subsidy protocol with subsidies internalizing the spillover in the second phase starting 2035. In the first phase, subsidies are set above the level that internalizes the spillover – as they act as a second-best instrument to substitute for carbon pricing. Mitigation costs are given as consumption losses from 2015 until 2100 with respect to a baseline without climate and technology policy, discounted at the baseline interest rate of around 5% p.a..

References

1. Conference of the Parties. *Adoption of the Paris Agreement* 2015.
2. Riahi, K. *et al.* Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change* **90,** 8–23 (2013).
3. Spencer, T. *et al. Beyond the numbers: understanding the transformation induced by INDCs. A Report of the MILES Project Consortium* 2015.
4. International Energy Agency. *World Energy Outlook 2014* (Paris, 2014).
5. World Bank. *State and Trends of Carbon Pricing* (2015).
6. Lehmann, P. & Gawel, E. Why should support schemes for renewable electricity complement the EU emissions trading scheme? *Energy Policy* **52,** 597–607 (2013).
7. De Coninck, H. *et al.* International technology-oriented agreements to address climate change. *Energy Policy* **36,** 335–356 (2008).
8. Van Asselt, H. & Zelli, F. Connect the dots: managing the fragmentation of global climate governance. *Environmental Economics and Policy Studies* **16,** 137–155 (2013).
9. Aldy, J. E. *et al.* Designing Climate Mitigation Policy. *Journal of Economic Literature* **48,** 903–934 (2010).
10. Jaffe, A. B. *et al.* A tale of two market failures: Technology and environmental policy. *Ecological Economics* **54,** 164–174 (2005).
11. Fischer, C. & Newell, R. G. Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management* **55,** 142–162 (2008).
12. Schneider, S. H. & Goulder, L. H. Achieving low-cost emissions targets. *Nature* **389,** 13–14 (1997).
13. Kverndokk, S. & Rosendahl, K. E. Climate Policies and learning by doing: Impacts and timing of technology subsidies. *Resource and Energy Economics* **29,** 58–82 (2007).
14. Kalkuhl, M. *et al.* Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics* **34,** 1–23 (2012).
15. Rao, S. *et al.* Importance of Technological Change and Spillovers in Long-Term Climate Policy. *The Energy Journal* **27,** 123–139 (2006).

16. Bauer, N. *et al.* The REMIND-R model: The role of renewables in the low-carbon transformation-first-best vs. second-best worlds. *Climatic Change* **114,** 145–168 (2012).

17. Kypreos, S. & Turton, H. Climate change scenarios and Technology Transfer Protocols. *Energy Policy* **39,** 844–853 (2011).

18. Marcucci, A. & Turton, H. Induced technological change in moderate and fragmented climate change mitigation regimes. *Technological Forecasting and Social Change* **90,** 230–242 (2013).

19. Bertram, C. *et al.* Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change* **5,** 235–239 (2015).

20. Leimbach, M. *et al.* Mitigation costs in a globalized world: Climate policy analysis with REMIND-R. *Environmental Modeling and Assessment* **15,** 155–173 (2010).

21. Goulder, L. H. & Mathai, K. Optimal CO2 Abatement in the Presence of Induced Technological Change. *Journal of Environmental Economics and Management* **39,** 1–38 (2000).

22. Gerlagh, R. *et al.* Optimal Timing of Climate Change Policy: Interaction Between Carbon Taxes and Innovation Externalities. *Environmental and Resource Economics* **43,** 369–390 (2009).

23. Pietzcker, R. C. *et al.* Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy* **64,** 95–108 (2014).

24. Bollinger, B. & Gillingham, K. Learning-by-Doing in Solar Photovoltaic Installations. *SSRN Electronic Journal* **2342406** (2014).

25. Benthem, A. V. *et al.* Learning-by-Doing and the Optimal Solar Policy in California. *The Energy Journal* **29,** 131–151 (2007).

26. Coady, D. *et al.* How Large Are Global Energy Subsidies? *IMF Working Paper* (2015).

27. Dellink, R. *et al.* Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change* **in press** (2015).

28. Pietzcker, R. C. *et al.* Using the sun to decarbonize the power sector: the economic potential of photovoltaics and concentrating solar power. *Applied Energy* **135,** 704–720 (2014).

29. Meinshausen, M. *et al.* Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications. *Atmospheric Chemistry and Physics* **11,** 1457–1471 (2011).

Kapitel 4

Mitigation in Sub-Saharan Africa
–
Development perspectives of Sub-Saharan Africa under climate policies[1]

Marian Leimbach
Niklas Roming
Anselm Schultes
Gregor Schwerhoff

[1] Submitted to Ecological Economics.

Long-term development perspectives of Sub-Saharan Africa under climate policies

1 Introduction

Does climate policy slow economic growth of countries in Sub-Saharan Africa? The answer to this question largely determines the incentives in this world region for participation in ambitious climate policy regimes. Turning away from proven development pathways based on fossil fuels requires costly additional investments into the energy system. Nevertheless, large renewable energy potentials, in particular for solar energy, and international technology diffusion could ease the transformation towards a low carbon economy and thus facilitate the adoption of emission reduction commitments. Additionally, countries in Sub-Saharan Africa could benefit from interactions with other world regions in the form of climate finance, international technology policies, and exports of bioenergy. While Sub-Saharan Africa consists of very heterogeneous countries, we consider a focus on the region as a whole a useful starting point for understanding the implications of an ambitious global climate policy regime.

In this paper we provide an aggregate and quantitative assessment of ambitious climate change mitigation on economic development in Sub-Saharan Africa. This assessment includes costs, in particular for the low-carbon transformation of the energy system, and benefits like climate finance and bioenergy trade. We take the renewable energy potential of Sub-Saharan Africa, international fossil fuel markets, and technology diffusion from other world regions into account. We find costs and benefits of climate change mitigation to be on the same order of magnitude, allowing Sub-Saharan Africa to participate in global mitigation efforts at roughly net zero costs. Additional benefits of climate policy would result from avoided climate impacts, which are not even taken into account in this study.

As a first contribution, we spell out the costs and benefits that are largely determined by the degree of international cooperation: countries in Sub-Saharan Africa benefit from rising demand for biomass on international markets under climate policies, and from international burden sharing agreements based on equal emissions allowances per capita. Second, while a limited degree of international cooperation on climate and technology policies raises the costs of reaching climate targets globally, countries in Sub-Saharan Africa may by contrast experience lower costs, though associated with increased inequality in the intergenerational distribution. Third, potentially very regressive effects due to rising fuel prices highlight the need for careful climate policy implementation and complementary policies within countries.

Cost-effectiveness analyses using Integrated Assessment Models (IAM) indicate that climate stabilization goals can be achieved at moderate GDP losses in global aggregate (Kriegler et al., 2014). Some of these studies spell out the regional losses and gains underlying the aggregate global losses (Tavoni et al., 2014, Aboumahboub et al., 2014, Luderer et al., 2012). Only very few studies give detailed consideration to individual regions. Calvin et al. (2013) and Lucas et al. (2015) analyze the effect of economic growth on future global energy demand and emissions under different baseline and climate policy assumptions for Sub-Saharan Africa. This paper presents the first IAM-based study with a particular focus on Sub-Saharan Africa. It quantifies the feedback of climate policy on economic growth in a set of scenarios and provides a breakdown into the different contributing factors.

Several aspects of climate change adaptation and mitigation in Sub-Saharan Africa have been investigated, including the role of migration (Gray and Mueller, 2012), of dams (Cole et al., 2014) and of gender (Van Aelst and Holvoet, 2016). Four categories have been identified as major drivers of the net effect of climate change mitigation on development in Africa. First, if principles of global equity are considered (as the Paris Agreement has indicated that they will), countries in Sub-Saharan Africa can expect to benefit from financial transfers, for example in the form of climate finance (Jakob et al., 2015). Second, African countries can draw on low-carbon technologies developed by technology leaders (Collier et al., 2008). Third, many countries in Sub-Saharan Africa are well positioned to decarbonize their energy systems due to large endowments of hydro and solar power potentials (Collier and Venables, 2012, Pietzcker et al., 2014). Fourth, Sub-Saharan Africa has a large potential for generating biomass (Dasappa, 2011), which could be used domestically or sold on international markets. This paper uses the detailed data and simulation output available from REMIND, a well-documented IAM (Leimbach et al., 2010), to quantify these effects and determine the net effect of climate change mitigation.

Historically, development has been based on the use of fossil fuels (Smil, 2000; Fouquet, 2010; Jakob et al., 2012). How low-income countries can "leapfrog" an emission intensive early phase and reach levels of high income with clean forms of energy use has been discussed intensively (Ward and Shively, 2012). Marcotullio and Schulz (2007) find that developing countries today are using energy in a cleaner and more efficient way than their earlier predecessors. Concerning Africa in particular, Sokona et al. (2012) find that "Africa has the benefit of diverse experiences and models, both successful and failed ones, to assist it in fast-tracking energy pathways". We follow this literature in the general idea that development patterns can change over time and explore how Africa can take advantage of its unique situation.

The paper is structured as follows. In Section 2 we give a brief description of the model and the scenarios that are explored in the following sections. Scenarios are designed along the dimensions of ecological efficiency, international cooperation on climate and technology policy, and equity in international agreements. The discussion in Section 3 focuses on the comparison of economic costs Sub-Saharan Africa as a model region is confronted with in the different scenarios. The analysis also addresses distributional impacts of different burden sharing schemes. Section 4 explores the requirements of the energy system transformation, including an ex-post analysis of distributional effects of this transformation within the region. We end with conclusions in Section 5.

2 Model description and scenario implementation

2.1 REMIND

REMIND is a global, multi-regional, energy-economy-climate model (Leimbach et al. 2010) used in long-term analyses of climate change mitigation (Bauer et al. 2012). The remainder of this section briefly introduces the model, while a detailed model description is provided by Luderer et al. (2015).

The world is divided into eleven model regions, one of which is Sub-Saharan Africa. This region contains all countries on the African continent except Algeria, Egypt, Libya, Morocco (incl. Western Sahara), South Africa, and Tunisia. It would be desirable to have resolution on a country level, but as climate change analysis requires a global model, the regional resolution is in general constrained by model size limitations. We consequently focus on Sub-Saharan Africa as a single model region interacting with other regions in a global model.

The macro-economic core of REMIND is a Ramsey-type optimal growth model in which intertemporal global welfare is maximized. The model computes a unique Pareto-optimal solution that corresponds to the market equilibrium in the absence of non-internalized externalities. Model regions trade final goods, primary energy carriers, and in the case of climate policy, emissions permits. Macro-economic production factors are capital, labor, and final energy.

Economic activity results in demand for different types of final energy (electricity, solids, liquids, gases, etc.), determined by a production function with constant elasticity of substitution, and differentiated by stationary and transport uses. The energy system accounts for regional exhaustible primary energy resources through extraction cost curves. Bioenergy is provided based on different kind of feedstocks: traditional biomass and first generation biomass, both assumed to phase out in the near future, as well as lingo-cellulosic residues and purpose-grown second-generation biomass. Region-specific details are also included for non-biomass renewable energy potentials. Sub-Saharan Africa, for example, has an annual potential of solar energy for photovoltaic production of 200EJ with high capacity factors (Luderer et al., 2015, Fig. 5). More than 50 technologies are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy. Techno-economic parameters (investment costs, operation & maintenance costs, fuel costs, conversion efficiency etc.) characterize each conversion technology.

The model accounts for CO_2 emissions from fossil fuel combustion and land use as well as emissions of other greenhouse gases (GHGs). A reduced form climate model is used to translate emissions into changes of atmospheric GHG concentrations, radiative forcing, and global mean temperature. It comprises an impulse-response function with three time scales for the carbon cycle, an energy balance temperature model with a fast mixed layer, and a slow deep ocean temperature box. Its key parameters are calibrated to reproduce MAGICC (Meinshausen 2011), with a climate sensitivity of around 3.0°C.

The baseline scenario in REMIND is calibrated to the GDP trajectory of the SSP2 scenario of the Shared Socioeconomic Pathways (Dellink et al., 2016). Changes of GDP under climate policies are computed endogenously. Population and labor force input is derived from the SSP2 population scenario (KC and Lutz, 2016). Under these assumptions, the global economy grows throughout the 21st century, while global population growth comes to a halt: Figure 1 shows global GDP and population developments and the rising share of Sub-Saharan Africa in both – which increases from 1% to 13% regarding GDP, and from 10% to 25% regarding population.

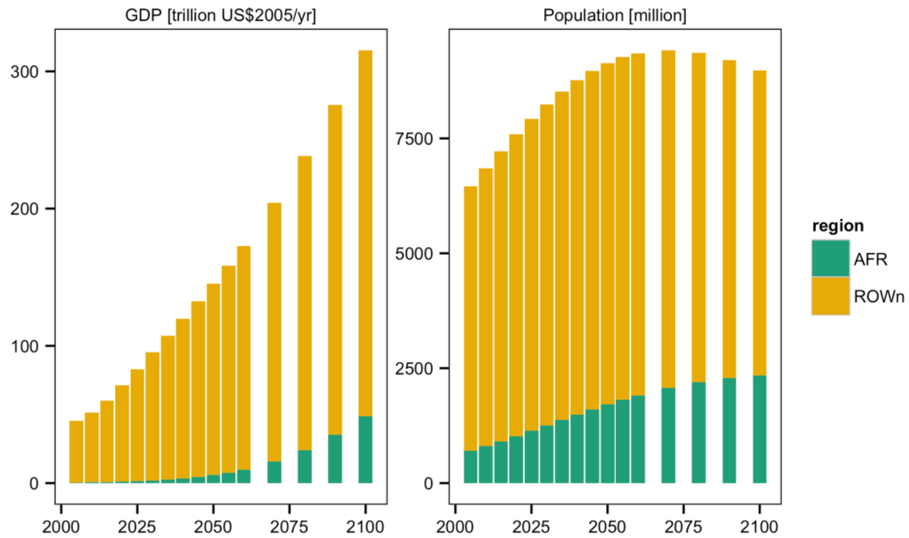


Fig.1: Global GDP and population scenario assumptions for the 21st century in REMIND. The regions Sub-Saharan Africa (AFR) and Rest of the World (ROWn) are differentiated by color.

2.2 Scenario design and implementation

We introduce in this section a set of climate policy scenarios that are differentiated along three dimensions, all of which are expected to have a significant development impact:

(1) Ecological efficiency: Level of climate stabilization (i.e. global climate target)

(2) Cooperation: Degree of international cooperation regarding technology and climate policy

(3) Equity: Climate finance and burden sharing.

All scenarios are summarized in Table 1, and their differentiation along the three dimensions is described in the remainder of this section.

Table 1: Scenario matrix

Climate target	**Cooperation**		**Climate finance and burden sharing**		
			No climate finance	**Population share**	**Per capita convergence**
Baseline		BAU			
450 ppm	**full cooperation**		450TAX	450POP	450CC
550 ppm			550TAX	550POP	550CC
450 ppm	**Limited cooperation**		450SPA		
550 ppm			550SPA		

The first dimension reflects varying levels of ambition in global climate policy: Apart from a baseline scenario with no climate policy, there are two scenarios that stabilize atmospheric greenhouse gas concentration at around 450 ppm[1] and 550 ppm in the year 2100. The 450ppm scenario has a high probability limiting the rise in global mean temperature in line with the 2 degree target (Clarke et al., 2014). The benefits from avoided climate impacts are not included in our model.

The second dimension describes that the international community may show limited or full cooperation with respect to two aspects: climate, and technology policy. Climate policy may be enacted immediately under full cooperation to achieve the long-term climate target. The climate target is then enforced by either a globally uniform carbon tax or an emissions trading regime. By contrast, in the scenarios with limited cooperation (named 450SPA and 550SPA), comprehensive climate policy only starts in the year 2040, but still reaches the same climate stabilization targets as in the cooperative scenarios. Until the year 2040, climate policies are assumed to be fragmented with regionally differentiated carbon prices. Sub-Saharan Africa starts at very low carbon prices of only 1 $/tCO_2$ in 2020 - compared to e.g. 12 $/tCO_2$ in USA or 5 $/tCO_2$ in China. Regional carbon prices converge towards a level of 100 $/tCO_2$ and 21 $/tCO_2$ in 2040 in the 450SPA and the 550SPA scenario, respectively, and further increase exponentially towards 1876 $/tCO_2$ and 386 $/tCO_2$, respectively, in 2100. The long-term carbon tax levels are substantially lower in the full cooperative scenarios, in particular in the 450TAX scenario with a level of 75 $/tCO_2$ in 2040 and of 1395 $/tCO_2$ in 2100.

The assumption on technology cooperation reflects whether international technology diffusion is actively supported or not. Emerging low-carbon technologies such as solar energy, wind power, and

[1] An intermediate overshoot in concentrations during the 21st century is allowed for the 450ppm scenario.

electric- and hydrogen-vehicles are subject to endogenous global technological learning in the REMIND model. Investments into these technologies cause spillover effects between model regions, as the costs for learning technologies decrease irrespective of where the capacity addition is made.

In the scenarios with full cooperation, these spillovers are assumed to be fully internalized – for example by international agreements on technology policy – and the diffusion of low-carbon technologies is consequently accelerated. In the scenarios with limited cooperation, by contrast, spillovers are not internalized -- simulating a world without cooperative technology policy. Technically, full and limited cooperation on technology are modeled by using two different solution algorithms, described in full detail in Leimbach et al. (2016).

The third scenario dimension reflects climate finance as part of international agreements on climate policy, and different underlying equity and fairness criteria. We consider three different possibilities here: No climate finance at all or climate finance realized by two different burden sharing schemes in international climate agreements motivated by equity considerations.

In the scenarios with no climate finance at all (named “TAX” and ”SPA”), regions enact carbon pricing in accordance with an international climate agreement starting in 2015 and 2040 in scenarios with full and with limited cooperation, respectively. There is neither an allocation of emission permits to regions, nor any other sort of financial transfer between model regions. Technically, we compute these scenarios using exponentially rising global carbon tax paths compatible with the respective global climate target[2] to arrive at a cost-efficient solution. In the absence of climate finance, developing regions would face rather high costs (Tavoni et al. 2014) which conflicts with the principle of common but differentiated responsibilities in the Paris agreement.

The two other climate finance scenarios assume an explicit burden sharing scheme as part of an international climate agreement in line with a global climate target. In these cases, climate finance is realized as the allocation of emission permits to regions in accordance to the burden sharing scheme. Once allocated, regions trade emission permits in our model, generating revenue for permit exporting regions – climate finance. Technically, we compute the cost-efficient solution by allocating a permit budget compatible with the global climate target to regions and making sure the permit market clears. We consider two different burden sharing scheme scenarios, motivated by equity considerations: per capita convergence (named “CC”) and population share (“POP”)[3]. In the CC scheme (Meyer, 2000), the global emission permits (determined by the globally optimal emission pathway) are allocated as a weighted average of the regional shares in global emissions in 2005 and an equal per capita share.

[2] Convergence towards the climate target is achieved by iteratively adjusting the initial tax according to the reaction of the climate system, without including the climate system as endogenous part of the optimization problem.

[3] A recent survey of burden sharing schemes is provided by Zhou and Wang (2016).

Weights of the latter increase linearly over time. As of 2050, permits are allocated to the different regions according to the equal per capita rule only.

The POP scheme, not yet used in integrated assessment studies so far, is based on a different rule of equal per capita allocation. The share S of region r in global permits is based on the cumulative population share over the 21st century (*t=1,…,T)*:

$$S_r = \sum_t \frac{P_{r,t}}{\sum_{r\prime} P_{r\prime,t}}$$

Population values $P_{r,t}$ are determined by the SSP2 population scenario described above.

Comparing the two allocation schemes, the POP scheme is more favorable towards developing countries than the CC scheme (and may thus be considered more equitable), especially in ambitious mitigation scenarios, for two reasons: First, In the early century global emissions are still quite high, and hence the global permit budget allocated in each period is large. In the CC scheme, countries with a high initial emission share receive most of these permits. In the POP scheme, by contrast, countries with large populations, in particular those countries with additional high population growth, benefit from the allocation. Second, global emissions have to decline in the second half of the century and can even become negative. As the global emission budget allocated in each period is small, countries with high population and high population growth that under the CC burden sharing scheme get a comparatively low amount of permits in early periods, do not benefit from the equal per capita permit allocation in the second half of the century.

Countries in Sub-Saharan Africa, which in general show high population growth rates, would likely benefit from the POP burden sharing scheme.

3 Development Impacts of Mitigation Policies

In this section we discuss the development impacts of mitigation policies by evaluating the economic cost of mitigation for Sub-Saharan Africa, also in comparison to other regions. As a measure for the mitigation cost, we choose discounted aggregated consumption losses of a mitigation scenario compared to the respective baseline scenario without climate policy. We find that differences in mitigation costs between regions in general are at least as significant as differences between scenarios. Noting that scenario-independent variation of mitigation costs identifies structural differences of regions, we find that regions with a comparatively high income share of energy or with a high share on fossil fuel exports face higher mitigation costs than other regions.

3.1. Mitigation costs in scenarios with varying climate target and cooperation

Differences in mitigation costs are largest along the scenario dimension of ecological efficiency (see Fig. 2). Global mitigation costs amount to 0.4% of discounted consumption for the 550TAX scenario and around 1.5% for the 450TAX scenario. All regions demonstrate higher mitigation costs with a more ambitious climate target. Sub-Saharan Africa faces mitigation costs above global average that amount to 1.4% and 2.9% for the 550TAX and the 450TAX scenario, respectively.

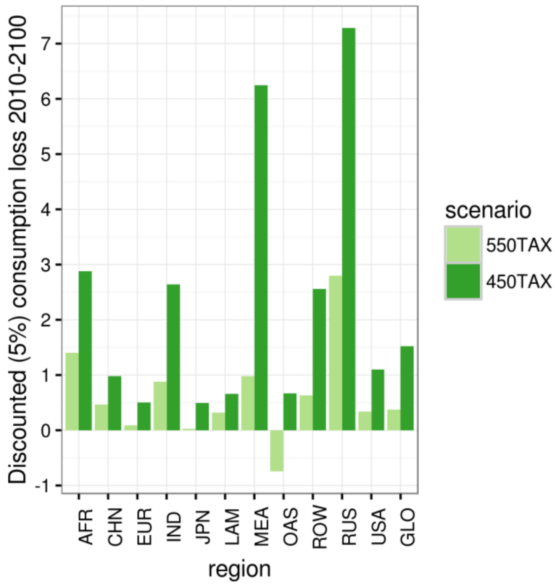


Fig. 2: Mitigation costs under scenarios with varying climate target (AFR - Sub-Saharan Africa, CHN - China, EUR - EU27, IND - India, JPN – Japan, LAM – Latin America, MEA – Middle east and North Africa, OAS – Other Asia, ROW- rest of the World, RUS – Russia, USA – USA, GLO – World)

Limited cooperation increases global mitigation costs. The combined effect of limited cooperation in technology and climate policy results in an increase of mitigation cost at the global level of around 0.04 and 0.2 percentage points for the 550 ppm scenario and the 450 ppm scenario, respectively (see Fig. 3). This is in line with other studies (e.g. Bertram et al., 2015). The isolated technology impact is comparatively small since knowledge spillovers exist in our model independently of whether investors internalize this externality or not. Hence, the cost increase through limited technology cooperation is much smaller than the one through a delay in climate policy.

With delayed cooperation in climate policies, there is a lock-in effect that becomes more costly when technological cooperation is weak. For some regions though, limited cooperation results in lower mitigation costs -- among others for Sub-Saharan Africa. Mitigation costs in Sub-Saharan Africa decline by 0.15 percentage points in the 550 ppm scenario and 0.5 percentage points in the 450 ppm scenario. We identify two reasons for the lower costs: First, increasing demand for modern biomass on international markets. Scenarios with limited cooperation exhibit a very high carbon price in late periods to compensate for higher emissions earlier in the century compared to the cooperative case – this increases the demand for biomass, as it can be used in combination with carbon capture and storage (BECCS) to effectively create negative emission. Sub-Saharan Africa has significant potential for growing biomass, resulting in increasing exports in scenarios with limited cooperation. Second, the very low carbon price in Sub-Saharan Africa early in the century in scenarios with limited cooperation reduces the amount of costly emission reduction measures, and thus lowers mitigation costs.

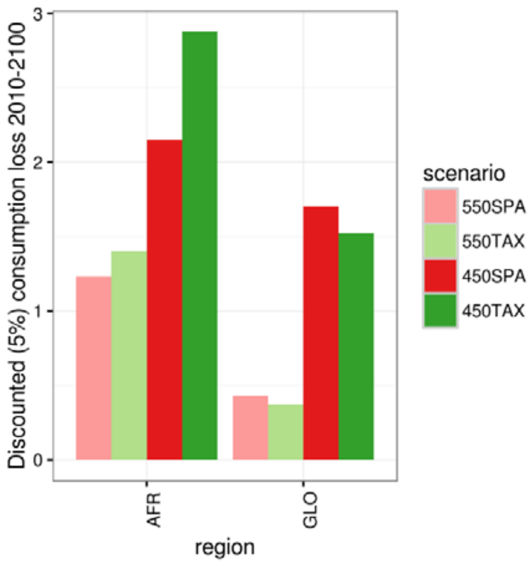


Fig. 3: Mitigation costs under scenarios with varying climate target and cooperation level (TAX – full cooperation, SPA – limited cooperation, AFR – Sub-Saharan Africa, GLO – World)

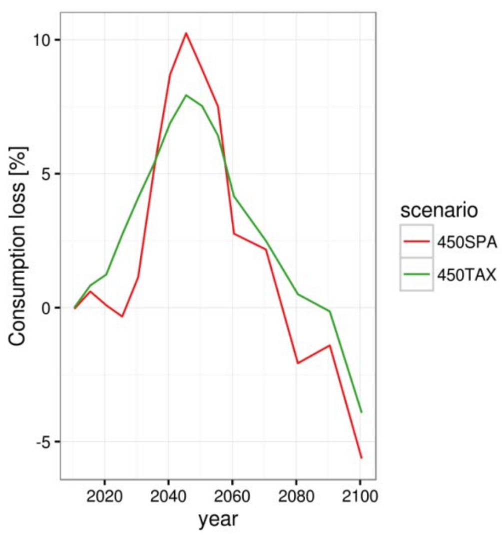


Fig. 4: Mitigation costs of Sub-Saharan Africa over time (mitigation costs are expressed as percentage reduction of baseline consumption in the 450SPA and 450TAX scenario)

While aggregated mitigation costs for Sub-Saharan Africa are lower in the scenario with limited cooperation, the intertemporal distribution of mitigation costs is more extreme compared to the cooperative scenario (Fig. 4). The generations living between 2040 and 2060 are exposed to the highest mitigation costs (between 3% and 10%), whereas the generations alive before 2030 and after 2075 bear no mitigation costs at all. While the cost profile in the cooperative scenario is similar, costs are less extremely distributed over time. This indicates that while immediate participation in a global climate policy agreement is in aggregate more expensive for Sub-Saharan Africa, it may attenuate intergenerational conflicts: a less extreme imbalance of costs and benefits of climate policy over time reduces the challenges associated with the distribution of net costs of climate policy across generations.

Regional mitigation costs have to be interpreted carefully. First, while for most regions mitigation costs are higher in the 450 ppm scenarios than in the 550 ppm scenarios, the more ambitious climate target implies more avoided climate change damages, which are not accounted for in our study. Second, in line with the majority of IA mitigation studies in the literature all climate policy scenarios considered so far assume an eventually uniform global tax to be implemented without any climate finance. While this ensures global efficiency, it disproportionately burdens less affluent countries. Burden sharing schemes that respect differences in historic responsibilities for emissions, as well as capacities to mitigate, change the distribution of mitigation costs, and are analyzed in detail in the next section.

3.2. Mitigation costs in scenarios with varying permit allocation

This section discusses the implications for mitigation costs along the scenario dimension of climate finance and burden sharing. This dimension has no significant global effect, implying that efficiency and distribution are separable in our model – a common feature of many IAMs. By contrast, the effect on the regional distribution of income is very strong: We discuss the implications of different climate finance regimes as introduced in Section 2 for Sub-Saharan Africa. To avoid interference with the dimension of ecological efficiency in interpreting the results, we only compare scenarios with the same climate target.

Sub-Saharan Africa's mitigation costs are very strongly influenced by the climate finance dimension (Fig. 5). Compared to the scenarios without climate finance (450TAX, 550TAX), Sub-Saharan Africa has lower costs in the burden sharing scenarios. Under the per capita convergence scheme and the moderate climate target (550CC), climate finance has a large effect, and even results in negative mitigation costs of -0.5% for Sub-Saharan Africa (see Fig. 5). Under ambitious climate policy, however, the costs only decline moderately to 2.1% (450CC). The reason for this is that at the time when Sub-Saharan Africa can take full advantage of the approached equal per capita allocation of emission permits coincides with the period where the annual global emission budget declines quickly to zero and even below. The second burden sharing scheme (450POP, 550POP), which is based on the cumulated population share, takes the underlying equity principle much better into account and reconciles the potentially opposite dynamics of the emission reduction paths and the demographic trajectory.

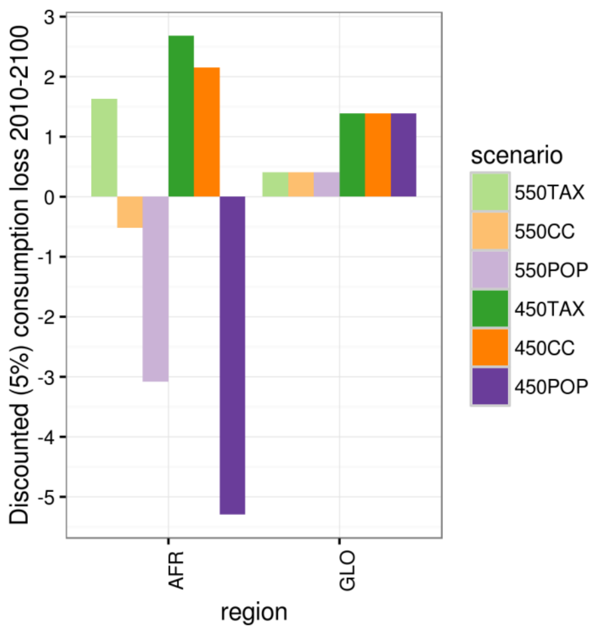


Fig. 5: Mitigation costs under scenarios with varying allocation rules (AFR – Sub-Saharan Africa, GLO – World)

Burden sharing according to population share (450POP, 550POP) results in much larger cost reductions for Sub-Saharan Africa than the CC scheme (Fig. 5). Net costs in the case without climate finance turn into net benefits of mitigation: almost -5.3% of discounted consumption in the 450 ppm scenario and -3.1% in the 550 ppm scenario. For all other regions in aggregate, this implies an increase of mitigation costs in the order of 0.2 percentage points.

To explain why mitigation costs for Sub-Saharan Africa are lower for the more stringent climate target in the 450POP scenario as compared to the 550POP scenario, we decompose the mitigation costs into their drivers (Fig. 6) according to the methodology described in Aboumahboub et al. (2014). In the 450POP scenario, a GDP loss of around 5% and higher energy system costs of around 4% are overcompensated by savings on investments (1%) and fossil imports (3%), combined with additional income from biomass export (3%) and emission permit export (7%). The permit export generates revenues in particular in the first half of the century (e.g. around 340 billion US$2005 in 2030). The mitigation cost structure in the 550POP scenario is qualitatively similar to the one in the 450POP scenario. However, compared to the 550POP scenario, the 450POP scenario exhibits benefits from additional biomass and permit exports that exceed the costs from higher GDP losses and energy system expenditures. In effect, this leads to lower net mitigation costs for Sub-Saharan Africa under the more stringent global target. The prospect of lower costs and net gains, respectively, may provide an incentive for countries in Sub-Saharan Africa to support more stringent climate targets in international negotiations.

The amount of revenues from permit and biomass trading implies huge financial transfers. Jakob et al. (2015) point out that large climate transfers might cause problems if administered poorly. Such a "climate finance curse" could be caused by high volatility of transfers due to large price changes for emission permits, a "Dutch disease" effect, and rent-seeking and corruption. These adverse effects could potentially be avoided through a number of measures including improved (financial) institutions, or international involvement through the Green Climate Fund. Financial transfers thus have a great potential to render a climate agreement equitable, but they must be administered with care.

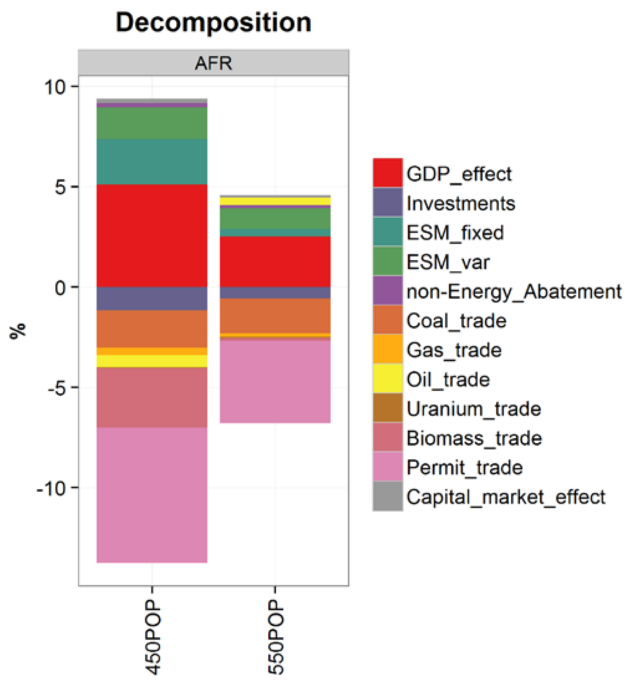


Fig. 6: Decomposition of mitigation costs (contribution of different factors to consumption losses in policy scenarios compared to baseline scenario – negative values represent consumption gains)

4 Transformation of the energy system

Mitigation costs as discussed in the last section arise from a transformation of the energy system away from being based mostly on fossil fuels towards low carbon energy supply. The drastic reductions in global GHG emissions necessary to meet ambitious climate targets are shown in Fig. 7. The climate target (dimension of ecological efficiency) by and large defines the global emission trajectory and hence the necessary mitigation efforts. In the baseline scenario, continued fossil fuel consumption increases greenhouse gas emissions to up to 87 $GtCO_2eq$ in 2080. By contrast, to reach low climate stabilization targets, emissions must decline almost immediately from today's level in the 450TAX scenario, or stabilize at around 55 $GtCO_2eq$ before declining in 2040 in the 550TAX scenario. In the long run, emissions are even negative (CO_2 removal from the atmosphere with technologies like BECCS) in the 450TAX scenario, or close to zero in the 550TAX scenario.

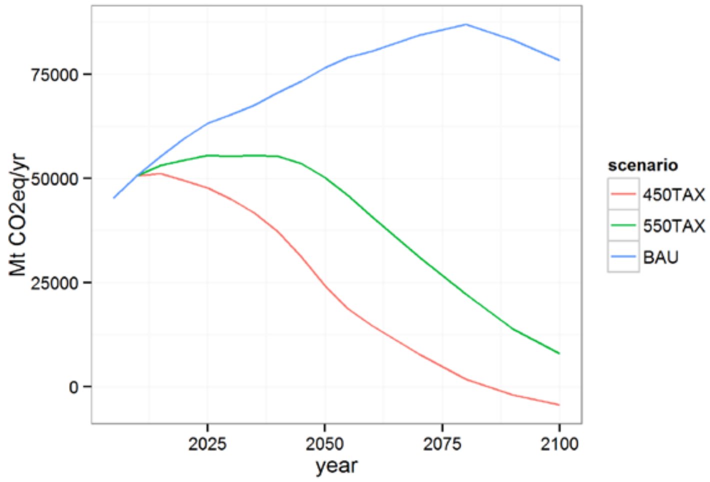


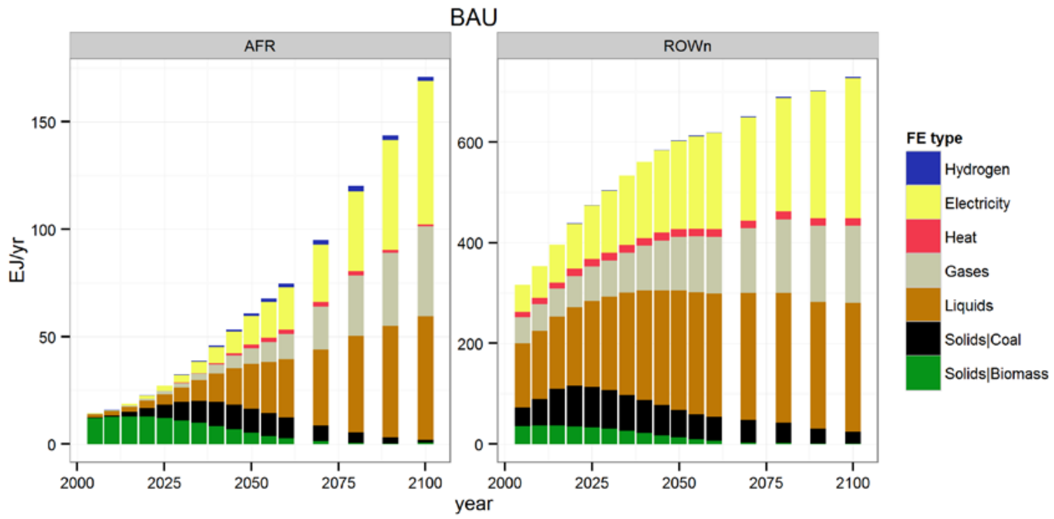
Fig. 7: Total GHG emissions in Mt CO_2 equivalent

4.1 Transformation under full cooperation

In this section, we discuss the challenges of the low carbon transformation of the energy system in Sub-Saharan Africa in the case of fully cooperative scenarios. As the equity dimension has no impact on this transformation, we focus on comparing BAU and TAX scenarios.

Sub-Saharan Africa has the highest growth rate in energy demand across model regions during the 21st century (Fig. 8). Acceleration of economic growth in early development stages is often very energy intensive. Under climate policy, countries in Sub-Saharan Africa face two mayor challenges regarding their energy system transformations: First, the growth in energy consumption has to be reduced from baseline levels. The 450TAX (Fig. 8) and 550TAX scenarios show around 20% less final energy consumption in 2050 and beyond, implying large efforts in increasing energy efficiency.

Second, while in the baseline scenario the use of final energy shifts slowly from solids (first traditional biomass, later coal) towards a balanced mix between liquids, gases, and electricity, the increase in the electricity share is much faster in climate policy scenarios. In the 450TAX scenario the electricity share is above 30% in 2050 and above 70% in 2100 - much higher than the share of 40% in 2100 in the baseline scenario. The higher electricity share requires increasing installed capacities by almost 10% per year over the next two decades, which is close to the 13% that Bazalian et al. (2012) mention as what is required to provide universal electricity access in Sub-Saharan Africa.



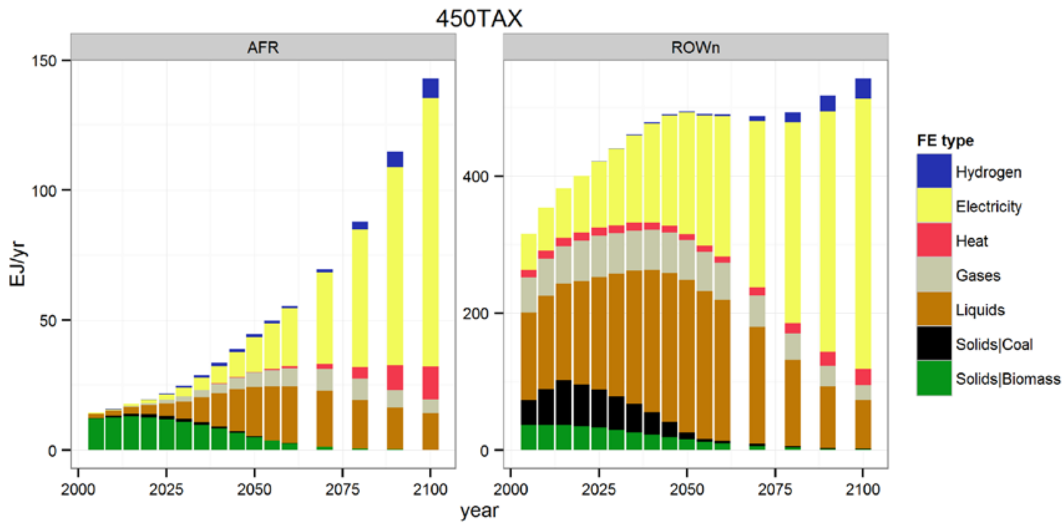


Fig. 8: Final energy demand of Sub-Saharan Africa and all other regions (ROWn) (upper panel: baseline scenario; lower panel: policy scenario)

Despite increasing energy demand, final energy intensity is decreasing over time in all regions under climate policy (Fig. 9): In the 450TAX scenario, the global average declines from 7.3 MJ/$US2005 to 2.3 MJ/$US2005. Sub-Saharan Africa converges towards the global average in 2100 starting from a final energy intensity of more than 30 MJ/$US2005 in 2005. Convergence of regional final energy intensity is less pronounced in relative terms. The ratio between the highest and lowest regional intensity decreases from around 10 to 5 between 2005 and 2100.

Final energy per capita also converges slowly across regions (Fig. 9). Countries in Sub-Saharan Africa increase their per capita demand significantly, while having still a lower demand than the developed regions that either keep their current levels or as for the USA reduce them substantially.

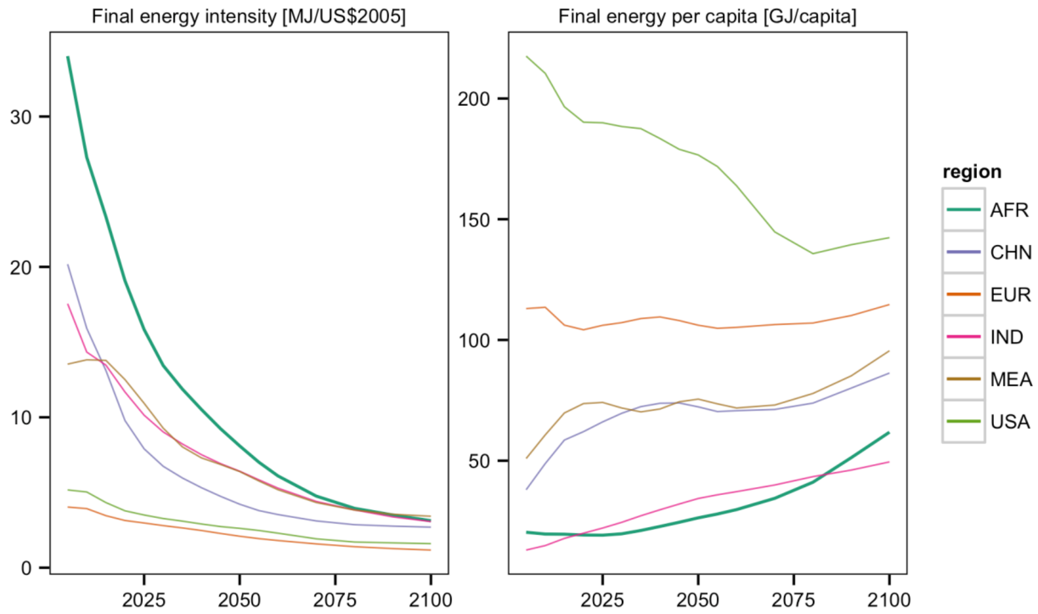


Fig. 9: Final energy intensity (left) and final energy demand per capita (right) in 450TAX scenario; the thick black line represents Sub-Saharan Africa

Climate policy implies a major shift from the use of conventional energy conversion technologies (e.g. coal-fired power plants) to modern and more capital intensive renewable energy technologies (solar and wind). While the primary energy mix in both policy scenarios already demonstrates some divergence from the baseline energy mix in 2050, it is completely different in 2100 (Fig. 10). In the short-term, the use of coal is nearly completely phased out and use of gas is significantly reduced in the policy scenarios. In the 450TAX scenario, coal and gas are only used in combination with CCS technologies. Oil is used over the whole century (to a smaller extent in the 450TAX scenario than in the 550TAX scenario) since a full decarbonization of the transport sector is more costly than mitigation options in other end use sectors.

Differences in the energy mixes between the 450TAX and 550TAX scenarios indicate different mitigation strategies. Up to 20% less primary energy consumption (e.g. in 2025 and 2070 – see Fig. 10) in the 450TAX scenario compared to the 550TAX scenario results from higher energy efficiency improvements in scenarios with more ambitious climate targets. Also CCS becomes much more relevant in these scenarios. CCS is of particular relevance when used in combination with biomass, as this allows to generate negative emissions.

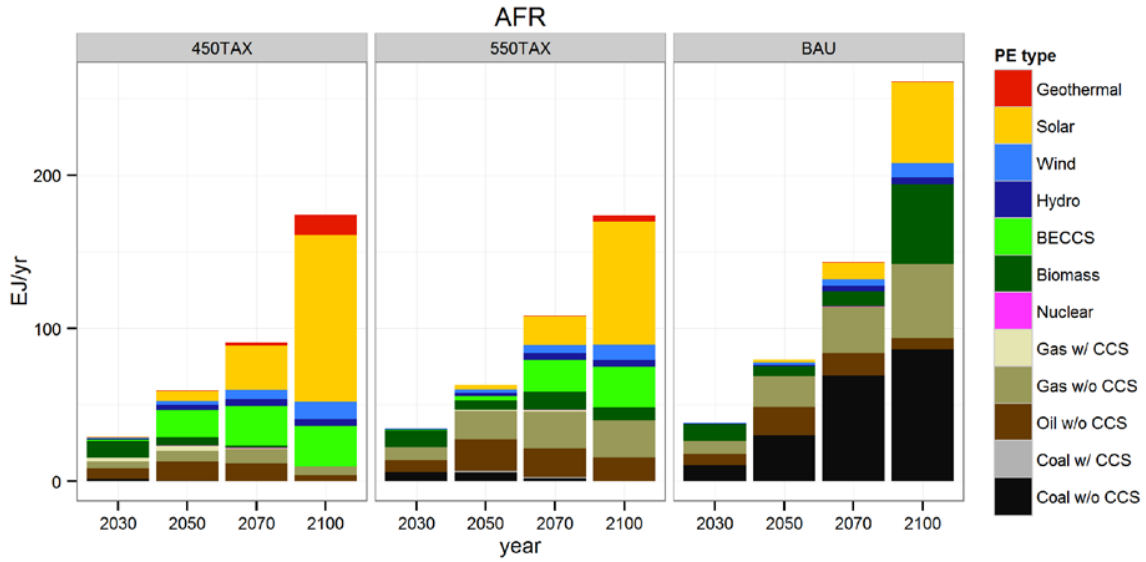


Fig. 10: Consumption of primary energy carriers in Sub-Saharan Africa at selected years for 450TAX, 550TAX and BAU scenarios (BECCS – biomass use with carbon capture technologies, CCS – carbon capture technologies)

The optimal primary energy consumption path of the model region Sub-Saharan Africa under ambitious climate policy can be summarized as follows: Until 2050, production of biomass is scaled up drastically. From mid-century on massive investments into renewable energies, predominantly solar energy, follow. This scenario thus hinges on the availability of the technology for modern biomass in the medium term and solar energy in the long term. While Sub-Saharan Africa is well endowed with natural capacities for biomass production and solar energy, second-best conditions may make the implementation of this first best strategy difficult (Staub-Kaminski et al, 2014). As one example, building up a specialized workforce in a technology-intensive energy sector is a huge challenge.

Ambitious climate polices requires significant increases in energy system investments. As shown in Fig. 11, energy system investments in 2100 in the 450TAX scenario exceed the baseline investments by more than 30% in Sub-Saharan Africa. This implies an increase of the energy investment share in GDP from 6% today to 10% over the next three decades. By contrast, the average share across other regions is below than 5% today and declining. Around one third of Sub-Saharan Africa's energy investments in the second half of the century are into solar power.

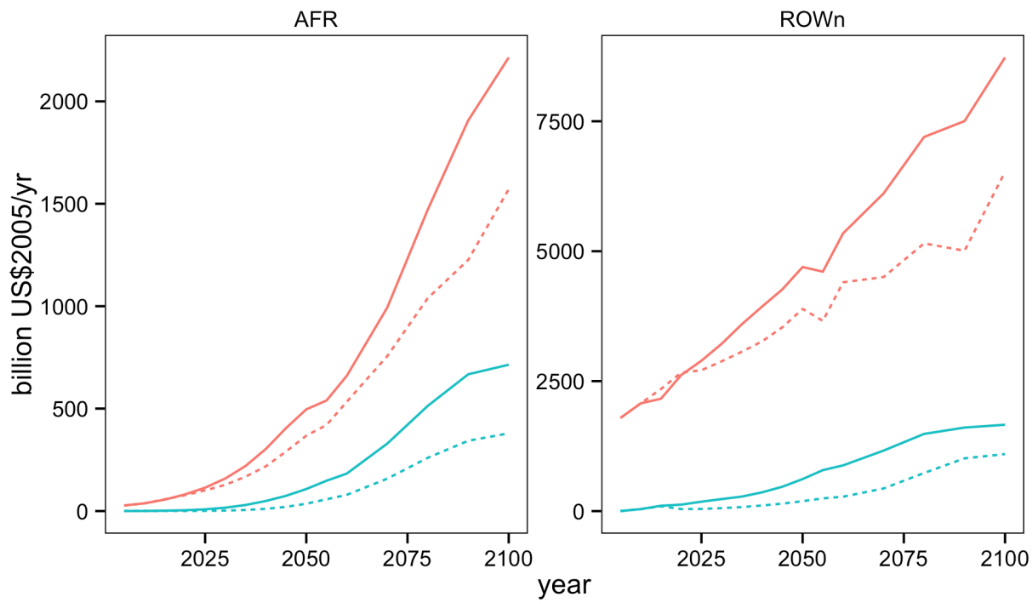


Fig. 11: Energy system investments in baseline scenario (dotted lines) and 450TAX scenario (solid lines); Total energy investments in red; investments in solar technologies in blue.

4.2. Transformation under limited cooperation

Scenarios that differ in their levels of cooperation show different global mitigation strategies, though the impact is less significant than for the variation of the climate target. In scenarios with limited cooperation, carbon pricing is very low early in the century in Sub-Saharan Africa, and technology diffusion is not actively supported by global technology policies. As a result, the buildup of low-carbon technologies is slowed down compared to a scenario with full cooperation. For example, the share of solar power in the electricity mix of Sub-Saharan Africa in 2050 is only 25% in the scenario with limited cooperation (450SPA), while much higher at 42% in the cooperative scenario (450TAX).

Furthermore, limited cooperation implies more fossil use and slower reductions in primary energy consumption: The coal share in primary energy is still around 20% in 2030 in the 450SPA scenario, while less than 5% in the 450TAX scenario. Primary energy consumption is also significantly higher in the year 2030: 33 EJ in the non-cooperative and 29 EJ in the cooperative scenario. Limited cooperation requires higher emission reduction rates in Sub-Saharan Africa midcentury compared to the full cooperative scenario.

While limited cooperation on climate policy implies lower mitigation costs for Sub-Saharan Africa, one of the risks is a potential carbon lock-in: For countries in Sub-Saharan Africa, many of which have to build up large power generation capacities in the near term, the low carbon price in the early periods in the limited cooperation scenarios results in a quite carbon-intensive energy mix, compared to the scenarios with full cooperation. This so called carbon lock-in, as discussed in detail in Bertram et al. (2015), may be problematic for at least two reasons: First, if countries should depart from the limited cooperation scenario and enact more stringent climate policy earlier than originally intended, parts of the fossil fuel infrastructure would have to be retired before the end of their long economic life-times – the risk of stranded assets. Second, there may be path-dependencies associated with energy investments, energy infrastructure, or the political economy beyond the ones reflected in our model. If that were the case, delayed climate policy like in the scenarios with limited cooperation would be more costly for countries in Sub-Saharan Africa, as they would face difficulties and bear costs beyond those modeled here during their low-carbon transformations later in the century.

4.3. Distributional effects of climate change mitigation within Sub-Saharan Africa

While REMIND is well suited to analyze distributional effects of climate change mitigation between regions, some conclusions can be drawn on the distributional effects within regions as well. A large share of the African population currently lives on incomes below the poverty line and a substantial fraction of expenses in poor households is used for energy. Kaygusuz (2011) states that "The International Energy Agency (IEA) expects that the number of people depending on biomass for cooking will rise to around 2.7 billion in 2020, from 2.5 billion today". Most of these people will likely live in Africa. Hailu (2012) finds that in 2011 585 million Africans (30.5%) had no access to electricity. Rising overall energy prices could worsen poverty and increase inequality, since people without access to electricity have to acquire liquid and solid fuels that are likely subject to relatively higher price increases (see below). They would thus be disproportionally affected by rising energy prices (Jakob and Steckel, 2013).

Higher energy prices due to climate policy might thus reduce the remaining income of the poor even more and cause or worsen energy poverty for this large part of the population. This can be illustrated with a simple identity,

$$I - pE = C \qquad (1).$$

Here I is the income of a certain income group, E is subsistence-level final energy consumption as defined in Barnes et al. (2011) for example, p is the price for energy and C is remaining consumption (including energy consumption above subsistence level).

In order to determine the long run development of the remaining consumption we can represent income as

$$I = \varphi Y \qquad (2).$$

φ is the income share of a particular income group, in our case the bottom 10% for example will be of particular interest. Y is total economic output. The growth rate of the remaining consumption is thus given by

$$\frac{\acute{C}}{C} = \acute{\varphi}\frac{Y}{C} + \acute{Y}\frac{\varphi}{C} - \acute{p}\frac{E}{C} - \acute{E}\frac{p}{C} \qquad (3).$$

It follows that this growth rate will be positive if and only if

$$\frac{\acute{\varphi}}{\varphi} + \frac{\acute{Y}}{Y} > \left(\frac{\acute{p}}{p} + \frac{\acute{E}}{E}\right)\frac{pE}{C+pE} \qquad (4).$$

We can thus study the effect of climate change mitigation on non-energy consumption by going through the parts of this inequality.

The amount of subsistence level energy consumption, E, seems to be constant over time. Barnes et al. (2011) point out that the minimum requirement may depend on culture, which determines cooking habits, and region, which determines heating requirements, but does not mention dependence on time. Krugmann and Goldemberg (1983) do not consider time variance either. We thus assume E to be time invariant.

The share of income received by the poorest households φ might change for two reasons. One reason is the natural evolution of inequality. Deininger and Squire (1996, Table 5), see the Gini coefficient in Africa fluctuating between 43 and 50 (on a scale from 0 to 100) between the 1960s and the 1990s. Alvaredo and Gasparini (2011) review several publications on inequality in Africa and find that it stayed quite stable in the 1990s and 2000s. We therefore assume that inequality within Africa is roughly stable over time. The second reason why the share of income for the poorest households may rise could be pro-poor redistribution by the government. In order to identify potential adverse consequences of climate policy, we assume that governments do not engage actively in reducing inequality and thus keep φ constant.

If E and φ are constant and C is small, inequality (4) shows that the sign of the growth rate of consumption for goods other than minimum energy requirements depends strongly on the relative size of the growth rate in output Y and the energy price p. To be precise, the growth rate is only positive if the growth rate of output is larger than the product of the growth rate of the energy price and the share of energy expenditures in total income *pE/(pE + C)*. In effect, as a rule of thumb, the growth rate of consumption is only positive if the growth rate of output is much larger than the grow rate of the energy price. Figure 12 shows the level of per capita income and final energy prices in REMIND compared to the base year 2010. The development of these variables in the business-as-usual scenario is contrasted to those in a scenario with ambitious climate policy. We chose the price for liquids as representative for energy from fossil fuels. The share of households in Sub-Saharan Africa using liquid fuels (kerosene and liquefied petroleum), although still low today, is significant and increasing. Its importance is emphasized by Pachauri et al. (2012). Climate policy sets up a carbon price and causes the price for liquid energy to rise much faster in the policy scenario (450TAX). While liquid fuels are to a significant share fossil-based even in the second half of the century, electricity generation has quickly been decarbonized, so that electricity prices grow much more slowly than prices for liquid energy in all scenarios.

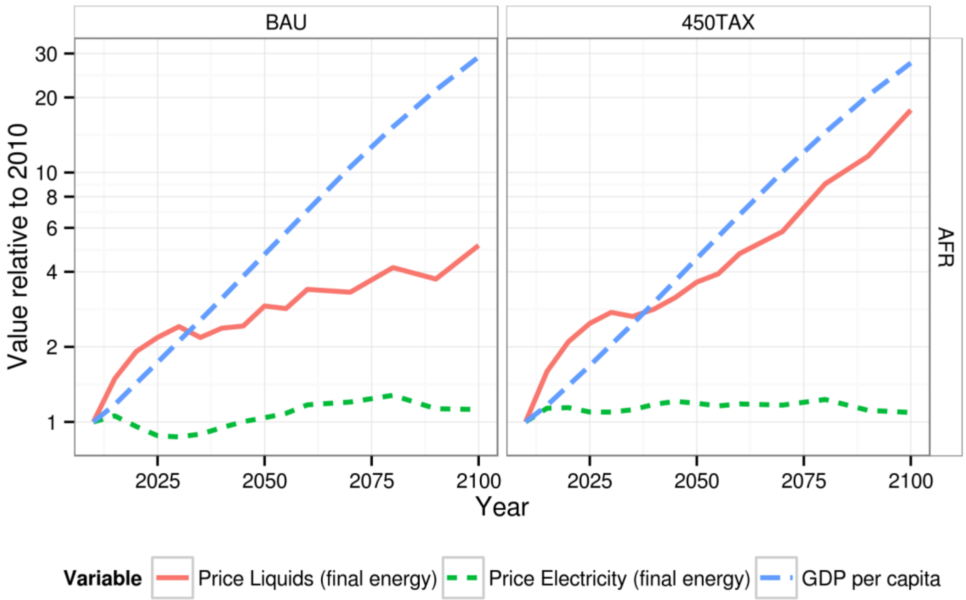


Fig.12: Time series of the growth in income per capita, prices for liquids, and the electricity price in the baseline and 450TAX scenario (variables are normalized to their values in 2010, and shown on a logarithmic scale)

The low rate of electrification in Africa cited above implies that the poorest households currently strongly rely on traditional biomass (solids) and fossil liquid fuels. If this dependence persists, the simulation results indicate that they will see a declining share of non-energy consumption until 2030. Climate policy would in addition strongly reduce the scope to increase it until the year 2100. The price of liquid fuels would increase five-fold in the business-as-usual scenario and by a factor of 18 in the climate policy scenario. Significant parts of additional income would have to be used in order to compensate this price increase. If the dependency on traditional biomass and fossil fuels would continue it could be argued that climate policy puts a severe burden on the poorest households.

Active redistribution policy would thus be needed to allow the poorest income group to benefit from growing GDP. One option is to increase their share φ of income so that they can consume more in spite of the higher expenses for liquid fuels. An alternative option, which is line with the high electricity share in the model results (see figure 8), would be to expand the electricity grid. In this way, ambitious climate policy, which entails a strong shift from fossil fuels to renewables and rapid electrification, will provide the poorest part of the population with access to a cleaner and more versatile kind of energy. Prices of electricity are expected to show a low rate of increase. According to model results, the price of electricity rises only by about 10% until 2100 in the case of cooperative climate policy (figure 12). Electrification and grid expansion is in line with previous proposals in the literature (Casillas and Kammen, 2010). There would thus be a strong synergy effect between poverty eradication and climate change mitigation.

5 Conclusion

Climate stabilization at acceptable global costs requires contributions of developing countries to global greenhouse gas emission reductions, which may put their development perspectives at risk. Our study provides a quantitative assessment of the costs and non-environmental benefits of global climate stabilization regimes for Sub-Saharan Africa. We show that countries in Sub-Saharan Africa could implement stringent climate policies at roughly zero net costs if international transfers facilitated by equitable burden sharing schemes are agreed upon by the international community. Revenues from the export of biomass – which is in high demand under stringent climate policies – present additional opportunities to reduce the costs of a climate stabilization regime. Net mitigation costs consequently vary between -5% and 3% across the range of analyzed scenarios.

The absence of painful trade-offs between economic development and climate protection given the commitment of the international community to an equitable burden sharing may provide policy makers with more options for climate policies than previously thought: First, the potentially low costs make joining climate stabilizations regimes more attainable for countries in Sub-Saharan Africa. Second, the potentially very regressive effects of climate policy found in our study require attention in policy design and the consideration of complementary policies. For example, there may well be synergies with poverty eradication through the provision of access to electricity.

It would be desirable to complement our analysis with case studies on specific countries of Sub-Saharan Africa and with models that emphasize the structural specifics of Sub-Saharan countries. This would allow validating the low-carbon transformation pathways we derive on an aggregated regional scale on the country level. Furthermore, it may be worthwhile to pursue more research on other climate finance options than the ones considered here. If the large transfers implied by burden sharing schemes deemed equitable should not be feasible, other ways to incentivize Sub-Saharan Africa and to implement the principle of common but differentiated responsibilities, as acknowledged by the Paris agreement, will have to be found.

Acknowledgements

Funding from the German Federal Ministry of Education and Research (BMBF) within the call Economics of Climate Change (funding code 01LA1105A, CliPoN) is gratefully acknowledged.

References

Aboumahboub, T., Luderer, G., Kriegler, E., Leimbach, M., Bauer, N., Pehl, M., and Baumstark, L. (2014). On the regional distribution of climate mitigation costs: The impact of delayed cooperative action. Climate Change Economics, 5(01).

Alvaredo,F. and Gasparini, L. (2011). Chapter 9 - Recent Trends in Inequality and Poverty in Developing Countries, In: Anthony B. Atkinson and François Bourguignon, Editor(s), Handbook of Income Distribution, Elsevier, 2015, Volume 2, Pages 697-805

Barnes, D., Khandker, S., and Samad, H. (2011). Energy poverty in rural Bangladesh. Energy Policy 39, 894-904.

Bauer, N., Baumstark, L., Leimbach, M. (2012): The REMIND-R model: the role of renewables in the low-carbon transformation - first-best vs. second best worlds. Climatic Change 114, 145-168.

Bazilian, M., Nussbaumer, P., Rogner, H.-H. et al. (2012): Energy access scenarios to 2030 for the power sector in Sub-Saharan Africa. Utilities Policy 20, 1-16.

Bertram, C., Luderer, G., Pietzcker, R., Schmid, E., Kriegler, E., Edenhofer, O. (2015). Complementing carbon prices with technology policies to keep climate targets within reach. Nature Climate Change 5, 235–239.

Calvin, K., Pachauri, S., De Cania, E., Mouratiadou, I. (2013): The effect of African growth on future global energy, emissions, and regional development. Climatic Change, DOI: 10.1007/s10584-013-0964-4.

Casillas, C. and Kammen, D. (2010). The energy-poverty-climate nexus. Science, 330(6008):1181-1182.

Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P.R. Shukla, M. Tavoni, B.C.C. van der Zwaan, and D.P. van Vuuren (2014), "Assessing Transformation Pathways", ", In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 1–31.

Collier, P. , Conway, G., Venables, T. (2008). Climate change and Africa. Oxf Rev Econ Policy 24 (2): 337-353.

Cole, M. A., Elliott, R. J., Strobl, E., et al. (2014). Climate change, hydro-dependency, and the african dam boom. World Development, 60(C):84-98.

Collier, P. and Venables, A. J. (2012). Greening Africa? Technologies, endowments and the latecomer effect. Energy Economics, 34:S75-S84.

Dasappa, S. (2011). Potential of biomass energy for electricity generation in sub-saharan africa. Energy for Sustainable Development, 15(3):203-213.

Deininger, K. and Squire, L. (1996). A new data set measuring income inequality. The World Bank Economic Review, 10(3):565-591.

Dellink et al. (2016), Long-term growth projections in Shared Socioeconomic Pathways. Submitted to Global Environmental Change, in press.

Fouquet, R. (2010). The slow search for solutions: Lessons from historical energy transitions by sector and service. Energy Policy, 38(11):6586-6596.

Gray, C. and Mueller, V. (2012). Drought and population mobility in rural ethiopia. World Development, 40(1):134-145.

Hailu, Y. G. (2012). Measuring and monitoring energy access: Decision-support tools for policymakers in Africa. Energy Policy 47, Supplement 1, 56-63.

Jakob, M. and Steckel, J. C. (2013). How climate change mitigation could harm development in poor countries. Wiley Interdisciplinary Reviews: Climate Change, 5(2):161-168.

Jakob, M., Steckel, J. C., Klasen, S., Lay, J., Grunewald, N., Martínez-Zarzoso, I., Renner, S., and Edenhofer, O. (2014). Feasible mitigation actions in developing countries. Nature Climate Change, 4(11), 961–968.

Jakob, M., Steckel, J. C., Flachsland, C., and Baumstark, L. (2015). Climate finance for developing country mitigation: blessing or curse? Climate and Development, 7(1):1-15.

Kaygusuz, K. (2011). Energy services and energy poverty for sustainable rural development. Renewable and Sustainable Energy Reviews, 15(2):936-947.

KC, S., Lutz, W. (2016). The Human Core of the SSPs: Population Scenarios by Age , Sex and Level of Education for all Countries to 2100. Global Environmental Change, in press.

Kriegler E, Weyant JP, Blanford GJ, et al. (2014) The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Climatic Change 123:353–367. doi: 10.1007/s10584-013-0953-7

Krugmann, H. and Goldemberg, J. (1983). The energy cost of satisfying basic human needs. Technological forecasting and social change, 24(1):45-60.

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

Leimbach, M., Schultes, A., Baumstark, L., Giannousakis, A., Luderer, G. (2016). Solution algorithms of large-scale Integrated Assessment models on climate change, submitted to Annals of Operations Research.

Lucas, P. L., Nielsen, J., Calvin, K., McCollum, D. L., Marangoni, G., Strefler, J., van der Zwaan, B. C., and van Vuuren, D. P. (2015). Future energy system challenges for africa: Insights from integrated assessment models. Energy Policy, 86:705-717.

Luderer G., DeCian E., Hourcade J.-C., Leimbach M, Waisman H., Edenhofer O. (2012). On the regional distribution of mitigation costs in a global cap-and-trade regime. Climatic Change 114, 59-78.

Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., Baumstark, L., Bertram, C., Giannousakis, A., Hilaire, J., Klein, D., Levesque, A., Mouratiadou, I., Pehl, M., Pietzcker, R., Piontek, F., Roming, N., Schultes, A. and Schwanitz, V. J., Strefler, J. (2015), Description of the REMIND Model (Version 1.6) (November 30, 2015). Available at SSRN: http://ssrn.com/abstract=2697070.

Marcotullio, P. J. and Schulz, N. B. (2007). Comparison of Energy Transitions in the United States and Developing and Industrializing Economies. World Development, 35(10):1650-1683.

Meinshausen, M., T. M. L. Wigley, and S. C. B. Raper (2011). Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications. Atmospheric Chemistry and Physics 11.4, pp. 1457–1471.

Meyer, A. (2000). Contraction & Convergence: the GlobalSolution to Climate Change. Schumacher Briefing No.5, Green Books Ltd., Foxhole.

Pietzcker, R., Stetter, D., Manger, S., Luderer, G. (2014). Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power. Applied Energy 135, 704-720.

Pachauri, S., A. Brew-Hammond, D. F. Barnes, D. H. Bouille, S. Gitonga, V. Modi, G. Prasad, A. Rath and H. Zerriffi, 2012: Chapter 19 - Energy Access for Development. In Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1401-1458.

Smil, V. (2000). Energy in the twentieth century: resources, conversions, costs, uses, and consequences. Annual Review of Energy and the Environment, 25(1):21-51.

Sokona, Y., Mulugetta, Y., Gujba, H., et al. (2012). Widening energy access in africa: Towards energy transition. Energy Policy, 47(S1):3-10.

Staub-Kaminski, I., A. Zimmer, M. Jakob, R. Marschinski (2014): Climate Policy in Practice: A Typology of Obstacles and Implications for Integrated Assessment Modeling. Climate Change Economics 5 (1).

Tavoni, M., E. Kriegler, E., K. Riahi, D. P. van Vuuren, T. Aboumahboub, A. Bowen, K. Calvin, E. Campiglio, T. Kober, J. Jewell, G. Luderer, G. Marangoni, D. McCollum, M. van Sluisveld, A. Zimmer, B. van der Zwaan (2014). Post-2020 climate agreements in the major economies assessed in the light of global models. Nature Climate Change DOI: 10.1038/NCLIMATE2475.

Van Aelst, K. and Holvoet, N. (2016). Intersections of gender and marital status in accessing climate change adaptation: Evidence from rural Tanzania. World Development, 79(C):40-50.

Ward, P. and Shively, G. (2012). Vulnerability, income growth and climate change. World Development, 40(5):916-927.

Zhou, P., Wang, M. (2016), Carbon dioxide emissions allocation: A review. Ecological Economics 125, 47-59.

Kapitel 5

Land Impacts

–

Biased Climate Damages and their Intergenerational Impacts[1]

Anselm Schultes
Ottmar Edenhofer
Marian Leimbach

[1] Submitted to The Scandinavian Journal of Economics.

Climate Damages on Land and their Intergenerational Impacts

Anselm Schultes*†‡, Ottmar Edenhofer †‡§, Marian Leimbach †

January 28, 2016

Abstract

Land is prone to climate change damages, and the reflection of such damages in the price of land changes the incentives for climate policy. We model climate impacts and policy for land-biased climate damages with distinct overlapping generation and endogenous capital formation. We find large economic impacts of land-biased damages caused by increasing distortionary land rents. Additionally, land-biased climate damages lower the incentive to enact climate policy, as avoiding climate damages would devalue land assets. In effect, this reduced incentive may lead climate policy further away from the social optimum, aggravating the intergenerational conflict that climate change is.

Keywords: climate damages; climate impacts; land rents; Integrated Assessment; asset pricing; Pareto-improving climate policy ; Portfolio effects
JEL classification system: E24,H23,Q54,E22,Q24

*Corresponding author: schultes@pik-potsdam.de; Potsdam Institute for Climate Impact Research, P.O.Box 601203, 14412 Potsdam, Germany; Phone +49 331 288 20781

†Potsdam Institute for Climate Impact Research

‡Technische Universität Berlin.

§Mercator Research Institute on Global Commons and Climate Change

1 Introduction

Climate change threatens human well-being and economic activity in many different ways. The simplistic representation of climate damages and impacts is a common criticism of Integrated Assessment Models of climate change (IAMs) (Pindyck 2013; Stern 2013). Our greenhouse gas emissions today will affect many future generations to come – generations who will also profit from our investments into various forms of capital and resulting economic growth, and eventually buy fixed assets from us. The most prominent fixed asset is agricultural land: It makes up a significant share of wealth in developing economies (World Bank 2010) and is particularly exposed to climate damages (Pachauri et al. 2014; World Bank 2013; Rosenzweig et al. 2013). Land forms a link between generations – the interaction with climate damages and the implications of that for climate policy are not fully captured by the usual IAMs.

We model the link between land-biased damages and long term economic growth driven by capital accumulation in a general equilibrium model with stock pollution. Land is a fixed factor in production, and is traded across generations. Generations are not assumed to be altruistic towards their successors. Today's price of land capitalizes future returns to land, reflecting damages from climate change – the price of land thus affects the incentive to enact climate policy. Climate policy in our model may either be enacted in a Pareto-improving way by generations responding to economic incentives, or may take the welfare of future generations into account through socially optimal climate policy. This paper addresses two main questions: What are the impacts of land-biased climate damages on long-term economic growth? How are the incentives for climate policy affected by land-biased damages? We do not strive to quantify climate impacts in this paper, this work instead focuses on impact *mechanisms* of damages – meant to inform quantitative modeling attempts.

IAMs are commonly used to evaluate optimal climate policy (Nordhaus 1993; Weyant et al. 1996); they extend a macro-economic core model by including representations of the energy, the climate, and the land-use system in varying detail. IAMs of the optimal growth used for cost-benefit analysis type typically make two assumptions: Perfect altruism of generations towards their successors, and climate damages on aggregated economic output only. First, assuming perfect altruism, distinct generations can be aggregated into an infinitely-lived agent (ILA) model, such as Ramsey's representative agent model (Ramsey 1928). However, there is evidence that altruism towards future generations is far from perfect (Laitner and Ohlsson 2001; Kopczuk and Lupton 2007). By contrast, overlapping generations (OLG) models do not assume perfect altruism (Barro 1974; Michel et al. 2006). As a consequence, distribution between the distinct generations in an OLG model can be meaningfully discussed, and land rents are not neutral as in the ILA model, because the distribution of rents has efficiency effects (Feldstein 1977; Calvo et al. 1979; Edenhofer et al. 2015). Second, IAMs rely on highly aggregated damage representations: damages are usually represented as a reduction in economic output only (Kopp et al. 2012).

We extend the results from Karp and Rezai (Karp and Rezai 2014b; Karp and Rezai

2014a), who use an OLG model, but keep the assumption of aggregated damages on output only. Karp and Rezai (2014b) argue that the asset price increase in response to mitigation has been neglected in the analysis of climate policy: The price increase transfers some of the future benefits from avoided damages to today's generation, increasing the incentive for mitigation. We go beyond their model in including two separate assets, capital and land, and allow for land-biased damages, and non-unitary elasticity of substitution in production.

We find two impact channels of climate damages on growth and climate policy that go unobserved in the existing literature: Land-biased damages raise future scarcity rents, shifting today's savings from productive capital investments towards buying land, in effect reducing growth. Additionally, the incentive to mitigate land-biased damages is reduced, as doing so would decrease the value of the land holdings: The asset price link between generations provides less incentives to internalize land-biased climate damages than in the case of the usual more aggregated damages specification.

The next section introduces the relation to the previous literature, followed by a description of our model in Section 3. Section 4 discusses the impact of land-biased damages on growth, and Section 5 includes climate policy as a mitigation option against those damages.

2 Literature

IAMs contain highly aggregated representations of climate damages: IAMs of the optimal growth type usually include a reduction in the level of output as the only climate damage (Kopp et al. 2012). Impacts on the growth rate, or on capital depreciation rates have been considered (Moyer et al. 2014; Moore and Diaz 2015) – and found to result in much more stringent optimal climate policy. By contrast, models of the computable general equilibrium type include sectoral damages in more detail, but fail to represent drivers of long-term economic growth (Ciscar et al. 2011) – and consequently miss out on potential climate impacts on growth. The microeconomic literature provides broad evidence of climate damages on, among others, labor productivity, crop yields, and human health (Dell et al. 2014; Dell et al. 2012). It is thus desirable to model climate impacts based directly on the damages on factor inputs and their productivities, instead of relying on highly aggregated damage functions.

Land is especially prone to damages from climate change. Agricultural yields will be strongly affected by climate change (Rosenzweig et al. 2013). Yield changes can be positive or negative depending on the region, but negative impacts are expected to outweigh the positive ones (Pachauri et al. 2014). In sum, climate change is one mayor factor among others contributing to the expected increase in economic pressure on the land use system (Hertel 2011).

While agricultural land makes up significant parts of total wealth in developing economies (World Bank 2010), land wealth in more advanced economies is mostly urban land (Caselli and Feyrer 2007). Recent literature argues out that distinguishing land and capital as separate assets is crucial to understand trends in wealth, and the wealth distribution among individuals in advanced economies (Stiglitz 2015; Homburg 2014a).

We build on the overlapping generations model of Karp and Rezai (Karp and Rezai 2014b; Karp and Rezai 2014a), who stress the importance of asset prices for climate policy. The asset price capitalizes future avoided climate damages and thus transfers some of the benefits from climate policy to today's asset owners. Karp and Rezai (2014a) confirm this result in a setting with endogenous capital accumulation and stock pollution, where the long-lived asset is capital subject to adjustment costs.

One strand of literature explicitly models investment choice including multiple assets: Feldstein (1977) shows that in the presence of multiple assets, the incidence of a tax on the fixed factor land may be shifted away from land by a Portfolio effect. Land rents and taxes on them are thus not neutral, meaning they have efficiency effects for the economy. Calvo et al. (1979) argue that this non-neutrality of rents depends on the modeling of distinct, non-altruistic generations, and rents are neutral once perfect altruism à la Barro (1974) is assumed. Taxing land rents may redirect savings from holding land into productive capital investments (Edenhofer et al. 2015). By the same token, Siegmeier et al. (2015) show that climate policy may have lower costs if it redirects fossil resource rents into productive capital investments.

In our work, we treat asset price effects from climate policy following Karp and Rezai (2014b) while including Portfolio effects to develop an understanding of the impact mechanisms of land-biased damages.

3 Model

We include the fixed factor land in the Diamond-Samuelson (Diamond 1965) overlapping generations model, following Homburg (1991) and Kim and Lee (1997). The modeling of distinct generations – instead of an infinitely-lived agent as in a Ramsey model – serves two purposes: First, as land is explicitly traded across successive generations, land and capital compete for the savings of each generation, and the interaction of land rents and capital accumulation can be studied. Second, the distribution of income between generations, and the incentives for each generation to enact climate policy are explicitly included. Additionally, overlapping generation models allow for a clear separation of private savings motives, and normative concerns of intergenerational equity and justice (Schneider et al. 2012).

3.1 Households

There is an infinite succession of non-altruistic, finitely lived households, interacting with firms in a competitive general equilibrium (Diamond 1965). Each household is born into the economy at time t and lives until the end of period $t+1$. Hence, two households are alive at each point in time, a young, and an old one. Total population is constant over time. Upon entering the economy, households are endowed only with one unit of labor, which they supply inelastically to firms while they are young, earning wage income w_t. They divide this wage upon consumption in their young age $c_{y,t}$ and savings; smoothing consumption over the life-cycle is the only motive for saving. Savings are divided upon physical capital savings s_t, and buying land m_t from the currently old generation at price p_t:

$$w_t = c_{y,t} + s_t + p_t m_t. \tag{1}$$

Capital is the numeraire good, p_t is the price of land relative to capital.

When old, households enjoy income from interest payments r_{t+1} on their physical capital holdings, and the land rent v_{t+1}. Land is sold to the next generation at price p_{t+1} at the end of the old age, and, together with the principal and the land rent, consumed as $c_{o,t+1}$:

$$c_{o,t+1} = (1 + r_{t+1})\, s_t + m_t\, (p_{t+1} + v_{t+1}) \tag{2}$$

Households discount utility at the private rate of pure time preference ρ, and maximize their lifetime utility u_t:

$$U_{y,t} = \log(c_{y,t}) + (1+\rho)^{-1} \log(c_{o,t+1}), \tag{3}$$

The first-order conditions (FOC) of the problem are:

$$\frac{c_{o,t+1}}{c_{y,t}} = \frac{1 + r_{t+1}}{1+\rho} \tag{4}$$

$$1 + r_{t+1} = \frac{p_{t+1} + v_{t+1}}{p_t}. \tag{5}$$

The first of these FOC optimally allocates consumption across young and old age. The second FOC, called no-arbitrage condition, equalizes the returns on both assets, capital and land: The left hand side is the total return on capital: the principal, and the net return r_{t+1}. The right hand side is the total return on holding land: the land price appreciation and the land rent v_{t+1} itself. This no-arbitrage equation can be transformed to express the land price as the sum over future returns to land, discounted at the endogenous interest rate[1]

$$p_t = \sum_{i=0}^{T} \prod_{k=0}^{i} \frac{v_{t+i+1}}{1 + r_{t+k+1}}. \tag{6}$$

3.2 Production

A representative firm uses CES technology and the factor inputs capital k_t, land m with productivity χ_t, and labor to produce output y_t. Output y_t, capital k_t, and

[1] While the model has an infinite time horizon ($T = \infty$), we truncate the numerical simulations at some finite value T. The price in the last period is set to a finite value $p_T = 0$; the value itself does not change the results.

land m are defined in per capita terms, and the technology in the intensive form reads

$$y_t = A\,\Lambda_t\left(ak_t^{\frac{\sigma-1}{\sigma}} + b + (1-a-b)\,(\chi_t m)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}. \tag{7}$$

Climate damages reduce either TFP through Λ_t, or the productivity of land χ_t, described in more detail below. The technology is characterized by the constant total factor productivity A, share parameters a and b, and the elasticity of substitution σ. We assume full capital depreciation during a 35 year time period. The net return on capital r_t, the land rent v_t, and wage w_t are:

$$1 + r_t = (1-\Gamma(\tau_t))\,\frac{\partial y_t}{\partial k_t} = (1-\Gamma(\tau_t))\,a\,(A\,\Lambda_t)^{\frac{\sigma-1}{\sigma}}\left(\frac{y_t}{k_t}\right)^{\frac{1}{\sigma}} \tag{8}$$

$$v_t = (1-\Gamma(\tau_t))\,\frac{\partial y_t}{\partial m} = (1-\Gamma(\tau_t))\,(1-a-b)\,\chi_t^{\frac{\sigma-1}{\sigma}}\,(A\,\Lambda_t)^{\frac{\sigma-1}{\sigma}}\left(\frac{y_t}{m}\right)^{\frac{1}{\sigma}} \tag{9}$$

$$w_t = (1-\Gamma(\tau_t))\,y_t - k_t\,(1+r_t) - mv_t. \tag{10}$$

Factor payments are subject to an ad-valorem tax of $\Gamma(\tau_t)$ to finance mitigation.

3.3 Equilibrium

The factor market for capital and land clear, and non-land savings s_t form the capital stock of the next period k_{t+1}: $s_t = k_{t+1}$. The total amount of land m is constant over time. The equation of motion for the capital stock can be expressed using the FOC; a constant fraction of wage income is divided upon capital savings and buying land:

$$k_{t+1} = \frac{w_t}{2+\rho} - p_t m. \tag{11}$$

Given initial values of the capital stock k_0 and the carbon stock e_0, the equilibrium path $\{c_{y,t}, c_{o,t}, k_t, e_t, p_t, y_t, r_t, v_t, w_t\}$ is fully determined by the first-order conditions of households and firms. The Diamond model including land is dynamically efficient, as demonstrated by Kim and Lee (1997). The introduction of a land rent tax does not impair dynamic efficiency, as long as the tax is non-confiscatory ($\nu < 1$) (Homburg 2014b).

3.4 Damages and Mitigation

The modeling of the carbon cycle follows Karp and Rezai (2014a), and mitigation options are similar to DICE (Nordhaus 1993). The share of unmitigated carbon emissions $(1-\tau_t)$ accumulates in the single atmospheric carbon box as a by-product of production, decays proportionally to the concentration, and the carbon stock e_t evolves according to

$$e_{t+1} = (1-\phi_D)\,e_t + (1-\tau_t)\,\phi_I\,y_t. \tag{12}$$

The carbon intensity of production is assumed to be constant[2] at $0.068\,10^{-12}\,\$^{-1}$ppm. The carbon stock e_t is measured with respect to its 2011 value of 0.390 ppt (Stocker et al. 2013), such that $e_0 = 0$. We approximate the decay rate of the atmospheric carbon stock from historic cumulative emissions (Stocker et al. 2013) at an annual rate 0.35 % per year, implying $\phi_D = 0.13$.

A fraction $\tau_t \in [0, 1]$ of total emissions can be mitigated at a cost $\Gamma(\tau)$

$$\Gamma(\tau_t) = \gamma_1 \tau_t^{\gamma_2}. \tag{13}$$

Mitigation costs are financed by an ad-valorem tax $\Gamma(\tau_t)$ on all factor incomes. We use $\gamma_1 = 0.052$,[3] and assume a convexity of $\gamma_2 = 3$. An overview of the parameter choices for the environmental part of the model is given in Tab. 1.

Parameter	Symbol	Value
CO_2 decay rate	ϕ_d	0.13
CO_2 intensity	ϕ_i	$0.068\,10^{-12}$ ppm $\$^{-1}$
Total mitigation cost (GDP share)	γ_1	0.052
Mitigation cost convexity	γ_2	3
Damage parameter	γ_d	0.2

Table 1: Parameter choices for stock pollution and mitigation.

Stock accumulation of carbon leads to higher atmospheric temperatures and climate damages. In our model, damages reduce the level – not the growth rate – of either the productivity of land, or TFP. The climate dependent reductions in TFP are equivalent to the most commonly used way of modeling damages, that is, on the level of output. Damages on the growth rate or the stock of TFP are a different matter (Kopp et al. 2012; Moore and Diaz 2015). For land damages, we assume that the productivity of a fixed supply of land depends on climate change, mimicking the crop yield impacts known in the literature (Pachauri et al. 2014; Rosenzweig et al. 2013). We argue that while the climate damages on specific types and pieces of land may be very different, and even negative, and some land may even be lost completely, for example to desertification or sea level rise, climate damages on global aggregate are best described by a reduction in the productivity of a fixed amount of land.

We assume a linear reduction in the productivities with rising concentration, with the following rationale: Bijgaart et al. (2015) and Golosov et al. (2014) find that in DICE-like models, with non-linear damages and more complex carbon cycles than in our model, damages are effectively linear in concentrations. This can be understood as stemming from the combination of a logarithmic increase of temperature

[2] The carbon intensity is estimated from the average values of the increase in the atmospheric CO_2 concentration in the first decade of the 21st century of 2.0 ppm yr^{-1} (IPCC, 2013: Summary for Policymakers.), the anthropogenic emissions of 8.3 GtC, of which 4.0 GtC ended up in the atmosphere (Stocker et al. 2013), and global GDP of 61 trillion US$ (Feenstra et al. 2013).

[3] We estimate γ_1 from the median annual growth reduction of 0.06 percentage points for climate stabilization are two degrees (Edenhofer et al. 2014), which implies $\gamma_1 = 0.052$.

with concentrations, and climate damages that are exponential or polynomial in temperature – in effect, climate damages are approximately linear in concentrations in these models.

We are aware that climate impacts on crop yields are highly region dependent and non-linear in general, and damages may act on growth rates rather than on levels (Burke et al. 2015; Dell et al. 2014; Dell et al. 2012). Still, we choose the simple linear damage specification to make our argument as straightforward as possible – this paper is about impacts mechanisms, not about numbers. Consequently, we contrast productivity damages on either the productivity of land, or TFP, that are linear in carbon concentration e_t [4]:

$$\chi_t = (1 - \gamma_d \, e_t) \qquad \text{land-biased damages} \tag{14}$$

$$\Lambda_t = \left(1 - \text{LS}^{-1} \, \gamma_d \, e_t\right) \qquad \text{TFP damages} \tag{15}$$

We scale the damage parameter γ_d in the case of TFP damages by the inverse of the income share of land LS, as we set out to compare the impact mechanisms of roughly comparable damages on the economy. For instance, the default value of $\gamma_d = 0.2$ implies a 20% reduction in the productivity of land at a CO_2 concentration of 1000ppm, or, in the case of TFP damages, a reduction of TFP by around 2%, as the income share of land is around 0.1. The default value of the damage parameter $\gamma_d = 0.2$ is an exemplary number, as this paper is about the mechanisms, not about quantification.

3.5 Climate policy scenarios

We distinguish three climate policy scenarios: First, the business-as-usual (BAU) scenario with climate damages, but no climate policy at all[5]. Second, a scenario with Pareto-improving climate policy of purely non-altruistic generations (PCP): The level of climate policy is decided upon at each point in time by maximizing the joint utility of the generations then alive, without taking into account the welfare of future generations. Third, a scenario with socially optimal climate policy (OPT): Climate policy is adjusted to maximize a social welfare function, which aggregates the utility of all generations. We describe the two climate policy equilibria in more detail later on.

As we are interested in comparing the long-run impacts of climate damages and climate policy, we compare between steady states of the model. The results in this model are driven by inherently dynamic effects though, as will become clear in the following sections.

[4] Our results do not depend qualitatively on this specific damage specification, but also hold for example for quadratic damages with either rational, or exponential mapping.

[5] For technical purposes only, there is also a BAU scenario without climate damages.

4 Damages and growth impacts

We contrast difference in the economic impact of the two damage specifications, damages on TFP, or on the productivity of land. There is no climate policy for now, we consider only the BAU scenario in this section.

In the initial point, we calibrate: output, the capital stock, the carbon stock, and income shares – see Appendix A for details. The price or the wealth share of land are not calibrated, those are endogenous to the model. The elasticity of substitution between labor, capital, and land in production – from now on just called elasticity – is set to $\sigma = 0.7$ by default. As there is no reliable estimate for the elasticity, we consider a variation of its value in deriving our results. We posit that including land in production, the elasticity should be significantly below unity, that is, production factors are complements[6].

The economy grows over the life span of many generations, driven only by physical capital accumulation; stock pollution accumulates and damages increase, until eventually a steady-state is reached[7]. Growth paths for the two different damage scenarios for BAU – land and TFP damages – are contrasted in Fig. 1, where relative deviations from the case without damages are shown for key variables. Each of these two scenarios is shown for two different choices of the elasticity of substitution: Production factors as complements, and as substitutes.

Concentrations stabilize at very similar levels of around 1000 ppm in all four scenarios. The resulting reductions in the productivities χ and Λ are around 0.8 in the land damage case, and 0.97 for TFP damages, but they are very similar regardless of the elasticity.

For TFP damages, the elasticity does have a very small effect on the growth path only: Irrespective of the elasticity, the land rent declines somewhat in the long term due to the climate damages on TFP. Capital accumulation also declines, and the land price is slightly lowered through the damages. In the long run, the output reduction in the TFP damage scenario is virtually independent of the elasticity.

By contrast, when damages are land-biased, the elasticity matters a lot: Land rents rise in response to damages when land is a complement, but fall when land is a substitute. This can be understood from an analytical expression of the change of land rents with productivity, which, ceteris paribus, is

$$\operatorname{sgn}\left(\frac{\partial v}{\partial \chi}\right) = \operatorname{sgn}\left(\mathrm{LS} + \sigma - 1\right)$$

and depends on the elasticity σ and the income share of land LS. If land were a good substitute in production ($\sigma > 1 - \mathrm{LS}$), land rents would decline in response to the damages on the productivity of land. With land a gross complement in production however, that is $\sigma < 1 - \mathrm{LS}$, damages on the productivity increase the land rent

[6] For neoclassical production functions using labor and capital only, the estimates of the elasticity are around $\sigma = 0.5$ (Chirinko 2008).

[7] While this model could exhibit multiple steady states (Mountford 2004), we observe convergence to a unique steady state for our parametrization in our numerics.

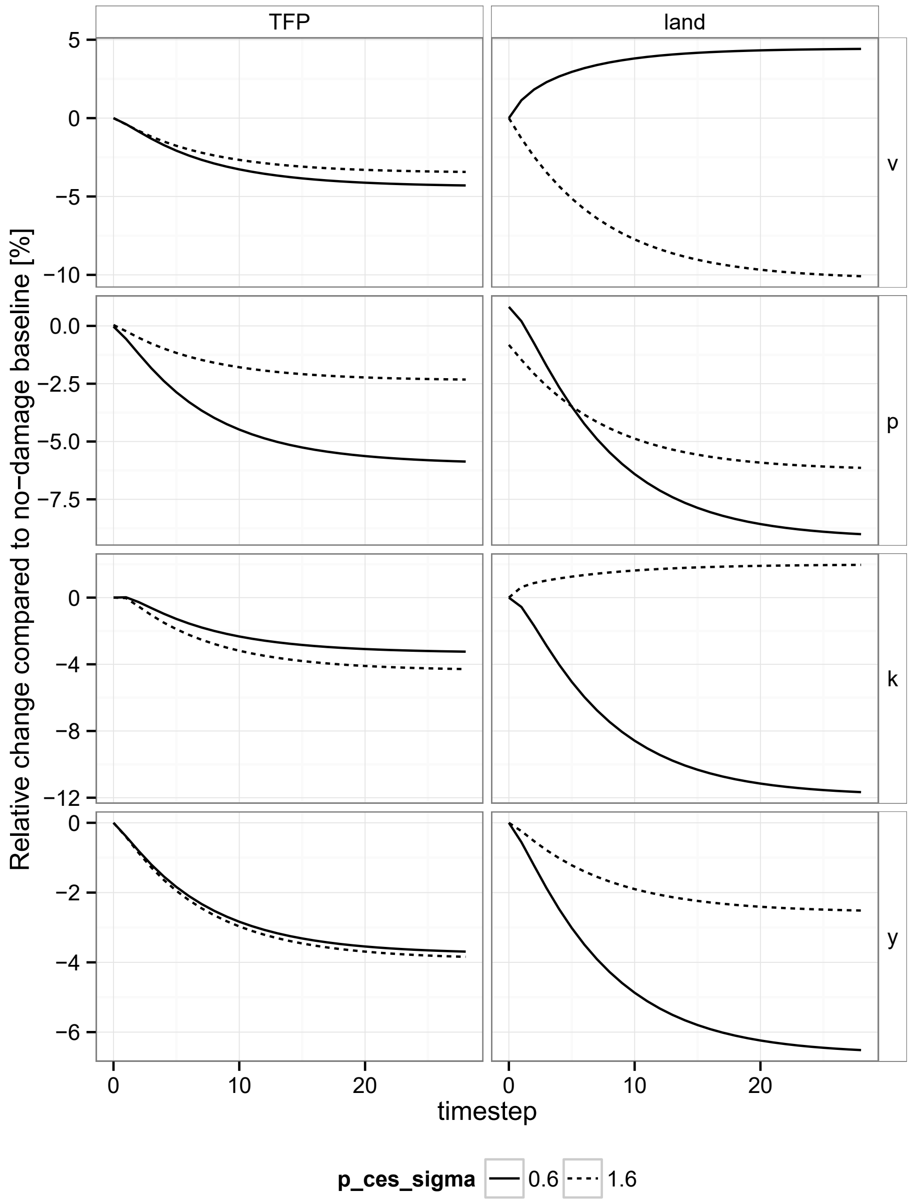


Figure 1: Long term time series of the relative changes in the BAU scenario of the land rent v_t, land price p_t, capital stock k_t, and output y_t, with respect to a baseline without damages. In the left panel, damages act on land, in the right panel on TFP. Land is either a complement in production ($\sigma = 0.6$), or a substitute ($\sigma = 1.6$). One time step corresponds to half a generation's lifetime, 35 years.

instead: Decreases in the productive power of land are overcompensated by rising scarcity rents – such that the land rent rises in effect. This effect is known from the literature on biased technological change, and is described in more detail in Appendix C.

If land rents rise, buying land is more attractive relative to investing into capital, and consequently capital investment changes through the Portfolio effect – which matters a lot for the economic impacts: In our example, the output reduction resulting from given land-biased damages is 2-6%, depending on the elasticity.

To quantify the dependence of the impact on the elasticity, we define an economic impact indicator: The reduction in steady state output relative to a baseline without any climate damages, normalized to the relative reduction in TPF or productivity of land respectively.

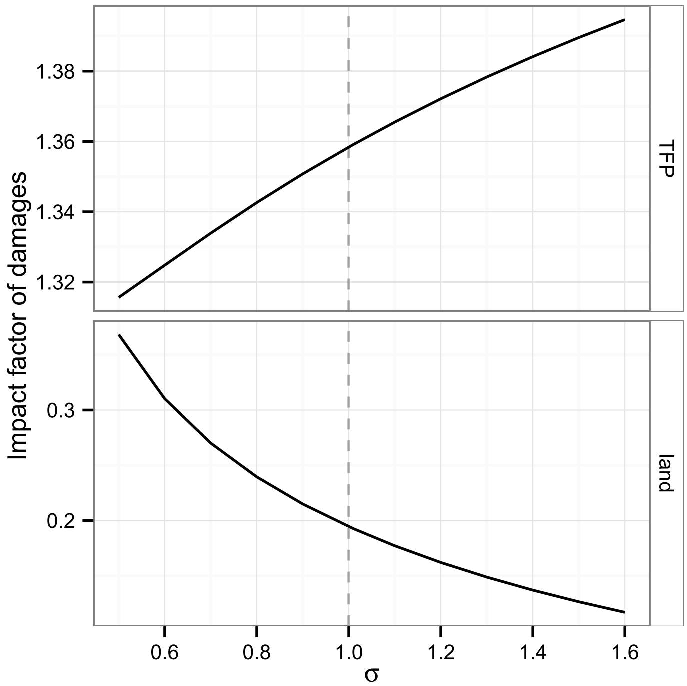


Figure 2: Economic impact indicator against elasticity for TFP damages in the upper facet, and for land damages in the lower facet. varies with the elasticity. The change in the land indicator is much larger than in the TFP case – note the differences in the scales.

The economic impact indicator is shown in Fig. 2, contrasting the two damage channels: An impact indicator of 1.3 means that the steady-state reduction in output is 1.3 times larger than the reduction in TFP due to the damages themselves – a number which does not vary much with the elasticity. For land damages, by contrast, the impact indicator varies strongly with the elasticity: For high elasticities, a 20% reduction in the productivity of land would imply only 2% of output reduction, while for an elasticity of $\sigma = 0.5$, the output reduction is 8%.

5 Climate policy

In this section, we derive the effect of marginal climate policy departing from the BAU scenario. Consequently, we introduce two different climate policy equilibria, a Pareto-improving, and a socially optimal one, to discuss the incentives for climate policy.

5.1 Marginal climate policy

We evaluate the utility changes from a marginal increase in climate policy, starting from the BAU scenario, which does not have any climate policy. Consider an infinitesimal exogenous increase in climate policy $\tau_t > 0$ at time t, while $\tau_{t'} = 0$ for all $t' \neq t$. Factor payments w_t, r_t, and v_t are not affected to first order[8], as the derivative of the mitigation cost function is zero at $\tau = 0$: The first bit of mitigation comes at no cost.

Still, climate policy does have first-order effects on the land price p_t, and the factor payments in the next period. The young generation's utility $U_{y,t}$ depends only on the change in the net return on capital r_{t+1}, which, to first order, always increases with τ_t. The utility effect for the old generation is more complex, as it depends on the change in the land price p_t, which is ambiguous in its sign[9]:

$$\begin{aligned} \operatorname{sgn}\left(\frac{\partial U_{y,t}}{\partial \tau_t}\right)\Bigg|_{\tau=0} &> 0 \\ \operatorname{sgn}\left(\frac{\partial U_{o,t}}{\partial \tau_t}\right)\Bigg|_{\tau=0} &= \operatorname{sgn}\left(\frac{\partial p_t}{\partial \tau_t}\right) \end{aligned} \tag{16}$$

This asymmetric effect of climate policy on the utility of the generations can be understood by considering the timing of the investment decision: Climate policy today τ_t changes the price of land p_t. The main utility effect for the currently old generation is then due to the change in the price of land, which they sell to the next generation at the end of their lives. In contrast to that, the young generation has yet to make their investment decision: For a changing land price, savings into capital are adjusted accordingly, such that for them the increase in the future return – which is the same on both assets and equal to the interest rate r_{t+1} – is the most important impact of climate policy.

The land price reacts to climate policy as it capitalizes all future returns to land, discounted at the endogenous interest rate. We cannot derive the price reaction

[8] Factor payments are not affected to first order: Even through the state variables $k_{t'}$ and $e_{t'}$ at all times change due to climate policy at τ_t, we disregard the changes for $t < t'$ as effects of higher order in this analysis.

[9] Our results are consistent with Karp and Rezai (2014a): In their similar model – where capital with adjustment costs takes the role of land in our model – they find that the welfare effect of climate policy (for logarithmic utility) on the young generation is positive, and the first-order effect on the old generation's welfare is zero for output damages.

analytically, but illustrate this effect within an approximation[10] and solve the full model numerically in the next section. While damages on TFP do not change the price in this (rather crude) approximation, damages on land do, as they affect the ratio of the marginal products of land and capital directly:

$$\operatorname{sgn}\left(\frac{\partial p_t}{\partial \tau_t}\right) \approx \begin{cases} 0 & \text{for TFP damages} \\ \operatorname{sgn}(\sigma - 1) & \text{for land damages} \end{cases} \tag{17}$$

Within this approximation, marginal climate policy lowers today's price of land if land is a complement in production, and would raise the price if land were a substitute.

Note that for the assumption of a Cobb-Douglas production function, the price change in response to damages would always be zero: the effect presented here crucially depends on changes in factor income shares.

Summing up, we find that the first-order impact of marginal climate policy is a change in the current land price, and the interest rate in the next period. Consequently, marginal climate policy increases the young generation's utility, and, for land-biased damages, decreases the old generation's utility if land is a gross complement in production.

5.2 Climate policy equilibria

In this section we introduce two different decision processes by which the optimal amount of climate policy is determined in society.

Pareto-improving climate policy

In the Pareto-improving climate policy (PCP) scenario, generations at each point in time cooperatively choose some climate policy as to maximize their joint lifetime utility without showing altruism towards future generations. Generations will thus only choose to enact climate policy if they are better off through it.

Generations trade off the costs of mitigation against the benefits from avoided damages that accrue during their remaining life-time. The decision on climate policy is influenced by the reaction of the land price, and thereby also by future generations' decision for climate policy, as the land price is the capitalized value of all future land rents, reflecting future damages as well as future mitigation decisions. The mitigation decision is thus an intertemporal game between non-altruistic generations who interact through backward looking stock pollution, and a forward looking land price.

The decision process works as follows: The two generations alive at each point in time agree to maximize their joint utility by choosing climate policy accordingly. This maximization of joint utility can be thought of as being delegated to a government

[10] The land price can be written as an infinite sum over factor returns: $p_t = v_{t+1}(1 + r_{t+1})^{-1} + v_{t+2}(1 + r_{t+1})^{-1}(1 + r_{t+2})^{-1} + ...$ In this crude approximation, we consider only the first term of the sum, assume no change in the capital stock k_{t+1}.

that is only in place for one period, whose only choice variable is the level of climate policy during this period τ_t:

$$\max_{\tau_t} U_t^* \quad \forall t \tag{18}$$

The joint utility U_t^* is the sum of the utilities of the young and the old generation, and can be expressed using the first-order conditions:

$$\begin{aligned} U_t^* &= U_t^y(c_{y,t}, c_{o,t+1}) + U_t^o(c_{o,t}) \\ &= \log(w_t) + (1+\rho)^{-1} \log(w_t(1+r_{t+1})) \\ &\quad + \log((1+r_t)k_t + m(p_t + v_t)) + \text{const} \end{aligned} \tag{19}$$

There are several effects of an increase in climate policy τ_t on joint utility: For all but the first unit, mitigation is not costless: factor payments w_t, r_t, and v_t are reduced by a tax on them in order to finance mitigation. Beyond that, there are two other effects contributing to the impact of climate policy on joint utility: First, the interest-rate effect: An increase in τ_t increases the interest rate in the next period as a result of avoided damages. This benefits the young generation, as the return on their assets increases, and thus contributes positively to joint utility. Second, an increase in mitigation changes the price of land p_t, reflecting future changes in land rents. The price change is ambiguous and depends strongly on the elasticity of substitution. Agents understand that the land price evolves according to the non-arbitrage equation (5).

We solve for the Markov-perfect equilibrium of this intergenerational game. Generations form expectations on climate policy and the land price in the next period dependent only on the current value of the two state variables, capital k_t, and carbon stock e_t. These expectation are not point expectations, but instead depend on the two stock variables, and thus include the reaction of today's policy decision through the change in the stock variables.

In this game, generations interact through their respective effect on the two state variables only. The solution in this non-cooperative game is a Markov perfect equilibrium (Klein et al. 2008). We follow Karp and Rezai (2014b) in solving for the equilibrium numerically – the solution algorithm is discussed in detail in Appendix B. In a nutshell, we find approximating functions for the expectations on climate policy and the land price by solving the first-order-condition for the policy problem in a numerical procedure implemented in Python (SymPy Development Team 2014), which are then fed back into the dynamic GAMS model.

We find that this PCP equilibrium supports some amount of climate policy by non-altruistic generations for both damage mechanisms.

Socially optimal climate policy

The OPT scenario prescribes a socially optimal policy path that maximizes a social welfare function. The social welfare function aggregates the utility of generations at the social utility discount rate ρ_S, and the optimization problem is then the choice of a path of climate policy τ_t that maximizes welfare:

$$\max_{\tau_t \forall t} \left(U_{o,0} + \sum_{t=0}^{T} (1+\rho_S)^{-t} U_{y,t} \right) \tag{20}$$

The policy optimization problem is implemented as a non-linear optimization problem, including the first-order conditions of the households and firms as constraints, using the GAMS software package (GAMS Development Corporation 2013).

This scenario assumes that there exists a long-term government or institution which is able to commit to the socially optimal climate policy, and implement it. Note however, that this institution only optimizes climate policy, and does thus not interfere with the private savings decisions.

Socially optimal climate policy will in general be stricter than in the PCP scenario, and involve a reduction in the utility of early generations due to increased mitigation efforts. We assume that the social discount rate is smaller than the private pure rate of time preference $\rho_S < \rho$, which is commonly believed to be a reasonable assumption (Robson and Szentes 2014; Heinzel and Winkler 2007).

5.3 Incentives for climate policy

We analyze here the effectiveness of PCP climate policy compared to socially optimal policy, which gives an indication of how strong the incentive for the individual non-altruistic generations is to enact climate policy.

Our indicator for the economic effectiveness is the share of output recovered by the PCP scenario with respect to the OPT scenario. We define the effectiveness $\eta(\bar{y})$ as the ratio of the steady state output levels of the PCP scenario and the OPT scenario, each measured from the BAU output level:

$$\eta(\bar{y}) = \frac{\bar{y}_{\text{PCP}} - \bar{y}_{\text{BAU}}}{\bar{y}_{\text{OPT}} - \bar{y}_{\text{BAU}}} \tag{21}$$

A value of $\eta(\bar{y}) = 0.5$ means that PCP climate policy recovers only half of the steady state output that would be socially optimal to recover.

For damages on TFP, the economic effectiveness of mitigation does not strongly depend on the elasticity, as seen in Fig. 3. By contrast, the effectiveness strongly depends on the elasticity for land-biased damages: PCP policy is much lower than the socially optimal level for land-biased damages. For an exemplary elasticity of $\sigma = 0.7$, PCP policy only recovers 11% of the output that would be socially optimal to recover, while for $\sigma = 1.5$ this figure is 25%.

This is readily understood from the point of view of a non-altruistic generation, as the incentive to enact climate policy depends strongly on the reaction of the land price: If, for example, land is a gross complement, the land price declines in response to mitigation, and thus devalue the land assets currently held by the currently alive old generation. Just in this case of a low elasticity though, the economic impacts of land-biased damages are largest – making it socially optimal to enact more stringent

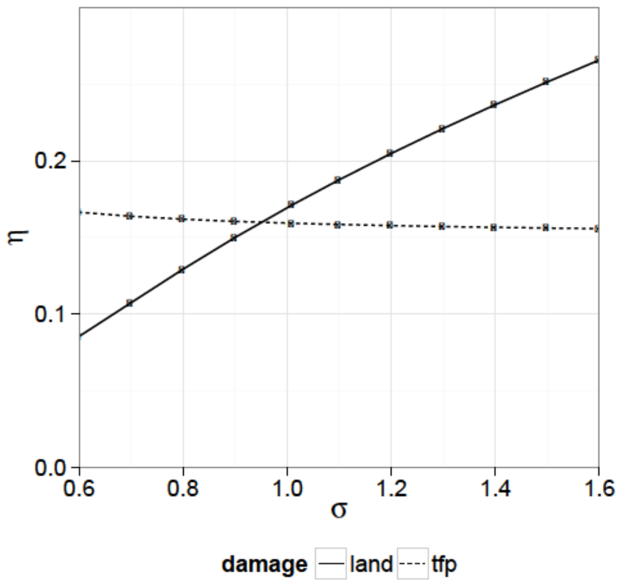


Figure 3: Economic effectiveness of climate policy $\eta(y)$ against the elasticity for different damage specifications.

climate policy. The gap between Pareto-improving and socially optimal climate policy thus opens up for low values of the elasticity.

The economic effectiveness depends of course on the private rate of pure time preference ρ of the individual households, and on the chosen social utility discount rate ρ_S – the effect of a variation of both rates is shown in Fig. 4: To read the figure, follow one of the two branches for a variation of the effectiveness with the respective parameter, while the other of the two parameters is kept at its default value: Increasing the social discount rate from the default value of $\rho_s = 0$ strongly increases the economic effectiveness from the default level at 11%, as the social optimum entails less stringent climate policy, and is thus closer the PCP policy. A private rate of time preference below the default value of 3% per year also increases the relative economic effectiveness: Lower private discounting means more stringent mitigation is in the self-interest of each generation, as the benefits avoided losses during the old age of the currently young are valued higher.

The dependence on other model parameters is shown as part of a separate sensitivity analysis in Fig. 5.

Distributional consequences

We discuss distributional consequences of climate policy under land-biased damages, comparing the steady states with, and without climate policy. The numbers here are for illustrative purposes.

Compared to BAU, wages rise slightly in the PCP scenario, and much more in the OPT scenario, raising consumption in the young age cohort by the same figures (Tab.

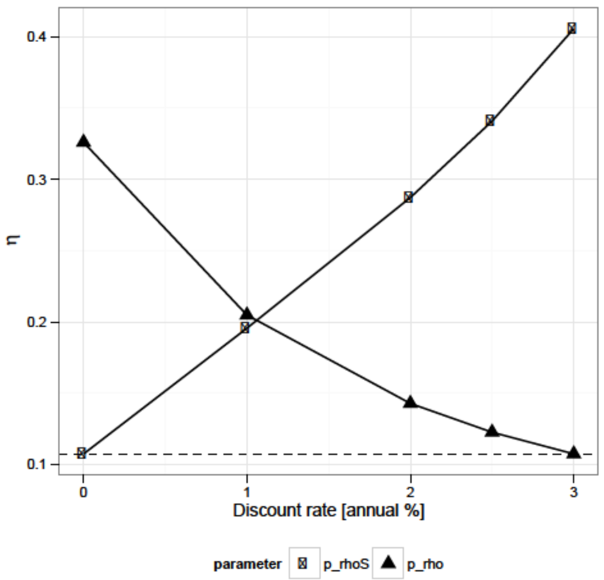


Figure 4: Economic effectiveness of climate policy for variation of private pure rate of time preference (triangles) and social discount rate for land-biased damages (circles). The elasticity is $\sigma = 0.7$.

2). The interest rate declines somewhat in the PCP scenario, and more strongly in the OPT scenario, which is one reason why consumption of the old cohort does not increases as strongly as for the young. Output itself increases by 0.5% for PCP, and by 4% in the OPT scenario. The land and capital share in income decrease slightly in the PCP scenario, and much more so in the OPT scenario. The share of land in total wealth decreases through climate policy, reflecting lower future scarcity due to avoided damages – the change in the OPT scenario is around ten times larger than in the PCP scenario.

6 Conclusion

We agree with the literature that asset price effects have been neglected in IAMs, but differ by arguing that land is the most relevant long-lived asset. We find that land-biased damages have a much stronger impact on growth than damages on TFP (or equivalently, on output) only: Future increases in the land rent raise the price of land, absorbing more savings and thus leaving less for productive capital investment. The intuition behind this mechanism is that climate damages on land increase the scarcity rent of land, and consequently make holding land more attractive than productive capital investments. In a way, this is an abstract mechanism of representing detrimental effects of increasing natural resource rents on economic growth. It might be useful to think about this in analogy to the resource curses found in the literature. The resource curse literature finds that economic growth is weaker in countries with a high share of primary exports in output, and brings up a number

Variable	PCP	OPT
Consumption young	0.5 %	3.5 %
Consumption old	0.2 %	0.6 %
Interest rate	-0.4 %	-3.9 %
Wages	0.5 %	3.4 %
Output	0.3 %	3.0 %
Capital share in income	-0.02 pp	-0.4 pp
Land share in income	-0.05 pp	-0.7 pp
Land share in wealth	-0.04 pp	-0.5 pp

Table 2: Exemplary distributional changes in the economy for PCP and OPT climate policy for land-biased damages, each compared to BAU

of explanations for this, including rent seeking (van der Ploeg 2011).

Furthermore, while future avoided damages on TFP increase the current land price, and thus always incentivize mitigation, avoided land-biased damages may decrease future scarcity rents and the land price. Decreases in the land price hurt the land owners – the currently old generation in our model, who's investment decision is sunk – by stranding their land assets. The incentive to mitigate land-biased damages is reduced due to the vested interest of the old generation, resulting in less stringent climate policy in the Pareto-improving climate policy scenario. Notice that households in our model differ only by their age. The vested interests are not due to heterogeneity in households themselves, but only due to the timing of the investment decision, as the households make their investment decision while they are young.

In summary, we argue that land-biased damages may reduce the incentives to internalize climate change – aggravating the intergenerational conflict that climate change is. Our results partly confirm the finding of Karp and Rezai (2014b), as we also find that some climate policy is Pareto-improving, but suggest that asset prices changes due to mitigation may play a more complex role through Portfolio effects and biased damages.

We conjecture that transfer payments from the young to the old generation – which we do not include in our model – could increase incentives for climate policy. These transfers would compensate the current asset owners for their losses incurred through climate policy, and may present an equity-efficiency trade-off: Transfers in this direction may be considered unethical by many, as the currently old generation already profited more than the young from burning fossil fuels, and will experience less of the impacts of climate change during their remaining life time.

Our results demonstrate the need to disaggregate climate damages to assess their economic impact beyond what is commonly done, and beyond what our model does. Damages on agricultural yields strongly depend on the location, and are even negative in higher latitudes (Rosenzweig et al. 2013; Pachauri et al. 2014), indicating the need for regional models.

Understanding the impact of increasing land rents on a microeconomic level, including political economy effects, requires models that go beyond the stylized representation of investment decisions in our model. Hvid and Henningsen (2014), for example, demonstrate the importance and ambiguity of the strength of institutions in translating rising land rents into welfare effects for farmers in developing economies. It would be fruitful to represent land in more detail in the model, and consider land use in different sectors of the economy, different qualities of land, trade in agricultural products, and rent-seeking in the political economy.

Climate stabilization at low cost depends on the availability of land-based mitigation options (Klein et al. 2014; Humpenöder et al. 2014) – the use of which may increase land rents (Gurgel et al. 2007). We conjecture that including land based mitigation in our model might counteract the land price reduction through damages, and thus increase the incentive to mitigate.

One final caveat: our model assumes that all land and capital are traded on stock markets, and that these markets function perfectly. Reflecting imperfect markets, and ownership by the operators of agricultural land is a promising direction for further research.

References

Acemoglu, D (2009). *Introduction To Modern Economic Growth.* Princeton University Press.

Barro, R. J. (1974). "Are Government Bonds Net Wealth?" *Journal of Political Economy* 82.6, p. 1095. DOI: 10.1086/260266.

Bijgaart, I, R. Gerlagh, and M. Liski (2015). "A Simple Formula for the Social Cost of Carbon". *mimeo.*

Burke, M., S. M. Hsiang, and E. Miguel (2015). "Global non-linear effect of temperature on economic production". *Nature* 527, pp. 235–239. DOI: 10.1038/nature15725.

Calvo, G. A., L. J. Kotlikoff, and C. A. Rodriguez (1979). "The Incidence of a Tax on Pure Rent: A New (?) Reason for an Old Answer". *Journal of Political Economy* 87.4, p. 869. DOI: 10.1086/260798.

Caselli, F and J Feyrer (2007). "The marginal product of capital". *Quarterly Journal of Economics* 122.2, pp. 535–568. DOI: 10.1162/qjec.122.2.535.

Chirinko, R. S. (2008). "Sigma: The long and short of it". *Journal of Macroeconomics* 30.2, pp. 671–686. DOI: 10.1016/j.jmacro.2007.10.010.

Ciscar, J.-C. et al. (2011). "Physical and economic consequences of climate change in Europe". *Proceedings of the National Academy of Sciences* 108.7, pp. 2678–2683. DOI: 10.1073/pnas.1011612108.

Dell, M., B. F. Jones, and B. a. Olken (2012). "Temperature shocks and economic growth: Evidence from the last half century". *American Economic Journal: Macroeconomics* 4.3, pp. 66–95. DOI: 10.1257/mac.4.3.66.

Dell, M., B. F. Jones, B. a. Olken, and M. Gates (2014). "What Do We Learn from the Weather? The New Climate-Economy Literature". *Journal of Economic Literature* 52.3, pp. 740–798. DOI: 10.3386/w19578.

Diamond, P. (1965). "National debt in a neoclassical growth model". *The American Economic Review* 55.5, pp. 1126–1150.

Edenhofer, O. et al. (2014). "Technical Summary". *Climate Change 2014:* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 1–33.

Edenhofer, O., L. Mattauch, and J. Siegmeier (2015). "Hypergeorgism : When is Rent Taxation as a Remedy for Insufficient Capital Accumulation Socially Optimal ?" *FinanzArchiv: Public Finance Analysis* fast track. DOI: 10.1628/001522115X14425626525128.

Feenstra, R. C., R. Inklaar, and M. P. Timmer (2013). "The Next Generation of the Penn World Table". DOI: 10.15141/S5159X.

Feldstein, M. (1977). "The Surprising Incidence of a Tax on Pure Rent : A New Answer to an Old Question". *Journal of Political Economy* 85.2, pp. 349–360.

GAMS Development Corporation (2013). *General Algebraic Modeling System (GAMS)*. Washington, DC.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). "Optimal Taxes on Fossil Fuel in General Equilibrium". *Econometrica* 82.1, pp. 41–88. DOI: 10.3982/ECTA10217.

Gurgel, A., J. M. Reilly, and S. Paltsev (2007). "Potential Land Use Implications of a Global Biofuels Industry". *Journal of Agricultural & Food Industrial Organization* 5.2, pp. 1542–0485. DOI: 10.2202/1542-0485.1202.

Heinzel, C. and R. Winkler (2007). "The Role of Environmental and Technology Policies in the Transition to a Low-carbon Energy Industry". *CER-ETH Working Paper* 07/71.

Hertel, T. W. (2011). "The global supply and demand for agricultural land in 2050: A perfect storm in the making?" *American Journal of Agricultural Economics* 93.2, pp. 259–275. DOI: 10.1093/ajae/aaq189.

Homburg, S. (1991). "Interest and growth in an economy with land". *The Canadian Journal of Economics* 24.2, pp. 450–459.

— (2014a). "Overaccumulation, Public Debt and the Importance of Land". *German Economic Review* 15.4, pp. 411–435. DOI: 10.1111/geer.12053.

— (2014b). "Property taxes and dynamic efficiency: A correction". *Economics Letters* 123.3, pp. 327–328. DOI: 10.1016/j.econlet.2014.03.013.

Humpenöder, F. et al. (2014). "Investigating afforestation and bioenergy CCS as climate change mitigation strategies". *Environmental Research Letters* 9, p. 064029. DOI: 10.1088/1748-9326/9/6/064029.

Hvid, A. K. and G. A. Henningsen (2014). "A new scramble for land or an unprecedented opportunity for the rural poor? Distributional consequences of increasing land rents in developing countries". *MPRA* 52919.

Karp, L. and A. Rezai (2014a). "Asset prices and climate policy". *mimeo.*

— (2014b). "The political economy of environmental policy with overlapping generations". *International Economic Review* 55.3, pp. 711–733.

Kim, K.-S. and J. Lee (1997). "Reexamination of dynamic efficiency with taxation on land". *Economics Letters* 57.2, pp. 169–175. DOI: 10.1016/S0165-1765(97)00216-4.

Klein, D. et al. (2014). "The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE". *Climatic Change* 123.3, pp. 705–718. DOI: 10.1007/s10584-013-0940-z.

Klein, P., P. Krusell, and J.-V. Ríos-Rull (2008). "Time-Consistent Public Policy". *Review of Economic Studies* 75.3, pp. 789–808. DOI: 10.1111/j.1467-937X.2008.00491.x.

Klump, R., P. McAdam, and A. Willman (2012). "The Normalized CES Production Function: Theory and Empirics". *Journal of Economic Surveys* 26.5, pp. 769–799. DOI: 10.1111/j.1467-6419.2012.00730.x.

Kopczuk, W. and J. P. Lupton (2007). "To leave or not to leave: The distribution of bequest motives". *Review of Economic Studies* 74.1, pp. 207–235. DOI: 10.1111/j.1467-937X.2007.00419.x.

Kopp, R. E., A. Golub, N. O. Keohane, and C. Onda (2012). "The Influence of the Specification of Climate Change Damages on the Social Cost of Carbon". *Economics: The Open-Access, Open-Assessment E-Journal* 6.2012-13. DOI: 10.5018/economics-ejournal.ja.2012-13.

Laitner, J. and H. Ohlsson (2001). "Bequest motives: a comparison of Sweden and the United States". *Journal of Public Economics* 79.1, pp. 205–236. DOI: 10.1016/S0047-2727(00)00101-8.

Michel, P., E. Thibault, and J. P. Vidal (2006). "Chapter 15 Intergenerational altruism and neoclassical growth models". *Handbook of the Economics of Giving, Altruism and Reciprocity* 2.06, pp. 1055–1106. DOI: 10.1016/S1574-0714(06)02015-X.

Moore, F. C. and D. B. Diaz (2015). "Temperature impacts on economic growth warrant stringent mitigation policy". *Nature Climate Change* 5.2, pp. 127–131. DOI: 10.1038/nclimate2481.

Mountford, A (2004). "Global analysis of an overlapping generations economy with land". *Macroeconomic Dynamics* 8, pp. 582–595.

Moyer, E. et al. (2014). "Climate Impacts on Economic Growth as Drivers of Uncertainty in the Social Cost of Carbon". *The Journal of Legel Studies* 43.2, pp. 401–425.

Nordhaus, W. D. (1993). "Rolling the 'DICE': An optimal transition path for controlling greenhouse gases". *Resource and Energy Economics* 15, pp. 27–50.

Pachauri, R. K. et al. (2014). "IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change".

Pindyck, R. S. (2013). "Climate Change Policy : What Do the Models Tell Us ?" *Journal of Economic Literature* 51.3, pp. 860–872. DOI: 10.1257/jel.51.3.860.

Ramsey, F. P. (1928). "A Mathematical Theory of Saving". *The Economic Journal* 38.152, pp. 543–559. DOI: 10.1017/CBO9781107415324.004.

Robson, A. J. and B. Szentes (2014). "A Biological Theory of Social Discounting". *American Economic Review* 104.11, pp. 3481–3497. DOI: 10.1257/aer.104.11.3481.

Rosenzweig, C. et al. (2013). "Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison". *Proceedings of the National Academy of Sciences* 14, pp. 1–6. DOI: 10.1073/pnas.1222463110.

Schneider, M. T., C. P. Traeger, and R. Winkler (2012). "Trading off generations: Equity, discounting, and climate change". *European Economic Review* 56.8, pp. 1621–1644. DOI: 10.1016/j.euroecorev.2012.08.006.

Siegmeier, J., L. Mattauch, and O. Edenhofer (2015). "Climate Policy Enhances Efficiency : A Macroeconomic Portfolio Effect". *CESifo Working Papers* 5161.

Stern, N. (2013). "The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models". *Journal of Economic Literature* 51, pp. 838–859. DOI: 10.1257/jel.51.3.838.

Stiglitz, J. E. (2015). "New Theoretical Perspectives on the Distribution and Wealth among Individuals: Part I. The Wealth Residual". *NBER Working Paper* 21189. DOI: 10.3386/w21189.

Stocker, T. F. et al. (2013). "Technical summary". *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by T. Stocker et al. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

Stocker, T. et al. "IPCC, 2013: Summary for Policymakers." *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by S. T.F. et al. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

SymPy Development Team (2014). *SymPy: Python library for symbolic mathematics; http://www.sympy.org*.

Van der Ploeg, F. (2011). "Natural Resources: Curse or Blessing?" *Journal of Economic Literature* 49.2, pp. 366–420. DOI: 10.1257/jel.49.2.366.

Weyant, J et al. (1996). "Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results". *Climate Change 1995: Economic and Social Dimensions of Climate Change*. December 2015. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

World Bank (2010). *The Changing Wealth of Nations*. The World Bank. DOI: 10.1596/978-0-8213-8488-6.

— (2013). *Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience*. Washington, DC.

A Calibration

In the initial period, output, income shares, and the capital stock are calibrated to literature values of the global economy in 2010. The annual global gross domestic product in 2010 is around 69 trillion US$_{2005}$, and the capital stock is estimated at 224 trillion US$ (Feenstra et al. 2013). We assume a labor share in income of $b_0 = 0.6$, and a pure rate of time preference of the households of 3% per year.

Caselli and Feyrer (2007) estimate the global wealth share of non-reproducible capital in total capital at 0.32 from a set of 53 very heterogenous countries. Around half of this wealth consists of urban land, followed by subsoil resources and cropland. We take this wealth share as a proxy for the income share of land - the non-reproducable asset in our model - and estimate the global income share of land at $1 - a_0 - b_0 = 0.32(1 - b_0) = 0.13$.

Parameter	Symbol	Value	Annual value
Global GDP	y_0	$2.24\,10^{15}$\$	$69\,10^{12}$\$
Capital stock	k_0	$0.224\,10^{15}$\$	
Labor share	b_0	0.6	
Capital share	a_0	0.27	
Land share	$1 - a_0 - b_0$	0.13	
PRTP	ρ	1.81	3%

Table 3: Calibration of the economy in first period. Flow values are given for the 35 year time steps of the model.

We follow Klump et al. (2012) in calibrating the CES production function in order to obtain consistent and comparable results for different values of the elasticity of substitution. Given an elasticity σ, the state variables k, e, and the production function, the economy in the first period is determined by

$$a_0 = \frac{k\frac{\partial y}{\partial k}}{y}, \qquad 1 - a_0 - b_0 = \frac{m\frac{\partial y}{\partial m}}{y},$$
$$y_0 = y, \qquad k_0 = k, \qquad e_0 = e.$$

The solution of this system of equations are the total factor productivity A, and the CES share parameters a, b.

B PCP solution algorithm

We calculate the optimal climate policy τ_t for the PCP scenario in Markov perfect equilibrium by solving the first-order condition for joint utility :

$$\frac{\partial U_t^*}{\partial \tau_t} = 0 \qquad \forall t \tag{22}$$

We follow the procedure described by Karp and Rezai (2014a), Karp and Rezai (2014b), and Klein et al. (2008). The old generation understand that the land price p_t evolves according to the arbitrage equation

$$p_t = \frac{P(k_{t+1}, e_{t+1}) + v_{t+1}}{1 + r_{t+1}},$$

where the function $P(k_{t+1}, e_{t+1})$ is their expectation of the price p_{t+1}, dependent only on the two state variables.

We compute the derivative in the first-order condition (Eq. 22) using a computer algebra system (SymPy Development Team 2014). We then approximate the climate policy decision variable τ_t and the land price p_t using forth degree Chebyshev polynomials in the two state variables, capital k_t, and carbon e_t:

$$\tau_t \rightarrow T(k_t, e_t)$$
$$p_t \rightarrow P(k_t, e_t)$$

Generations also understand the equations of motion for both state variables:

$$k_{t+1} = \frac{w_t}{2 + \rho} - P(k_t, e_t)\, m$$
$$e_{t+1} = (1 - \phi_D)\, e_t + (1 - \tau_t)\, \phi_I\, y_t$$

Starting from a guess for the coefficients of T and P, we first compute new coefficients for T from the first-order condition for climate policy (22) by finding the root numerically. Second, using the new approximation for T, the new coefficients of P are determined using the arbitrage equation:

$$P(k_t, e_t) = \frac{P(k_{t+1}, e_{t+1}) + v_{t+1}}{1 + r_{t+1}}$$

These two steps are iterated until there is sufficiently little change in the approximations coefficients between iterations.

C Productivity and Rents

This section is a partial equilibrium analysis on the effect of changes in the productivity of land χ on the land rents v. It is partial in the sense that we assume both state variables, capital k and carbon e to be exogenous. We suppress time indices whenever no ambiguity arises as a result. For an increase in the productivity of land - which has the factor share LS - the sign of the change in the rent is

$$\operatorname{sgn}\left(\frac{\partial v}{\partial \chi}\right) = \operatorname{sgn}(\mathrm{LS} + \sigma - 1). \tag{23}$$

When land and non-land production factors are substitutes $\sigma > 1$, land rents always increase in response to an increase in productivity, and thus decrease in response to damages. However, when they are complements $\sigma < 1$, two competing effect determine the sign of the rent change: First, lower productivity decreases the return

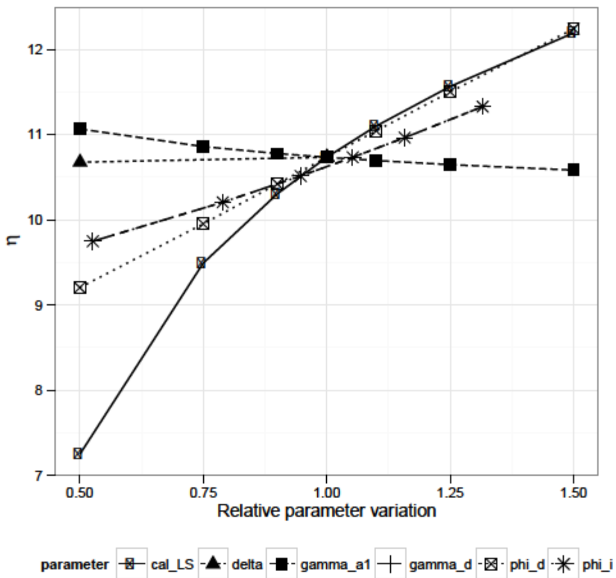


Figure 5: Sensitivity analysis for Fig. 3.

to land by lowering total output. Second, land rents increase, because the decrease in productivity moves production away from the optimal factor proportions, thus increases the scarcity rents accruing to land. For low elasticities of substitution σ and small shares of land in production LS, the rent decreases in response to an increase in productivity. This is a well-known effect from the theory of biased technological change (Acemoglu 2009).

This rent change however is a temporary effect, as the capital and carbon stocks will endogenously adjust to the new optimal factor ratio over time. The endogenous reaction of the capital stock cannot be included in this analytical analysis, but is instead treated in the full numerical model.

D Sensitivity analysis

Fig. 5 shows the sensitivity of the economic effectiveness, as introduced in Fig. 3: For default parameter values at a $\sigma = 0.7$, the effectiveness is around $\eta = 11\%$. From there, we vary the most important parameters in the model from 0.5 times their default value to 1.5 times. The resulting change in the effectiveness varies from 7% to 12%.

Kapitel 6

Fiscal Policy

–

Is Capital Back? The Role of Land Ownership and Savings Behavior[1]

Max Franks
David Klenert
Anselm Schultes
Kai Lessmann
Ottmar Edenhofer

[1] Submitted to European Economic Review.

Is Capital Back? The Role of Land Ownership and Savings Behavior.

Max Franks[a,b,*], David Klenert[b,c], Anselm Schultes[a,b], Kai Lessmann[a], Ottmar Edenhofer[a,b,c]

[a]*Potsdam Institute for Climate Impact Research (PIK). Telegrafenberg A31, D-14412 Potsdam, Germany*
[b]*Berlin Institute of Technology, Economics of Climate Change*
[c]*Mercator Research Institute on Global Commons and Climate Change (MCC)*

Abstract

Wealth inequality is one of the major political concerns in most OECD countries. Under this premise we analyze different policy instruments in terms of their impact on wealth inequality and output. We use a general equilibrium model in which we disaggregate wealth in its capital and land components, and savings in their life-cycle and bequest components. Households are heterogeneous in their taste for the 'warm glow' of leaving bequests. We show that a government has considerable freedom in reducing wealth inequality without sacrificing output: A land rent tax enhances output due to a portfolio effect and reduces wealth inequality slightly. The bequest tax has the highest potential to reduce inequality, and its effect on output is very moderate. By contrast, we confirm the standard result that a tax on capital income reduces output strongly, and show that it only has moderate redistributive effects. Furthermore, we analyze different revenue recycling options and find that lump-sum recycling of the tax revenue to the young generation enhances output the most and further reduces wealth inequality.

JEL Classification: D31, E62, H23, H24, Q24 **Keywords:** Fiscal policy, Wealth distribution, Capital tax, Bequests, Land rent tax

*Corresponding author. Email: franks@pik-potsdam.de

Preprint submitted to Elsevier *December 3, 2015*

1. Introduction

In many OECD countries wealth-to-income ratios are rising (Piketty and Zucman, 2014) and inequality is relatively high, which is a matter of concern to policy makers. Saez and Zucman (2015) for instance find that the US wealth concentration is high by international standards and has considerably increased in recent decades. To counteract the concentration of wealth Benhabib et al. (2011) and Piketty and Saez (2013)[1] recommend taxes on capital. However, capital taxes discourage investment and reduce economic growth. Further, these authors do not distinguish between capital and wealth (Homburg, 2015), which is inconsistent with empirical findings as Stiglitz (2015) points out. In particular, Stiglitz highlights the fundamental role of land rents for the distribution of wealth.[2] Therefore, we compare taxes on capital income, land rents, and bequests in an overlapping generations model in which we disaggregate wealth into capital and land.

We show that governments have considerable freedom in reducing wealth inequality without sacrificing output. There is a range of combinations of land rent and bequest tax rates under which output remains unchanged, but public revenues and the wealth distribution can be varied.

Explicitly distinguishing the stocks of land and capital is crucial due to their inherently different dynamics. While capital is reproducible, land is fixed. The differing evolution of the capital- and housing-shares of wealth underline this point: In several developed economies, the increase of the wealth-GDP ratio in the post-WWII-era is caused by an increase of the value of land (see, e.g., Homburg, 2015, Fig. 3).

In analogy to Piketty and Saez (2013), we choose preferences for bequests as the source of heterogeneity in our analysis. We do so since bequests are a key

[1] Although Piketty and Saez (2013) is titled *A Theory of Optimal Inheritance Taxation*, the tax on bequests which they analyze is equivalent to a capital tax (p. 1854, Footnote 4). Accordingly, the title of their working paper version Piketty and Saez (2012) is *A Theory of Optimal Capital Taxation*.

[2] In contrast to Stiglitz (2015), Homburg (2015) seems to dismiss the distributional implications of the dynamics of land rent ownership in the conclusion of his article.

determinant of wealth inequality (Cagetti and De Nardi, 2008), and intergenerational transfers of wealth make up approximately half of total capital formation (Gale and Scholz, 1994), yet “theoretical implications of inequality in received inheritances are not yet fully understood and are likely to lead to arguments for positive taxation of bequests” (Kopczuk, 2013, p. 332).[3]

Next to Benhabib et al. (2011) and Piketty and Saez (2013) there are many other studies which analyze the distributional effects of taxation in heterogeneous agent models. Two classic papers on optimal taxation, Judd (1985) and Chamley (1986), establish that capital taxes are inefficient, and should not be used to redistribute wealth when households have heterogeneous preferences. More recently, Chiroleu-Assouline and Fodha (2014) implement heterogeneity through differences in skill among workers. They find that if capital taxes (interpreted in their analysis as environmental taxes) are regressive, a complementary change of the income tax rules is Pareto efficient and renders the tax system progressive again.

To our knowledge, the only other study with heterogeneous agents that takes land into account apart from ours is Stiglitz (2015). However, the author takes only the polar case of two types of households into account: workers, who save only for consumption during their own old age, and capitalists, who save only to leave bequests to their offspring. He finds that taxing capital income cannot reduce wealth inequality since the capitalists always shift the tax burden to workers.

By contrast, we model heterogeneity in greater detail. We let different households have both savings motives, but to different degrees, respectively. Thus,

[3] We are aware of exceptions in the literature: In their empirical contributions Wolff and Gittleman (2014) and Bönke et al. (2015) find that bequests are not an important driver of wealth inequality. However, both studies do not take the top 1% of the wealth distribution fully into account. Further, the results of Wolff and Gittleman (2014) rest on the assumption that “(...) if wealth transfers are eliminated, there would be no effect on the savings behavior of those who have received transfers or are expecting them and that there would be no effect on the savings of those who intend to give a bequest.” (p. 465). Due to the methodological difference to Wolff and Gittleman (2014) we are able to take exactly that counterfactual case into account in which transfers are eliminated and households actually change their savings behavior.

our framework is flexible enough to be calibrated to the empirical data on the distribution of wealth compiled by the OECD (2015). Due to our assumptions of endogenous saving and bequest heterogeneity instead of class membership, a capital tax in our model reduces inequality in wealth.

We show that in fact all three instruments considered in our study reduce wealth inequality. However, they differ strongly in their effect on output (and thus also households' incomes). Taxing capital income has a negative effect on output levels for two reasons: The tax reduces households' incentive to save in general, but it also shifts investments away from capital towards land – a macroeconomic portfolio effect. Conversely, land rent taxation shifts private savings and investments away from land and towards capital, thereby enhancing output.[4] Bequest taxes do not affect the composition of the households' portfolio, so they have a significantly smaller effect on output. The effect is ambiguous due to the heterogeneity in households' savings behavior. Wealthy households save less when bequests are taxed. Thus, since the wealthy own most of the capital in the economy, the interest rate increases. Due to this price effect, less wealthy households in turn save more. Output changes according to the change in aggregate savings.

Further, the savings behavior of households determines the redistributive effect. Each of the three tax instruments discourages savings to a certain extent, and thus also reduces bequests to the following generation. Since wealthy households' income consists of a relatively high amount of bequests, a reduction of the latter decreases their income more strongly than that of poorer households. The potential to redistribute wealth using land rent and capital income taxation is only moderate compared to bequest taxes, which directly targets the

[4] Feldstein (1977) was the first to identify the portfolio effect, which Petrucci (2006) later formalized. **?** extend the formal analysis of the portfolio effect by introducing a social welfare function as benchmark for evaluating fiscal policy, in particular land rent taxes. The present paper focuses on the economic impacts of fiscal policy and does not consider a social welfare function. Nevertheless, we find that under land rent taxation the winners of the policy could theoretically compensate the losers. Thus, land rent taxation fulfills the Kaldor-Hicks criterion (see Appendix D).

source of inequality. Once all land rents are taxed away, or capital investments are choked, respectively, no further redistribution of wealth is possible.

Finally, different ways of recycling tax revenues to the economy have different impacts. Using the tax revenues to finance infrastructure investments only raises the steady-state level of output, but does not change the distribution of wealth. If public revenues are instead recycled as lump-sum transfers to households, we find an impact both on output and on the distribution of wealth: The more a government directs the transfers to the young, the higher the level of output in the steady-state will be and the more equal wealth will be distributed. Our finding thus gives support to the proposal of the stakeholder society (Ackerman and Alstott, 1999), also voiced by Corneo (2011), Atkinson (2015), and **?**.[5]

The rest of the paper is structured as follows. In Section 2 we introduce a simplified version of our model with sequential generations. Here, we highlight the importance of endogenous prices to justify our choice of a deterministic model with complete markets – an approach which we understand as complementary to Piketty and Saez (2013) and Benhabib et al. (2011), who model individual households' rate of return on capital and the distribution of wealth as determined by stochastic processes. In Section 3 we introduce overlapping generations and land, and perform the policy instrument analysis which is central to our paper. Sensitivity and robustness of our results are tested in Section 4. Section 5 concludes.

[5] Inspired by the idea of the stakeholder society, the United Kingdom introduced Child Trust Funds in 2005, which were replaced by Junior ISAs in 2011.

2. A simple model of bequest heterogeneity

In the present section we develop a simple model of bequest heterogeneity to explain fundamental mechanisms at work. In particular, we want to demonstrate the importance of the impact of taxes on the interest rate for the distribution of wealth. Land as a production factor and the life cycle savings motive are omitted here and will be introduced in the next section.

Our simple model is based on Acemoglu (2008). To the best of our knowledge, it is the most parsimonious model of an economy in which new generations enter the economy each period and leave bequests to the next generation.

In each period t a new generation arrives in the economy and the old generation leaves the economy. There are N different types of households in each generation, which differ in their preferences. Each type of household $i \in \{1, ..., N\}$ lives for one period, during which it receives income $y_{i,t}$. It divides its income between consumption $c_{i,t}$ and bequests for the next generation $b_{i,t}$, which are taxed at the uniform rate τ_B. A household derives utility from consumption and the "warm glow" (Andreoni, 1989) of leaving net-of-tax bequests:

$$u_{i,t} = \log(c_{i,t}) + \beta_i \log(b_{i,t}(1 - \tau_B)). \tag{1}$$

The budget equation is given by

$$y_{i,t} = w_t + (1 + R_t(1 - \tau_K))b_{i,t-1}(1 - \tau_B) = c_{i,t} + b_{i,t}, \tag{2}$$

where w denotes wage income, R is the rate of return on inherited wealth, that is, the bequests from the previous generation, and $0 < \beta_i < 1$ determines the preference for leaving bequests for the household of type i of the next generation $t + 1$. We assume that capital does not depreciate after use,[6] and that the offspring of a household has the same preferences as its parents.[7] Households

[6] Assuming positive depreciation does not alter the results qualitatively.

[7] This simplifying assumption may be justified by recent findings on the determinants of intergenerational wealth transmission which suggest potential roles for intergenerational

may have to pay taxes τ_K on capital income or taxes τ_B on the bequests they receive.

Production is given by a standard neoclassical production function in intensive form $f(k)$ that satisfies the usual conditions. Then, for the equilibrium wage rate we have,

$$w_t = f(k_t) - f'(k_t)k_t, \tag{3}$$

and

$$R_t = f'(k_t).$$

We assume that all bequests are invested in capital k used for production:

$$k_{t+1} = \frac{1}{N}\sum_i b_{i,t}.$$

2.1. Basic properties

Households choose the levels of consumption and bequests in order to maximize their utility (1) subject to their budget equation (2). This yields the first-order conditions

$$b_{i,t} = \frac{\beta_i}{1+\beta_i} y_{i,t} = \varphi_i\Big(w_t + (1 + R_t(1-\tau_K))b_{i,t-1}(1-\tau_B)\Big) \quad \forall t, \tag{4}$$

where $i \in \{1, ..., N\}$ and $\varphi_i := \frac{\beta_i}{1+\beta_i}$.

With (4) it is possible to deduce a condition on the curvature of the production function which ensures the existence of a steady-state (see Appendix A). This condition is, for instance, fulfilled by CES-type production functions. Then, the steady-state level of bequests is given by

$$b_i^* = \frac{w^*\beta_i}{(1 - R^*(1-\tau_K)\beta_i)(1-\tau_B)}, \tag{5}$$

transmission of preferences (Black et al., 2015).

where asterisks denote steady-state levels. Further, if a steady-state exists, it follows directly from (4) that a higher preference parameter β_i for bequests implies a higher steady-state level of bequests for household i.[8]

2.2. Fiscal policy

We consider a linear tax on capital income or on bequests which is implemented in the first time period of the model and remains constant for the whole time horizon. The main aim here is to highlight that the impact of the tax on the interest rate is crucial for how the tax affects the wealth distribution.

Lemma 1. *Assume a steady-state exists (cf. Corollary A, Appendix A).*

1. *An increase in the bequest tax leads to a decrease in wealth inequality, if and only if*

$$\frac{\mathrm{d}R^*}{\mathrm{d}\tau_B} < 0. \tag{6}$$

2. *An increase in the capital income tax leads to a decrease in wealth inequality, if and only if*

$$\frac{\mathrm{d}R^*}{\mathrm{d}\tau_K} < \frac{R^*}{1-\tau_K}. \tag{7}$$

By a decrease in wealth inequality we understand a decreasing steady-state bequest ratio b_i^*/b_j^* of households i and j whenever $\beta_i > \beta_j$ (i.e. household i has a higher preference for leaving bequest than household j).

Proof. Let $i, j \in \{1, ..., N\}$ such that $\beta_i > \beta_j$ and thus $b_i^* > b_j^*$ holds. Using (5) it is straightforward to calculate whether a marginal increase of a tax increases or decreases the ratio of steady-state bequest levels:

1. $\frac{\mathrm{d}}{\mathrm{d}\tau_B}\left(\frac{b_i^*}{b_j^*}\right) = \frac{b_i^*}{b_j^*}(1-\tau_K)\frac{\beta_i-\beta_j}{(1-R^*(1-\tau_K)\beta_i)^2}\frac{\mathrm{d}R^*}{\mathrm{d}\tau_B}$

2. $\frac{\mathrm{d}}{\mathrm{d}\tau_K}\left(\frac{b_i^*}{b_j^*}\right) = \frac{\mathrm{d}}{\mathrm{d}\tau_K}\frac{\beta_i}{\beta_j}\frac{1-R^*(1-\tau_K)\beta_j}{1-R^*(1-\tau_K)\beta_i} = \frac{\beta_i}{\beta_j}\frac{\beta_i-\beta_j}{(1-R^*(1-\tau_K)\beta_i)^2}\left((1-\tau_K)\frac{\mathrm{d}R^*}{\mathrm{d}\tau_K} - R^*\right)$

□

The intuition behind conditions (6) and (7) is that wages, which all households receive equally and which are linked to the interest rate R via equation

[8] To see this, note that $\frac{\mathrm{d}b_i^*}{\mathrm{d}\beta_i} > 0$.

(3), should not decrease too much. If conditions (6) or (7) hold, respectively, there is an upper bound for the marginal product of capital $f'(k)$, and thus a lower bound for the capital stock, output, and wages.

Our interpretation of the above lemma is that prices matter for a comprehensive policy instrument analysis. Any statement about the impact of taxes on the distribution of wealth should consider how the taxes affect factor prices endogenously. In Section 3 we will build on this insight to derive more precisely how taxes affect an economy with heterogeneous agents and land.

3. The role of land rents and savings behavior for the economic impact of fiscal policy.

We extend the analytical model described in Section 2 by introducing two additional features. First, we assume that agents live for two periods instead of only one. Thus, in each period there are two generations that overlap. We make this assumption to differentiate between the life-cycle savings motive and the savings motive for leaving bequests, and also in order to have a market for land, on which old households may sell their land to young ones. Land thus serves both as a fixed factor of production and an alternative asset for households' investments.

We first give a model description. Then, in Section 3.2, we show how taxes on capital income, land rents, and bequests affect output and the wealth distribution in the steady-state, without taking the spending side into account. Finally, in Section 3.3, we consider different ways of using the public funds generated by fiscal policy.

3.1. Model

The economy consists of N different types of households which differ with respect to their preferences and which live for two periods. Further, there is one representative firm and the government. The different preferences of each type of households imply different levels of wealth. As already seen in Section 2, higher preferences for bequests imply higher steady-state levels of wealth. For the rest of the paper we set $N = 5$ and use the index i to identify the household belonging to the ith wealth quintile, where households are ordered from lowest to highest preferences for bequests. We assume that the offspring of a household has the same preferences as its parents. Further, we shall assume a finite time horizon, i.e. $t \in \{1, ..., T\}$, where one time step represents a period of 30 years (one generation). All variables are stated in per capita terms.

3.1.1. Households

The utility of households is given by an isoelastic function with elasticity parameter η. It depends on their consumption when young $c^y_{i,t}$, consumption when old $c^o_{i,t+1}$, and net-bequests left to their children $b_{i,t+1}(1-\tau_B)$, on which the government may levy bequest taxes.

$$u\left(c^y_{i,t}, c^o_{i,t+1}, b_{i,t+1}\right) = \frac{(c^y_{i,t})^{1-\eta} + \mu_i(c^o_{i,t+1})^{1-\eta} + \beta_i\left(b_{i,t+1}(1-\tau_B)\right)^{1-\eta}}{1-\eta} \tag{8}$$

For the parameters we assume that $\mu_i, \beta_i \in (0,1)$. Households maximize their utility subject to the following budget equations.

$$\begin{aligned} c^y_{i,t} + s_{i,t} &= w_t + b_{i,t}(1-\tau_B) \\ s_{i,t} &= k^s_{i,t+1} + p_t l_{i,t+1} \\ c^o_{i,t+1} + b_{i,t+1} &= (1 + R_{t+1}(1-\tau_K))k^s_{i,t+1} + l_{i,t+1}(p_{t+1} + q_{t+1}(1-\tau_L)) =: v_{i,t+1} \end{aligned}$$

In period t a young household i earns wage income w_t, receives bequests from the currently old generation, and pays taxes on the bequests. The household uses its income to consume or save. Savings $s_{i,t}$ can be invested in capital $k^s_{i,t+1}$ or land $l_{i,t+1}$ which are assumed to be productive in the next period and may be taxed at rates τ_K and τ_L, respectively. We assume that capital is the numeraire good and land has the price p. When households are old, they receive the return on their investments according to the interest rate R_{t+1}, the price of land p_{t+1}, and the land rent q_{t+1}. We define household's wealth $v_{i,t}$ as the sum of the values of the stocks of capital and land, and also the returns to investments in these stocks. Old households use their wealth to consume or to leave bequests for the next generation.

The first-order conditions of the households' optimizations are given by

$$(c^o_{i,t+1})^\eta = \mu_i(1 + R_{t+1}(1-\tau_K))(c^y_{i,t})^\eta \tag{9}$$

$$\beta_i(1-\tau_B)^{1-\eta}(c^o_{i,t+1})^\eta = \mu_i b^\eta_{i,t+1} \tag{10}$$

$$\frac{p_{t+1} + q_{t+1}(1-\tau_L)}{p_t} = 1 + R_{t+1}(1-\tau_K). \tag{11}$$

Note that the no-arbitrage condition (11) can be reformulated as the discounted sum of future rents:

$$p_t = \sum_{i=1}^{T} \frac{\widetilde{q}_{t+1}}{\prod_{j=T-i+1}^{T}(1+\widetilde{R}_{t+j})},$$

where $\widetilde{q}_t := q_t(1-\tau_L)$ and $\widetilde{R}_t := R_t(1-\tau_K)$, and we assume that in the final period T the price of land is zero, $p_T = 0$, since there is no following generation to buy the land. The no-arbitrage condition ensures that households invest in capital and land in such a way that the returns are equalized across the two assets. The returns are determined by the aggregate quantities of the input factors. Beyond this, the no-arbitrage condition does not impose any restrictions on how the asset portfolios of individual households are composed.[9]

3.1.2. Firm

The representative firm produces one type of final good using capital k, land l and labor, where the latter two are assumed to be fixed factors. We assume that the production function is of CES type. In intensive form it is defined as

$$f(k_t) = A_0[\alpha k_t^\sigma + \gamma l^\sigma + 1 - \alpha - \gamma]^{\frac{1}{\sigma}},$$

where A_0 is total factor productivity and $\sigma = \frac{\epsilon-1}{\epsilon}$ is determined by the elasticity of substitution ϵ. The firm's demand for capital k_t equals the aggregate of capital that is supplied by households $k_{i,t}^s$. The clearing of factor markets is described by

$$k_t = \frac{1}{N}\sum_{i=1}^{N} k_{i,t}^s \quad \text{and} \quad l = \frac{1}{N}\sum_{i=1}^{N} l_{i,t}.$$

[9] We shall make use of the convention that all households choose the same asset composition. More precisely, in every period t there is an $X_t > 0$ such that $X_t = k_{i,t}^s / l_{i,t}$ for all $i \in \{1, ..., N\}$. We use this convention because there is an infinite continuum of possible combinations of individual asset portfolio compositions of each household i which have no bearing on any of our results.

In each period the firm maximizes its profit, which we assume to be zero due to perfect competition. Thus, the first-order conditions are

$$f_k(k_t) = R_t \quad \text{and} \quad f_l(k_t) = q_t$$

3.1.3. Government

The government levies taxes on capital income τ_K, land rents τ_L, or bequests τ_B. Throughout Section 3.2, we assume that public revenues g_t are used for public consumption which has no effect on the economy. In Section 3.3 we relax this assumption and analyze alternative recycling schemes.

$$g_t = \tau_K R_t k_t + \tau_L q_t l + \frac{1}{N} \sum_i \tau_B \, b_{i,t}.$$

3.2. The revenue side of fiscal policy

The hetereogeneity in household preferences and the introduction of land as additional factor of production yield complex results which go beyond of what is analytically tractable. Thus, we solve the model numerically using GAMS (Brooke et al., 2005). The parameter values (cf. Appendix B) are chosen such that the level of output and the distribution of wealth in the steady-state match recent OECD data on the distribution of wealth (OECD, 2015). In the present section we focus on the revenue side of fiscal policy and assume that the public revenues are not used for a specific purpose.

3.2.1. The policy-option space of output, redistribution, and public revenue

We evaluate fiscal policy along three dimensions: Their impact on output, their consequences for the wealth distribution, and their potential to raise public revenue.

We summarize our main result in Figure 1. The graphs show the feasible combinations of output f^*, the Gini coefficient of the wealth distribution $\{v_i^*\}_{i=1,\ldots,5}$, and the magnitude of public revenues g^* in the steady state if only one of the three tax instruments is used at a time. If taxes are set to zero, per capita output is about 1 million US$ per time step (30 years) and the Gini coefficient of the wealth distribution has a value of about 0.74. This point is marked by the intersection of the two dashed lines.

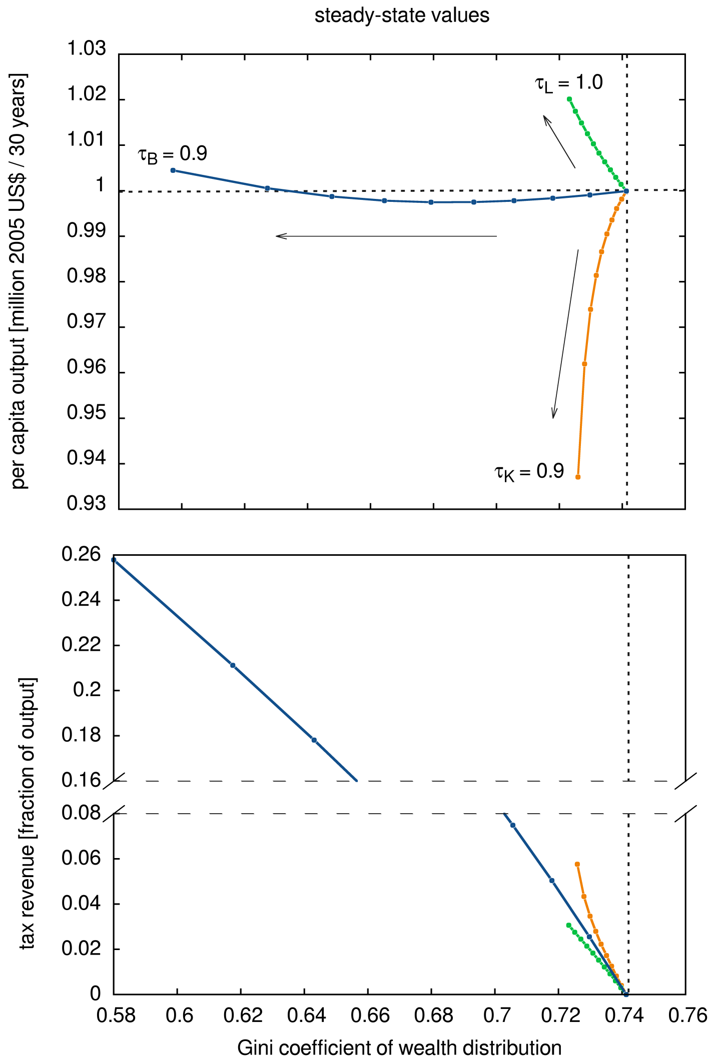


Figure 1: Depending on which tax instrument is used, the government may achieve different coordinates in the policy-option space of output, redistribution, and public revenue. Each curve represents the set of coordinates which are achievable with the use of one single tax instrument. The arrows in the upper panel indicate increases in the respective tax rate. The data points are chosen for tax rates in steps of 10%. They range from 0 to 100% for the land rent tax, and from 0 to 90% for the capital income and the bequest tax.[10] Note the broken axis in the lower panel.

As the tax rates are increased above zero, respectively, we observe that all taxes reduce the Gini coefficient. Output increases under the land rent tax and decreases under the capital income tax. The bequest tax reduces output below the level of the no-tax case as long as its rate is less than approximately 80% – above this value, output is in fact increased. By far the highest public revenues can be generated with the bequest tax. Its base is rather characterized as a stock, while the capital income and land rent taxes are only based on flows.[11]

The distribution of wealth depends on how fiscal policy affects the two components of the young households' income, i.e., wages and bequests. Rich households draw a higher proportion of their income from bequests than the poor. When a tax affects the two sources of income differently, the distribution of wealth will change accordingly. It turns out that the capital income tax and the land rent tax reduce the after tax return to savings $1 + R(1 - \tau_K)$, which discourages savings and thus reduces bequests. As a consequence, the income of richer households is reduced by a higher proportion than the income of poorer ones – the taxes have a progressive effect on the distribution of wealth (see Table 1).

[10] Capital income and bequest tax rates of 100% produce extreme results which we have left out here for expositional reasons.

[11] Consider, e.g., a one hundred percent tax on capital. Under such a tax, households lose all interest income, but at least they keep the principal. If, instead, all bequests were confiscated, they would lose all of their wealth which they do not spend on consumption at old age.

	household i	$\tau_K = 0.2$	$\tau_L = 0.2$	$\tau_B = 0.2$	$\tau_K = 0.7$	$\tau_L = 0.7$	$\tau_B = 0.7$
income y^*							
	1	0.995	1.004	0.997	0.964	1.018	0.997
	2	0.994	1.003	0.991	0.961	1.014	0.97
	3	0.992	1.002	0.980	0.956	1.008	0.93
	4	0.990	0.9995	0.964	0.948	0.9999	0.87
	5	0.978	0.985	0.874	0.904	0.949	0.63
bequests b^*							
	1	0.979	0.987	1.09	0.907	0.952	1.53
	2	0.978	0.986	1.08	0.904	0.948	1.47
	3	0.976	0.984	1.06	0.897	0.940	1.36
	4	0.974	0.981	1.04	0.889	0.930	1.24
	5	0.960	0.965	0.93	0.841	0.876	0.82

Table 1: Different tax instruments and rates imply different reductions in the steady-state levels of income and bequests. We assume that only one tax is implemented at a time. The numbers give the respective fractions of the case in which no taxes are implemented. All tax instruments reduce the income and the received bequests of rich households by a greater fraction that that of poor households.

The level of output is influenced by households' choices on whether to invest in land or capital. Since land and labor are fixed, fiscal policy that stimulates (hampers) investment in capital will unambiguously increase (decrease) output. While a bequest tax only indirectly affects asset prices, taxes on capital income and land rents have a relatively strong impact. As the relative prices of assets change, households will react by changing the composition of their portfolio.[12] Since the tax on land rents shifts investment toward capital, output actually increases. The capital income tax has the exact opposite effect.

The central effects caused by bequest taxes concern households' incomes and their substitution behavior. The immediate effect is to reduce households' income, which follows from the budget equations. A second immediate effect of bequest taxes is that they also increase demand for bequests relative to consumption in both periods of life, which follows from households' first-order conditions.

[12] For a graphical exposition of this fact see Figure Appendix C.1.

τ_B	R^*	k^*	s_1^*	s_2^*	s_3^*	s_4^*	s_5^*
0	0.361	109	4.3	37.2	96.9	177.7	650.5
0.1	0.372	107	4.4	38.2	98.9	179.6	621.2
0.2	0.381	105	4.5	39.4	101.3	182.2	595.5
0.3	0.388	104	4.6	40.9	104.3	185.6	573.3
0.4	0.392	103	4.7	42.7	108.1	190.1	554.7
0.5	0.392	103	4.8	45.1	113.1	196.2	540.1
0.6	0.388	104	5.1	48.3	119.9	204.8	530.4
0.7	0.376	106	5.4	52.9	129.6	217.7	527.2
0.8	0.353	111	6.0	60.4	145.4	238.7	534.8
0.9	0.308	123	7.1	76.1	177.7	281.5	566.8

Table 2: Interest rate, capital (10^3 2005 US\$), and savings (10^3 2005 US\$ per generation) in the steady-state under variation of the bequest tax rate.

Thus, under a bequest tax, the income of the richest households is reduced by a much greater factor than the income of the others since the income of the latter mainly comes from wages. Further, since the richest households owns the largest fraction of assets, the total supply of capital falls, and the interest rate increases. The poor and middle income households now benefit from the increase in the interest rate and save more. The two effects render the bequest tax progressive in its impact on the distribution of wealth. Table 2 summarizes the underlying data.

In terms of output, the bequest tax can even achieve an increase above the no-tax case, if the government sets the tax higher than approximately 80%.[13] The increase in savings by the poorer households is overcompensated by the decreased savings of the rich until the tax rate reaches about 80%. Here, the total capital supply – and thus also output – reaches the level of the no-tax case again. An increase of the bequest tax beyond 80% further increases the demand for bequests relative to life-time consumption. In other words, above the threshold the substitution effect overcompensates the income effect.

Since the bequest tax discourages the richest from saving, but stimulates more savings from the other households, it has a strong potential for wealth redistribution from the rich to the poor. With the bequest tax the Gini coefficient can, thus, be reduced to a significantly lower level than with the taxes on land

[13] The threshold depends on the elasticity parameter η of the utility function, as we show in Section 4.2, Figure 5.

rents or capital income.

The latter two have natural limits. Once all land rents are taxed away, there is no more scope for further tax increases and wealth redistribution.[14] As capital income taxes are increased, investment in the main source of productivity is choked, and the economy collapses.

3.2.2. Output-neutral tax reform.

Figure 1 suggests that several combinations (τ_L, τ_B) of land rent tax and bequest tax rates can redistribute wealth while at least maintaining the same steady-state level of output. In Figure 2 we show how the Gini coefficient changes under different combinations of bequest and land rent tax rates which do not reduce the steady-state level of output below the level of the benchmark case in which $\tau_K = 0.2$, and $\tau_L = \tau_B = 0$. The assumed fixed capital income tax rate of 20% is roughly in line with the according average tax rate in OECD countries.

It turns out that a typical OECD government has considerable freedom in choosing the desired value of the Gini coefficient without having to bear any costs in terms of forgone output. In our experiment, the Gini coefficient may be reduced from its benchmark value 0.74 down to almost 0.5, and public revenues increase from 0.8% to about 40% of output, as Table 3 shows.

[14] As we show in Section 4, the scope of the land rent tax depends on the calibration of the production function.

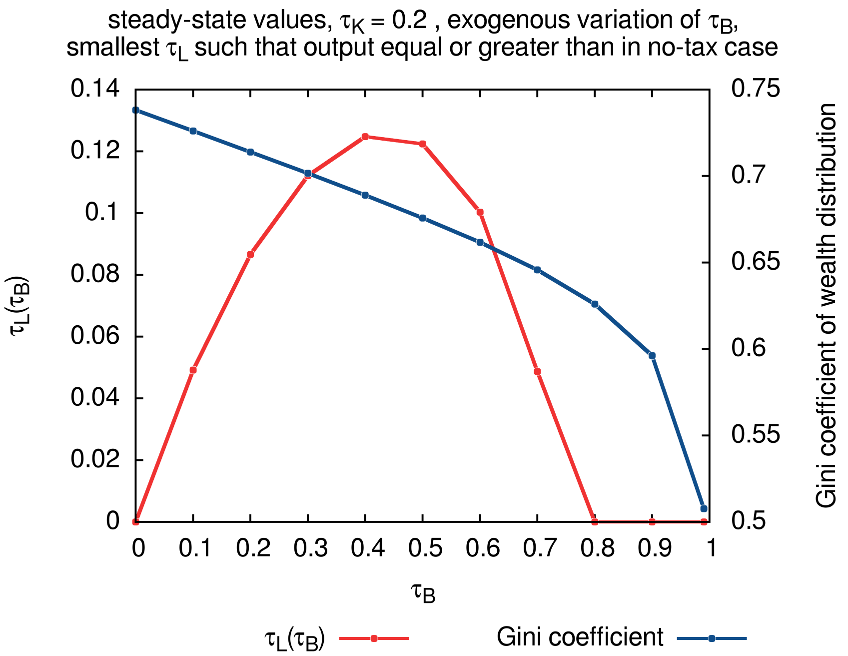


Figure 2: Combinations of bequest- and land rent taxes which imply the same (or higher) steady-state level of output as in the benchmark case in which $\tau_K = 0.2, \tau_L = \tau_B = 0$.

τ_B	τ_L	Gini	public revenue	output
0.00	0.00	0.74	8	996
0.10	0.05	0.73	34	996
0.20	0.09	0.71	59	996
0.30	0.11	0.70	83	996
0.40	0.12	0.69	106	996
0.50	0.12	0.68	130	996
0.60	0.10	0.66	155	996
0.70	0.05	0.65	181	996
0.80	0.00	0.63	214	997
0.90	0.00	0.60	261	1001
0.99	0.00	0.51	396	1015

Table 3: Combinations of bequest- and land rent taxes which imply the same (or higher) steady-state level of output as in the benchmark case in which $\tau_K = 0.2, \tau_L = \tau_B = 0$. Tax revenue and output are given in 10^3 2005 US$ / 30 years.

3.3. The spending side of fiscal policy

So far, we have only considered the revenue side of fiscal policy. Thereby we have assumed that the public revenues do not feed back into the economy. However, since public revenues are an endogenous variable and can become quite substantial, we now turn to the analysis of alternative uses of these revenues. Here, we show how different ways of recycling the revenues as lump-sum transfers to young and old households affect the policy-option space. In Section 4.3, we also consider the alternative case of productivity enhancing public spending, for example through infrastructure investments.

3.3.1. Lump-sum transfers to young and old households

We analyze the impacts of different transfer schemes by varying the distribution parameter $\delta \in [0, 1]$. Its value indicates the fraction of total transfers going to the old generation. Now, the budget equations of the young and the old households living in period t are given by

$$c^y_{i,t} + s_{i,t} = w_t + b_{i,t}(1 - \tau_B) + (1 - \delta)g_t,$$
$$c^o_{i,t} + b_{i,t} = (1 + R_t(1 - \tau_K))k^s_{i,t} + l_{i,t}(p_t + q_t(1 - \tau_L)) + \delta g_t.$$

As Figure 3 shows, it makes a significant difference whether the government transfers the public revenues only to young households ($\delta = 0$), only to old households ($\delta = 1$), or to both[15]. The more the government directs transfers to the young, the higher the level of output in the steady-state will be and the more equal wealth will be distributed. This outcome is most pronounced for the bequest tax.

If a transfer increases a young household's income, it directly increases consumption as well as savings (an income effect), and thus also capital supply and output. By contrast, a transfer to old households can in principle increase savings only indirectly. Through the direct income effect the old consume more and leave more bequests. Leaving more bequests, as second-order effect, increases

[15]Here, we use $\delta = \frac{1}{2}$. In general, of course, any $0 < \delta < 1$ implies transfers to both.

the income of the descendants. If bequests are taxed, then the second-order increase of the income of descendants is even smaller. However, it turns out that transfers to the old actually reduce savings through a substitution effect: Since young households anticipate the higher income in old age, they save less. The substitution effect is stronger for those households that have relatively low preferences for leaving bequests (and, thus, for savings). An overcompensation of the income effect through the substitution effect explains why the Gini coefficient increases and the output level decreases with δ.

It is worth mentioning that there is a relatively low threshold for the percentage of transfers which go to the old ($0 < \delta < 0.5$) above which the substitution effect is so strong, that steady-state output falls below the case in which public revenues are not even fed back into the economy (cf. Figure Appendix C.3).

If the government uses the bequest tax, public revenues are highest under recycling scheme $\delta = 1$. The more transfers are directed to the young, the lower the bequest tax revenues become. Revenues from land rent and capital income taxes show no substantial change under variation of δ.[16] This difference is due to the fact that, unlike with the factor taxes, the choice of the redistribution parameter δ directly changes the tax base of the bequest tax.

[16] See Figure Appendix C.2 for a graphical exposition of this fact.

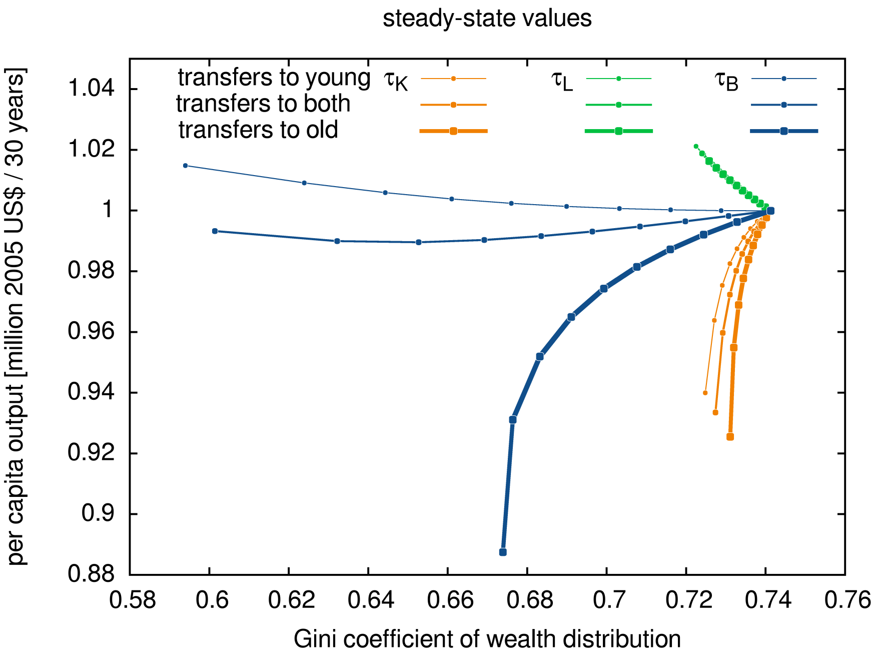


Figure 3: Impact of different recycling schemes on output and the distribution of wealth.

4. Robustness checks and sensitivity analysis

4.1. The role of preferences

We calibrate the model parameters to match observed data on the distribution of wealth in OECD countries under the assumption that the capital income tax rate is 20%, while land and bequests are not taxed. To reproduce the data with our model in the most parsimonious way, we assume that the only source of wealth inequality lies in different preferences for leaving bequests, i.e., $\beta_i < \beta_j$ for $1 \leq i < j \leq 5$. Preferences for consumption when old are thus equal for all households, i.e. $\mu_i = \mu$ for $i \in \{1, ..., 5\}$. To reproduce the relatively high degree of wealth inequality in the data described by a Gini coefficient of 0.74, we must choose a value for μ which is two orders of magnitude lower than the average of the β_i (cf. Figure 4 and Table B.5).

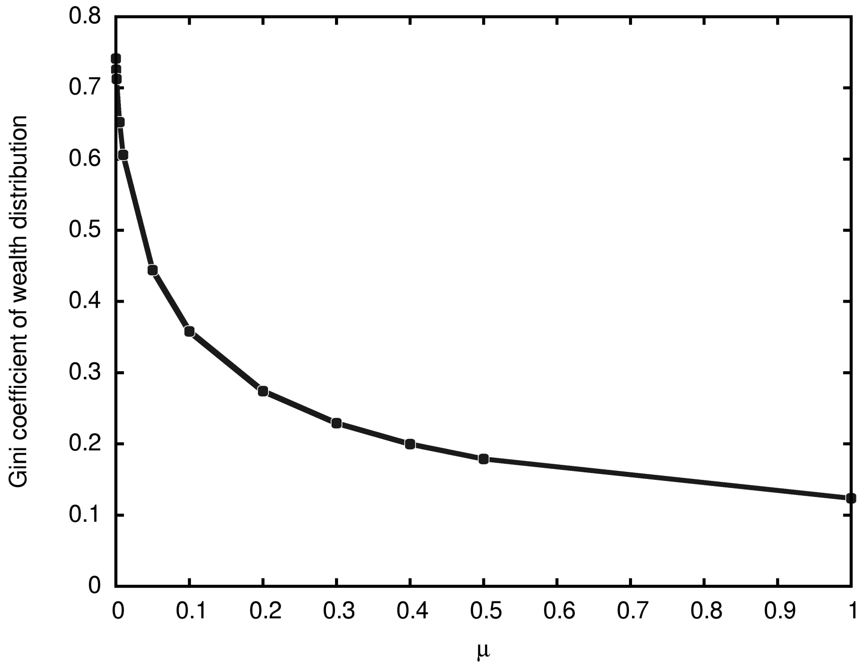


Figure 4: Variation of μ, the preference parameter for consumption in old age.

The assumption about the different roles of the preference parameters μ and β is justified, as the following experiment shows. If we would switch the roles, i.e., choose heterogeneous preferences for consumption when old and homogeneous preferences for leaving bequests, the equilibrium wealth distribution would be much more equal. Then, it would not be possible anymore to calibrate the model to the observed data without using highly unrealistic economic parameters.

To see this, we have performed a linear variation of the degrees of heterogeneity in both preference parameters. More precisely, let $\hat{\beta}_i$ and $\hat{\mu}$ denote the parameter values of the benchmark calibration (see Table B.5 in the appendix). Then we define

$$\mu_i = \hat{\mu}(1-\lambda) + \lambda\hat{\beta}_i$$
$$\beta_i = \hat{\beta}_i(1-\lambda) + \lambda\hat{\mu}$$

and vary from $\lambda = 0$ (the benchmark case) to $\lambda = 1$, the case in which the heterogeneity lies only in the preferences for consumption when old. Table 4 shows that in the former case, wealth is much more unevenly distributed than in the latter. The experiment reveals a clear cut monotonic relationship between the type of preference heterogeneity and the distribution of wealth.[17]

λ	Gini coefficient of wealth distribution
0	0.74
0.2	0.71
0.4	0.69
0.6	0.68
0.8	0.66
1	0.64

Table 4: Linear variation of heterogeneity in preferences. If $\lambda = 0$, i.e. only preferences for bequests are heterogeneous and $\mu_i = \mu$ for all $i \in \{1, ..., 5\}$ wealth inequality is higher than when only preferences for consumption when old are heterogeneous ($\lambda = 1$).

[17] This relationship is consistent with the claims voiced in previous literature, e.g., by Cagetti and De Nardi (2008), that in order to explain the observed high degree of wealth inequality, theoretical models need to incorporate bequests. The importance of including intergenerational transfers of wealth is further highlighted by the fact that they make up approximately half of total capital formation (Gale and Scholz, 1994).

4.2. Sensitivity analysis of the impacts of fiscal policy

We have varied all model parameters to learn about the sensitivity and robustness of our results. Here, we only present those results of the sensitivity analysis which reveal some non-trivial relationship between parameter choice and model results.

4.2.1. Utility function

As shown in Section 4.1, the wealth distribution depends on the relative weights of preferences for life-cycle savings and leaving bequests. However, the qualitative behavior of the economy in reaction to fiscal policy does not change significantly under the above variation. For the impact of fiscal policy the elasticity parameter η plays a more important role.

First note, though, that η also has a significant impact on the distribution of wealth and, moreover, on output, even when taxes are not taken into account (see Figure 5). Ceteris paribus, the steady-state level of output increases with η, while the Gini coefficient decreases. The reason is that households' substitution behavior depends on η. The first-order conditions (9) and (10) determine the relative demand for consumption and bequests. It turns out that higher values of η induce poorer households to save more, while it does not discourage rich households from leaving bequests significantly. Taken together, total wealth increases, in particular capital, and thus also output.

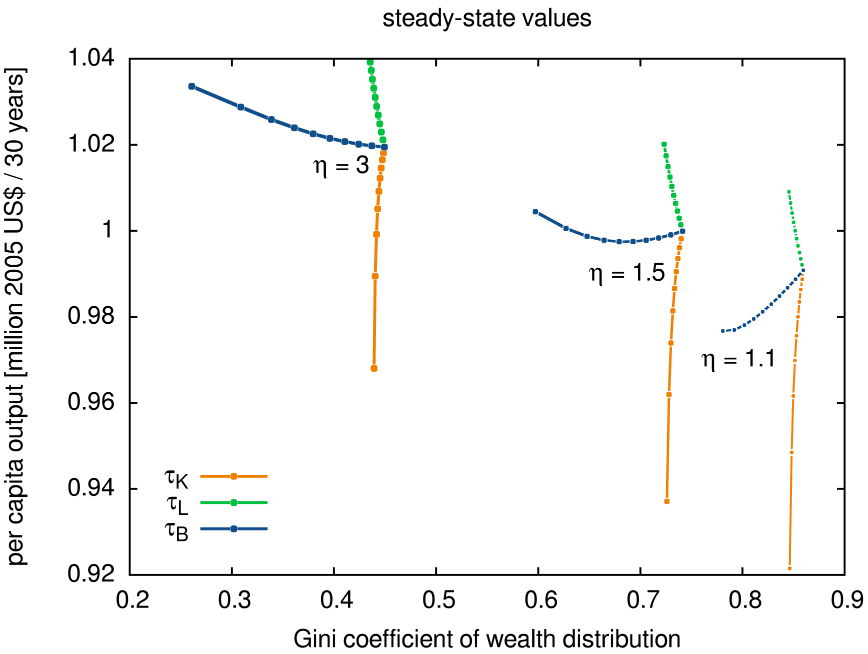


Figure 5: Policy-option space under variation of preference parameter η.

Coming back to the impact of fiscal policy, we see that the behavior of the economy in reaction to the bequest tax is sensitive to changes in the elasticity parameter. The greater η is, the more elastic households' preferences for leaving bequests are, thus, the greater is the scope for wealth redistribution via the bequest tax.

Further, for relatively high values of η, the bequest tax unambiguously increases output, while the opposite is the case for lower values. Here, we see how η determines the relative size of income and substitution effects of the bequest tax (recall the analysis of the bequest tax in Section 3.2.1). For high η, the tax-induced substitution effect outweighs the income effect, households redirect their income away from consumption towards leaving bequests. Therefore, they need to save more, which implies more capital, and thus a higher output level. For low η the exact opposite is the case.

4.2.2. Production function

The impact of fiscal policy on wealth distribution and output also depend on the parametrization of the production function. As Figure 6 shows, the scope of the land rent taxation crucially depends on the relative importance of land in production, i.e., its share parameter γ. We can draw two conclusions from the variation of γ. First, the more important land is in production (the higher γ is), the stronger the impact of the land rent tax is on output and the distribution of wealth. Second, as long as α remains constant[18], an increase in γ implies a decrease of the share parameter of labor. The latter clearly puts the poorer households at a disadvantage since their main source of income, wages, is reduced. As a consequence, the distribution of wealth becomes more unequal, ceteris paribus.[19]

[18] A simultaneous variation of α and γ such that their sum (and, thus, the share parameter of labor) remains constant shows that then the wealth distribution is much less sensitive. Increasing γ by 300%, e.g., increases the Gini coefficient by a mere 2%. We thus conclude that the presence of land *per se* has no distributional implications.

[19] Solow (2015) recently expressed his concern about the US labor market by referring to the same mechanism. He argues that wages do not keep up with the productivity increase because workers lack bargaining power. Thus, the income from (monopoly) rents accrues exclusively to capital owners.

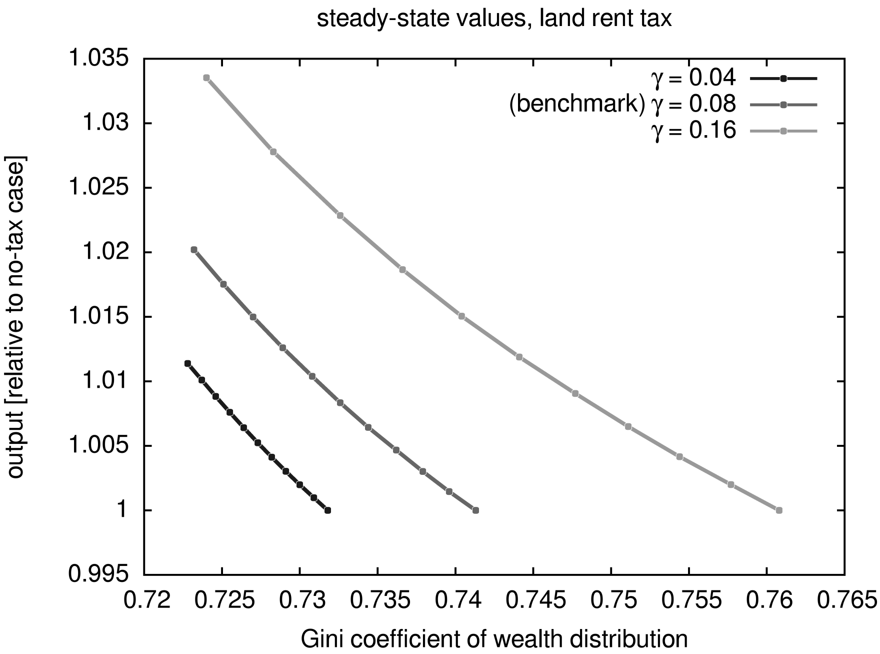


Figure 6: Scope of land rent tax depends on relative importance of land in production, i.e. the share parameter γ.

4.3. Alternative spending option: Infrastructure investments

In Section 3.3 we considered different way of recycling tax revenues as lump-sum transfers to the households. Here, we briefly show how results change under the alternative assumption that the government spends tax revenues to enhance firms' productivity, for example through infrastructure investments. In the following, we assume a simple linear relationship between public revenues and total factor productivity A:

$$A_t = A_0 + x_1 g_t$$

The impact of varying the efficiency parameter x_1 on output and the distribution of wealth are summarized in Figure 7. Independent of which tax instrument is used, an increase in the efficiency of public expenditures also increases the steady-state level of output. This is most pronounced for the bequest tax, which has the highest revenue raising potential.

While output is quite sensitive to changes in x_1, the wealth distribution remains almost unchanged. The reason is that increasing x_1 raises incomes for all types of households equally. The so-caused increase in total factor productivity does not only increase wages, but also the return on savings. In sum, the incomes of all households increase by almost the same factor and the wealth distribution remains virtually unchanged.

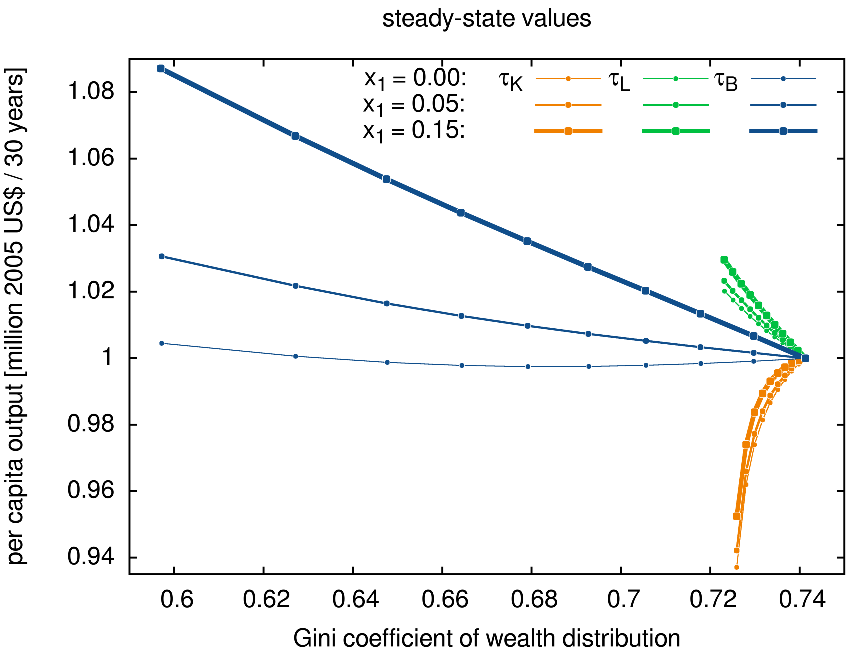


Figure 7: Impact of different degrees of effectivity of infrastructure on output and the wealth distribution

5. Conclusion

Is capital back? Thomas Piketty and Gabriel Zucman claim that this is the case by highlighting that the currently observed increased levels of inequality are due to a concentration of capital ownership at the top (Piketty, 2014, Piketty and Zucman, 2014). Recent literature, however, suggests that land ownership and bequest heterogeneity play a more important role in the process of wealth concentration (Homburg, 2015; Stiglitz, 2015; Cagetti and De Nardi, 2008). We illustrate this in an overlapping generations model that accounts for both features.

Our conclusions differ from Piketty's. Life-cycle saving (when invested in capital) should be left untaxed, while taxing bequests has a higher scope for redistribution at lower policy costs. Further, taxing the land rent component of wealth has a moderate scope for redistribution and strongly enhances output, due to a beneficial portfolio effect: Households shift investments away from the fixed factor land towards capital. The increase in capital investments directly increases output. Accordingly, capital taxes reduce output since they discourage capital investments.

Atkinson (2015) takes up the idea of the stakeholder society (Ackerman and Alstott, 1999) and proposes, among other measures, to reduce inequality by endowing young households with a one-time transfer at adulthood. That transfer, according to Atkinson, should be financed by a wealth- or inheritance tax. We demonstrate that financing such a transfer indeed reduces inequality. We find that the more the transfers are directed to the young and the less they are directed at the old, the higher output in steady-state is and the more equal the wealth distribution is. In this case, reducing inequality goes hand in hand with enhancing output.

While heterogeneity in bequests is a key driver of the wealth distribution, it is not the only one which has been suggested by the literature. Entrepreneurial risk taking, income inequality, or the type of earnings risk at the top of the distribution (Cagetti and De Nardi, 2008; De Nardi, 2015), as well as differences in education (Pfeffer and Killewald, 2015) also may play an important role in determining the shape of the distribution and how it changes over time. The quantitative importance of each factor is still an open research question, and the design of tax policies crucially depends on its answer. Accordingly, our results will differ from findings based on other assumptions about the drivers of wealth inequality. Extending our analysis of policy instruments to a framework with multiple drivers of wealth inequality, as used for instance by De Nardi and Yang (2014), could yield valuable insights.

There is a further promising avenue for future research based on the present article. The policy instrument analysis conducted here has focused only on the impact of exogenously determined tax reforms on the steady state. It would be desirable to embed our analysis within a framework of optimal taxation and social welfare maximization, and thus combine the theory of optimal taxation with the literature on household heterogeneity.

Acknowledgements

Acknowledgements suppressed during review process.

Role of funding source

The authors declare that their work was funded by their respective institutions and that they did not receive any third party funding.

References

Acemoglu, D., 2008. Introduction to modern economic growth. MIT Press.

Ackerman, B., Alstott, A., 1999. The stakeholder society. Yale University Press.

Andreoni, J., 1989. Giving with impure altruism: applications to charity and Ricardian equivalence. The Journal of Political Economy , 1447–1458.

Atkinson, A.B., 2015. Inequality: What Can Be Done? Harvard University Press.

Benhabib, J., Bisin, A., Zhu, S., 2011. The Distribution of Wealth and Fiscal Policy in Economies With Finitely Lived Agents. Econometrica 79, 123–157.

Black, S.E., Devereux, P.J., Lundborg, P., Majlesi, K., 2015. Poor Little Rich Kids? The Determinants of the Intergenerational Transmission of Wealth. Working Paper 21409. National Bureau of Economic Research.

Brooke, A., Kendrick, D., Meeraus, A., Raman, R., Rosenthal, R., 2005. GAMS – A Users Guide. GAMS Development Corporation.

Bönke, T., Corneo, G., Westermeier, C., 2015. Erbschaft und Eigenleistung im Vermögen der Deutschen: Eine Verteilungsanalyse. Discussion Papers 2015/10. Free University Berlin, School of Business & Economics.

Cagetti, M., De Nardi, M., 2008. Wealth inequality: Data and models. Macroeconomic Dynamics 12, 285–313.

Chamley, C., 1986. Optimal Taxation of Capital Income in General Equilibrium with Infinite Lives. Econometrica 54, 607–622.

Chiroleu-Assouline, M., Fodha, M., 2014. From regressive pollution taxes to progressive environmental tax reforms. European Economic Review 69, 126–142.

Corneo, G., 2011. Stakeholding as a new development strategy for Saudi Arabia. Review of Middle East Economics and Finance 7, 1–19.

De Nardi, M., 2015. Quantitative Models of Wealth Inequality: A Survey. Working Paper 21106. National Bureau of Economic Research.

De Nardi, M., Yang, F., 2014. Bequests and heterogeneity in retirement wealth. European Economic Review 72, 182–196.

Feldstein, M., 1977. The surprising incidence of a tax on pure rent: A new answer to an old question. The Journal of Political Economy 85, 349–360.

Gale, W.G., Scholz, J.K., 1994. Intergenerational Transfers and the Accumulation of Wealth. The Journal of Economic Perspectives 8, 145–160.

Homburg, S., 2015. Critical remarks on Piketty's Capital in the Twenty-first Century. Applied Economics 47, 1401–1406.

Judd, K.L., 1985. Redistributive taxation in a simple perfect foresight model. Journal of Public Economics 28, 59–83.

Kopczuk, W., 2013. Taxation of Intergenerational Transfers and Wealth, in: Auerbach, A.J., Chetty, R., Feldstein, M., Saez, E. (Eds.), Handbook of Public Economics. Newnes. volume 5.

OECD, 2015. In It Together: Why Less Inequality Benefits All. OECD Publishing, Paris .

Petrucci, A., 2006. The incidence of a tax on pure rent in a small open economy. Journal of Public Economics 90, 921–933.

Pfeffer, F.T., Killewald, A., 2015. How Rigid is the Wealth Structure and Why? Inter-and Multigenerational Associations in Family Wealth. Research Report 15-845. Population Studies Center.

Piketty, T., 2014. Capital in the 21st Century. Belknap Press.

Piketty, T., Saez, E., 2012. A Theory of Optimal Capital Taxation. Working Paper 17989. National Bureau of Economic Research.

Piketty, T., Saez, E., 2013. A theory of optimal inheritance taxation. Econometrica 81, 1851–1886.

Piketty, T., Zucman, G., 2014. Capital is Back: Wealth-Income Ratios in Rich Countries 1700–2010. The Quarterly Journal of Economics 129, 1255–1310.

Saez, E., Zucman, G., 2015. Wealth inequality in the United States since 1913: Evidence from capitalized income tax data. Technical Report. Center for Equitable Growth, UC Berkeley.

Solow, R., 2015. The Future of Work: Why Wages Aren't Keeping Up. *http://www.psmag.com/business-economics/the-future-of-work-why-wages-arent-keeping- up*, last accessed 25 August 2015.

Stiglitz, J.E., 2015. New Theoretical Perspectives on the Distribution of Income and Wealth among Individuals: Part III: Life Cycle Savings vs. Inherited Savings. Working Paper 21191. National Bureau of Economic Research.

Wolff, E.N., Gittleman, M., 2014. Inheritances and the distribution of wealth or whatever happened to the great inheritance boom? The Journal of Economic Inequality 12, 439–468.

Appendix A. Mathematical tools

Here we develop some mathematical tools to analyze the simple model from Section 2.

Lemma A. *If there exists a period t' such that for all $i \in \{1, ..., N\}$ it holds that $b_{i,t'} = b_{i,t'+1} > 0$, then there are b^* and k^* such that $k_{t'+l} = k^*$ and $b_{i,t'+l} = b_i^* \quad \forall l \geq 1$.*

Proof. Let t' be such that $b_{i,t'} = b_{i,t'+1}$ $\forall i$. Then it follows that

$$k_{t'+2} = \frac{1}{N} \sum_i b_{i,t'+1} = \frac{1}{N} \sum_i b_{i,t'} = k_{t'+1},$$

which implies $w_{t'+1} = w_{t'+2}$ and $R_{t'+1} = R_{t'+2}$. Using this we have

$$\begin{aligned} b_{i,t'+2} &= \varphi_i \Big(w_{t'+2} + (1 + R_{t'+2}(1 - \tau_K)) b_{i,t+1} (1 - \tau_B) \Big) \\ &= \varphi_i \Big(w_{t'+1} + (1 + R_{t'+1}(1 - \tau_K)) b_{i,t} (1 - \tau_B) \Big) \\ &= b_{i,t'+1}. \end{aligned}$$

The iteration of these two steps closes the proof.

Corollary A. *If the condition*

$$\lim_{k \to \infty} f''(k)(\beta_i f(k) - k) = 0 \tag{A.1}$$

holds for all i (e.g., when the production function is of CES- or Cobb-Douglas type), there exists a steady-state with capital-labor ratio k^*, bequest levels $b_i^* = \frac{w^* \beta_i}{1+\beta_i(1-R^*)}$, and factor prices w^*, R^*.

Proof. Considering Lemma A we have to show that for some $t' \in \mathbb{N}$ the equations

$$b_i := b_{i,t'} = b_{i,t'+1} > 0, \quad i \in \{1, ..., N\} \tag{A.2}$$

have a solution, respectively. To see this, we use Equation (4), which states that

$$b_{i,t'+1} = \varphi_i \Big(w_{t'+1} + (1 + R_{t'+1}(1 - \tau_K)) b_{i,t} (1 - \tau_B) \Big).$$

W.l.o.g. we assume that $\tau_B = 0 = \tau_K$. Plugging in Equation (A.2), we have

$$\begin{aligned} & b_i = \varphi_i(w_{t'+1} + (1 + R_{t'+1})b_i) \\ \iff \quad & b_i = \frac{\varphi_i w_{t'+1}}{1 - \varphi_i(1 + R_{t'+1})} \quad \forall i. \end{aligned} \tag{A.3}$$

When Equation (A.2) holds, we always have $\varphi_i(1 + R_{t'+1}) < 1$. This can be seen by using Equation (4), from which follows that

$$\begin{aligned} b_i = \varphi_i(w_{t'+1} + (1 + R_{t'+1})b_i) & \iff (1 + R_{t'+1})b_i\varphi_i = b_i - \varphi_i w_{t'+1}, \\ & \iff (1 + R_{t'+1})\varphi_i = 1 - \underbrace{\frac{\varphi_i w_{t'+1}}{b_i}}_{>0} < 1. \end{aligned} \tag{A.4}$$

It remains to be shown that under condition (A.1) the Equations (A.3) have a solution. To see this, let's define

$$\psi(b_i) := \frac{\varphi_i w_{t'+1}}{1 - \varphi_i(1 + R_{t'+1})}.$$

Due to constant returns to scale in the production function we have

$$\psi(b_i) = \varphi_i \frac{f(k_{t'+1}) - f'(k_{t'+1})k_{t'+1}}{1 - \varphi_i(1 + f'(k_{t'+1}))}.$$

It is straightforward to calculate the first derivative of ψ with respect to b_i. Note that $k_{t'+1} = \frac{1}{N}\sum_j b_j$, so $\frac{\mathrm{d}}{\mathrm{d}b_i} k_{t'+1}(b_i) = \frac{1}{N}$. Thus it holds that

$$\psi'(b_i) = \underbrace{\frac{\varphi_i f''(k_{t'+1})}{(1 - \varphi_i(1 + f'(k_{t'+1})))^2 N}}_{<0} \left[\varphi_i f(k_{t'+1}) - k_{t'+1}(1 - \varphi_i)\right],$$

and

$$\psi'(b_i) \begin{cases} > 0\,, & \text{if } 0 > \varphi_i f(k_{t'+1}) - k_{t'+1}(1 - \varphi_i) \\ = 0\,, & \text{if } 0 = \varphi_i f(k_{t'+1}) - k_{t'+1}(1 - \varphi_i) \\ < 0\,, & \text{if } 0 < \varphi_i f(k_{t'+1}) - k_{t'+1}(1 - \varphi_i) \end{cases}$$

Due to the monotonicity of the production function, there is only one non-zero value of $k_{t'+1}$ at which it is equal to $\frac{\varphi_i}{1-\varphi_i} f(k_{t'+1})$. Thus, as b_i increases from 0 on, ψ first falls monotonically, then reaches its minimum, and from then on increases monotonically. Depending on the values of the other b_j, $j \neq i$, the capital stock $k_{t'+1}$ could already be greater than $\varphi_i f'$ when $b_i = 0$. Now taking the limit of ψ', we see that

$$\lim_{b_i \to \infty} \psi'(b_i) = \lim_{b_i \to \infty} \frac{\beta_i}{N} f''(\beta_i f - k_{t'+1}).$$

So if Equation (A.1) holds, then ψ approaches some constant value. From Equation (A.4) we know that ψ is always positive. Thus, it must have at least one intersection with the function that maps b_i to itself, which is equivalent to the existence of a solution to Equation (A.3). $\square$

Appendix B. Model parameters and calibration

To calibrate the model, we fix the steady-state levels of output and wealth to average OECD data (OECD, 2015), the capital income tax rate at its approximate OECD average, and set the land rent and bequest tax rates to be zero. Then we solve for the parameters which describe household preferences and production technology. Table B.5 summarizes these values.

Preferences	elasticity parameter	η	1.55
	for consumption when old	μ	0.0001
	for leaving bequests	β_1	0.0001
		β_2	0.0073
		β_3	0.0328
		β_4	0.0813
		β_5	0.4798
Production	share parameter of capital	α	0.2
	share parameter of land	γ	0.08
	elasticity of substitution	ϵ	0.71
	total factor productivity	A_0	527.7
Tax rates	capital income tax	τ_K	0.2
	land rent tax	τ_L	0
	bequest tax	τ_B	0
Other	time horizon	T	40

Table B.5: Benchmark parameters which reproduce observed data on the wealth distribution in OECD countries.

Appendix C. Additional figures

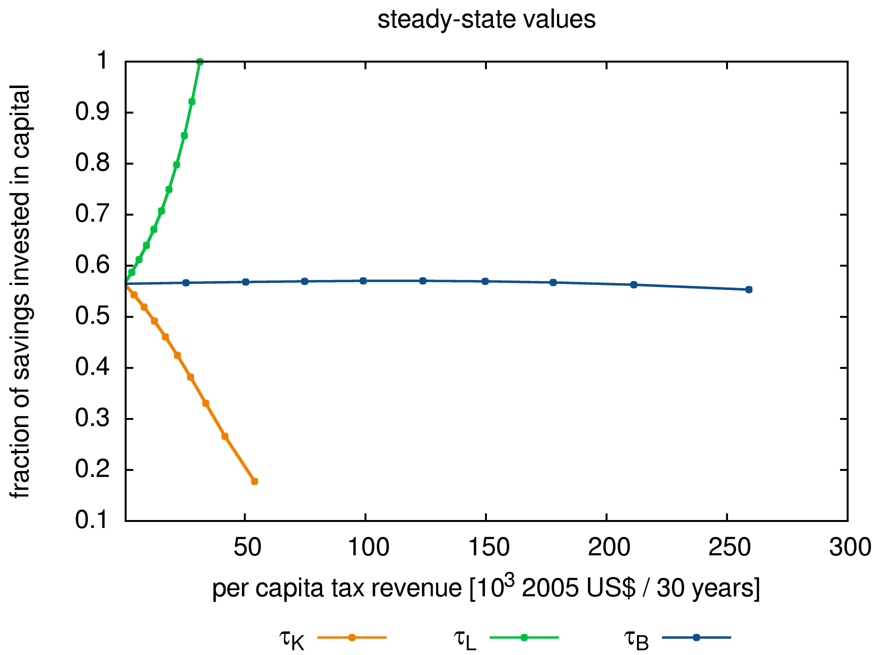


Figure Appendix C.1: Aggregate composition of assets (cf. Footnote 12) under variation of fiscal policy. Fiscal policy that stimulates (hampers) investment in capital will unambiguously increase (decrease) output. While a bequest tax only indirectly affects asset prices, taxes on capital income and land rents have a relatively strong impact. As the relative prices of assets change, households react by changing the composition of their portfolio. Since the tax on land rents shifts investment toward capital, output actually increases. The capital income tax has the exact opposite effect.

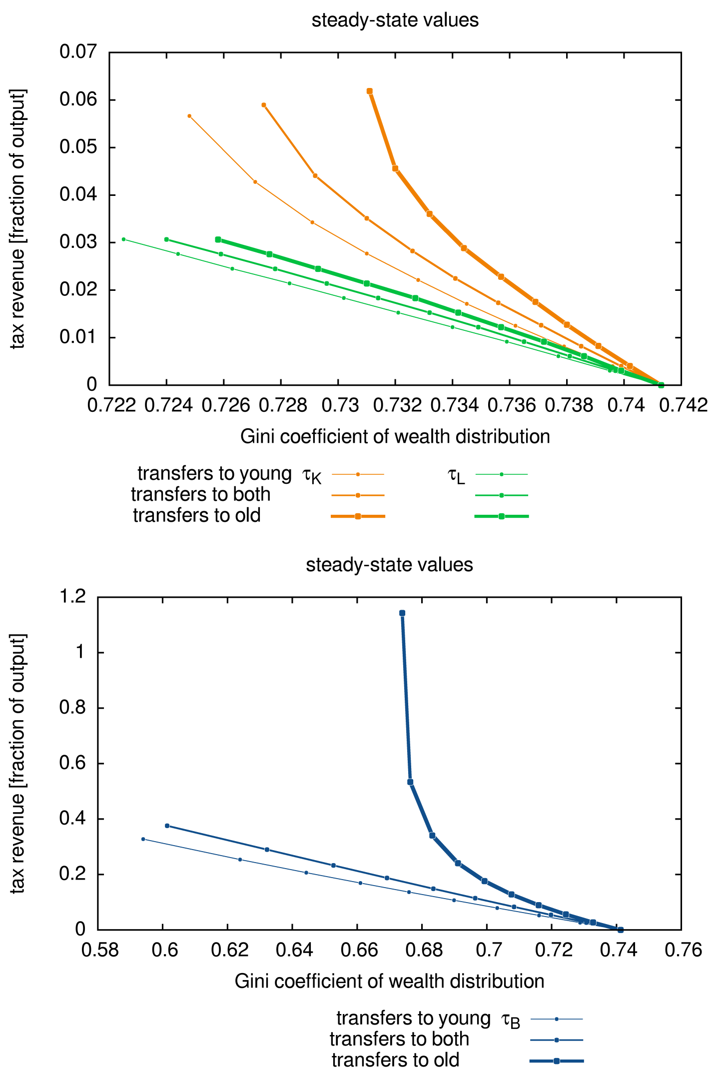


Figure Appendix C.2: The revenue raising potential of fiscal policy depends on the recycling scheme used. For all policy instruments, public revenues are higher the higher the share of transfers to the old. Figure 3 shows how the choice of the transfer scheme affects output.

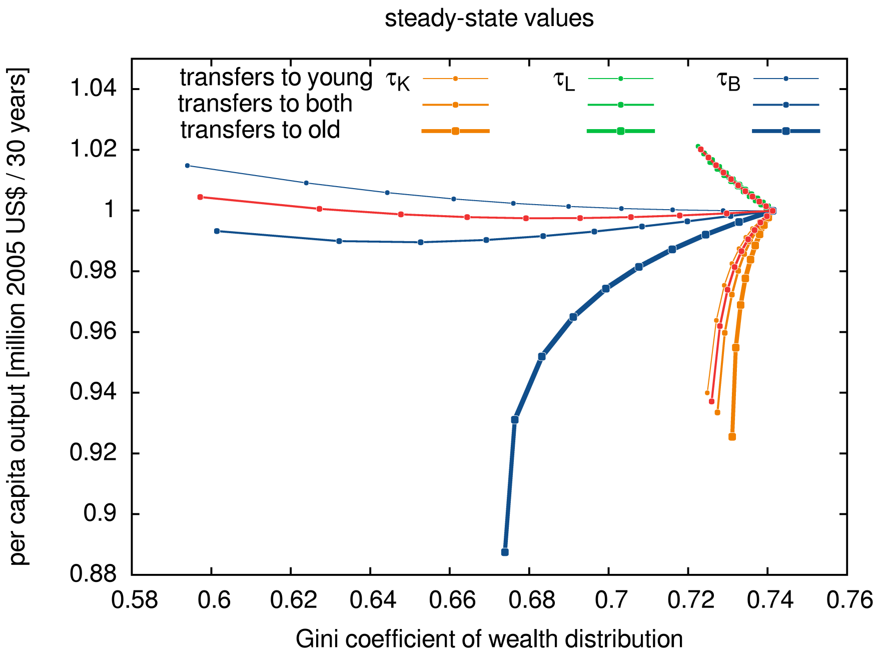


Figure Appendix C.3: Impact of different recycling schemes on output and on the wealth distribution (cf. Figure 3). The red lines mark the option space for the case in which public revenues are not redistributed.

Appendix D. Kaldor-Hicks criterion

Even though we find that recycling all public revenues to the young as lump-sum transfers enhances output and reduced inequality, a Pareto improvement is not possible. However, we find that at least there are cases in which the Kaldor-Hicks criterion is fulfilled. Consider, for instance, the case in which all land rents are skimmed off and redistributed to the young ($\tau_L = 1$, $\delta = 0$) shown in Figure Appendix D.4. Absent any additional transfer mechanism between winners and losers, the households belonging to the first old generation always bear the burden, except those in the lowest wealth quintile $i = 1$, whose utility does not change under the 100% land rent tax. Further, not only the first old generation, but in fact all generations belonging to the top wealth quintile $i = 5$ suffer under the tax.

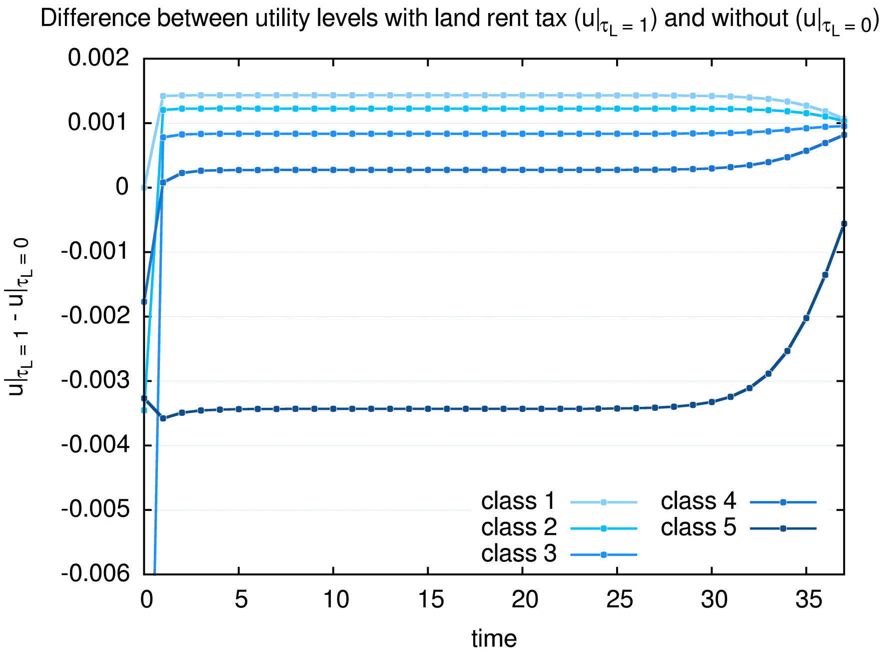


Figure Appendix D.4: When land rents are taxed at 100% and recycled as lump-sum transfers to the young, the first old generation and the richest households bear the burden. Their utility under taxation is less than without taxation, i.e., $u|_{\tau_L=1} - u|_{\tau_L=0} < 0$. All other households benefit from the policy.

Now, we introduce a mechanism which allows intertemporal transfers between households. Instead of the lump-sum transfers from public revenues g_t, young and old households may now receive a transfer or have to pay a lump-sum tax X. Their budget equations thus are

$$c^y_{i,t} + s_{i,t} = w_t + b_{i,t}(1 - \tau_B) + X^y_{i,t}$$
$$c^o_{i,t} + b_{i,t} = (1 + R_t(1 - \tau_K))k^s_{i,t} + l_{i,t}(p_t + q_t(1 - \tau_L)) + X^o_{i,t}.$$

Further, we assume that funds can be shifted over time via banking and borrowing at the market interest rate R. Then, for the total volume of the transfers it has to hold that

$$\sum_t \frac{g_t}{\Pi^t_{s=1}(1 + R_s)} \geq \frac{1}{N} \sum_{i,t} \frac{X^y_{i,t} + X^o_{i,t}}{\Pi^t_{s=1}(1 + R_s)}.$$

Our numerical experiments confirm that there are feasible combinations of $\{X^y_{i,t}, X^o_{i,t}\}_{i=1,\ldots,N,\ t=1,\ldots,T}$ such that the winners of the 100% land rent tax can compensate the losers, i.e., that

$$u_{i,t}|_{\tau_L=1} \geq u_{i,t}|_{\tau_L=0} \quad \forall i, t.$$

Kapitel 7

Conclusion

In this thesis, I strive to understand the distributional implications and conflicts from climate change impacts and mitigation policies. I do so by exploring the frontiers of IAMs on the topics of distribution, technology policy, and land. In this concluding chapter, I summarize the main findings of the five contributions in this thesis and discuss their implications and significance in a first section. A second section points to gaps in and limitations of the findings, and reflects on the methods and paradigms. In a final section I comment on the prospects for future research and directions for Integrated Assessment.

7.1 Summary of findings, implications, and significance

In this section, I synthesize the findings of this thesis, derive implications, and discuss their significance by going through the five contributions consecutively.

In chapter NASH REMIND, a methodological contribution, I develop an effective decentralized solution algorithm for the trade interaction of regions in the REMIND model, a global EECM. The algorithm increases the computational effectiveness by up to an order of magnitude over the formerly used Negishi algorithm, scales favorably with the number of regions in the model, and enables the inclusion of non-cooperative regional interactions.

This contribution allows for a better assessment of climate change mitigation for two reasons: First, the algorithm is computationally very effective and consequently allows for an increase in the regional resolution. Increasing the regional resolution enables more realistic modeling of transformation pathways of the energy and land-use system under climate policy and could lead to better estimates for the regional incentives as well as the aggregate global cost. The need for the assessment of individual national policies and their contribution to climate stabilization will likely rise in the light of the Paris Agreement in 2015 (UNFCCC Conference of the Parties 2015).

Second, the algorithm is able to represent non-cooperative interactions between regions, specifically with respect to interregional externalitites, such that the regional or national incentives for cooperative climate policy can be studied in more detail. Understanding the national incentives is crucial for the research on international cooperation and coalition formation, and may support decision-makers in strengthening international climate policy in the iterative process adopted in the Paris agreement.

In chapter TECHNOLOGY POLICY, I derive optimal climate and technology policy based on the methodology developed in the previous chapter. I assume a global spillover externality in LbD for emerging low-carbon technologies and derive optimal international climate and technology policy for the 2°C target: more than US$1 trillion in cumulative subsidies from 2020 until 2100 for low-carbon technologies – mostly for solar technologies, electric-, and hydrogen cars – could be part of cost-efficient policy for the 2°C target if carbon emissions were fully priced from 2015 on. A global treaty on cost-efficient climate stabilization would complement carbon pricing by low-carbon subsidies of around 6% of the value of the global climate rent. The opportunity costs of adopting a treaty based on carbon pricing only, without any subsidies, are very small. By contrast, if carbon pricing is delayed any further, the costs of climate stabilization rise strongly, and can only be reduced to some extent by increasing low-carbon subsidies in the near term.

My results show that external spillovers from global learning have a rather small influence on optimal cooperative climate policy only, confirming that carbon pricing is by far the most important instrument for climate stabilization. The reason for the very low opportunity costs of a carbon-pricing-only policy is the structure of technological change in the model: As there is perfect foresight in the REMIND model, the transition to a high share of renewables is very smooth even under carbon pricing only, and there are no severe lock-ins in the energy system.

The analysis suggests that current climate policies are, in global aggregate, far from cost-effective, as they rely too heavily on low-carbon subsidies: Renewable energy subsidies of globally more than US$100 billion were paid out in 2013 (International Energy Agency 2014), much more than the value of priced GHG emissions of US$50 billion in 2014 (World Bank 2015). My study finds optimal carbon pricing pathways that imply a value of priced GHG emissions of around US$1 trillion in 2020 alone, much more than the US$50 billion in 2014. I find that today's level of subsidies for intermittent renewables energies could round about have an economic rationale in optimal policy for the 2°C target, but *only* given full and immediate carbon pricing, and under the rather generous assumption of full learning-by-doing spillovers. The most pressing recommendation from this work is thus to price carbon as quickly as possible.

In chapter MITIGATION IN SUB-SAHARAN AFRICA, I turn to the distributional implications for developing countries under stringent climate policy. A cooperative global climate stabilization regime may imply significant income redistribution between and within countries, which in particular affects the least-developed regions. Our study focuses on the non-environmental incentives and distributional implications for Sub-Saharan Africa as an aggregate region from the perspective of an EECM. We find significant gross costs through a reduction in economic growth and increasing energy system investment costs of more than 5% of cumulative GDP throughout the 21st century. The net costs may well end up being negative even before avoided damages, depending primarily on the allocation scheme of emissions permits under a global cap and trade regime. Furthermore, the sale of biomass on international markets can be a significant source of revenue for Sub-Saharan Africa, and even more so in the case of delayed international cooperation. For those within the region without access to electricity, the distributional impact of climate policy could be regressive due to a drastic increase in liquid fuel prices.

The considerable reductions of GDP in Sub-Saharan Africa may in some scenarios even be overcompensated by revenue from permit and resource exports, implying a shift of income sources from domestic economic activity to dependence on exports if stringent climate policy is enacted. Our ex-post analysis of distributional consequences within the region can only start to gauge the regressivity of stringent climate policy, as neither income classes, nor fiscal policy and infrastructure are explicitly represented in the model. Still, as prices of liquid fuels increase much faster than electricity prices, people without access to the electricity grid will be hit hardest, if not compensated for their income losses by transfers. Another way to alleviate the regressive effect from rising fuel prices may be, in line with previous recommendations (Casillas und Kammen 2010), to increase access to the electric grid, as we find that the prices of electricity do not rise strongly in response to climate policy.

Land and land use play a central role not only in the mitigation of climate change, but also for the impacts of climate change, as I argue in chapter LAND IMPACTS. I use a simple IAM based on overlapping generations to demonstrate two mechanisms related to land-biased damages that are not included in current IAMs or EECMs – in fact, the effects are hidden due to the use of ILA models and the aggregation of climate damages. First, land-biased climate damages reduce economic growth strongly compared to aggregate damages by distorting capital accumulation. Specifically, land-biased damages increase the land rent, and make holding land more profitable than productive capital investments, consequently decreasing capital accumulation. Second, land-biased damages reduce the incentive for generations to mitigate climate damages for non-altruistic reasons. The incentive is reduced as mitigating climate change would lower future scarcity rents accruing to land, and thus put the value of land assets at risk, and their current owners at a potential loss.

The first of these results claims: if land rents rise globally in response to the pressure from land-biased damages, economic growth may decline strongly from an investment shift away from capital towards buying land assets, increasing the economics impact of land-biased damages. Of course, this effect is derived in the stylized model of chapter LAND IMPACTS, which assumes that all land is traded on stock markets with perfect foresight. Still, this may well be a useful way to think about distortionary effects of increasing natural resource rents on an aggregate level. More detailed research exemplifies such effects: Doupé (2014) shows how avoided deforestation triggered by carbon pricing can lower output in the short run, partly due to reduced investments in capital. There may be other mechanisms at work for such distortions: Hvid (2015) give the example of land-grabbing or rent-seeking in the political system.

As the second result, I find that the incentive for generations to enact climate policy is reduced by land-biased damages, as mitigating would decrease future scarcity rents, and thus the price of land. The owners of the asset, the old generation in my model, accordingly has a rationale to obstruct climate policy to protect the value of their assets – a rent-seeking effect. My results qualify the findings by Karp und Rezai (2014b) somewhat: They always find an asset price *increase* in response to some climate policy, leading to some amount of Pareto-improving climate policy that is enacted by non-altruistic generations. In my contribution, land-biased damages instead *decrease* the asset price in response to climate policy. Consequently, the incentive to enact climate policy decreases somewhat for land-biased damages, as compared to aggregate damages on output that Karp und Rezai (2014a) consider. The resulting level of Pareto-improving climate policy consequently is further away from the social optimum.

Chapter FISCAL POLICY investigates the roles of land and bequests for the accumulation of wealth, and the inequality in wealth ownership. In the model, we differentiate land from capital assets, as well as life-cycle savings from savings for bequests to compare fiscal policy options to reduce wealth inequality in rich countries. It is found that taxing bequest has a high redistributive potential at relatively low efficiency costs. A tax on land rents increases output due to a Portfolio effect, but has only a moderate scope for redistribution. Furthermore, the standard result that capital taxes discourage investment, and accordingly reduce output, is confirmed. Finally, recycling tax revenue to the young generation instead of the old generation decreases wealth inequality, while increasing economic growth.

The findings on wealth inequality indicate that governments in rich countries have considerable scope in reducing inequality through tax reforms without efficiency costs. The efficiency gains from land rent taxation can to some some degree compensate the efficiency losses from bequest taxation, which itself has great redistributive potential. The combination of these two fiscal policy instruments enables significant redistribution without efficiency losses. The non-neutrality of revenue recycling, as seen in the efficiency effects of recycling towards the young generation, is a strong argument for the need to explicitly model the income distribution in general equilibrium in order to judge the redistributive effects of fiscal policy.

7.2 Gaps, limitations, and paradigms

Using the methodology developed in chapter NASH REMIND, I calculate the non-cooperative solution of an EECM with respect to a global LbD externality. The internalization of this externality by optimal international technology policy is described in TECHNOLOGY POLICY. However, the internalization of the LbD externality is not per se a Pareto-improvement across the regions in the model, when compared to the solution without cooperative technology policy – and it turns out that some regions are in fact slightly worse off through it. Selfish regional players would consequently not accept such a policy, leading to the question of how the regional incentives could be adjusted accordingly. Transfers could for example be used to make cooperative technology policy a Pareto-improvement, and possibly reach the social optimum of the cooperative solution – an area for future research.

In addition, the decentralized solution algorithm developed in chapter NASH REMIND can be used to find the non-cooperative solution with respect to other interregional externalities in EECM, for example the climate externality itself. While this has been done in the literature on self-enforcing climate agreements (Lessmann u. a. 2014; Barrett 1994), this strand of literature relies on IAMs, such that the application of a more detailed

EECM such as REMIND may provide new insights.

Finally, the non-cooperative solution concept of REMIND can be useful starting point to explore strategic international interactions, and possibly find new rationales for climate policy: The most obvious interaction between countries is trade, and trade sanctions may be a way to enhance participation in climate agreements, as shown in models using simple IAMs (Lessmann u. a. 2009; Nordhaus 2015). Beyond that, Franks u. a. (2015) demonstrate that international tax competition can give governments a rationale for a unilateral carbon tax before even taking into account avoided climate damages, as a carbon tax captures some of the global fossil fuel scarcity rents.

I confirm in chapter TECHNOLOGY POLICY that in the optimal mix of carbon pricing and low-carbon subsidies for climate stabilization, carbon pricing is by far most important of the two policies. As noted in the introduction, my study contributes to the extensive literature on this issue because I include more technology detail, and the results in the literature depend very much on such modeling detail in energy technologies. Some qualifications to the results thus also relate to the modeling of technology in the REMIND model: Only some energy technologies are subject to investment cost reductions through LbD. Other technologies, such as bioenergy or unconventional fossil fuel extraction are not represented as learning technologies, even though one may expect significant experience effects in those technologies as well. Furthermore, energy technologies in the REMIND model are subject to adjustment costs, and those costs are anticipated under perfect foresight – resulting in a smooth ramp-up of investment. However, one may doubt that the incidence of adjustment costs is always perfectly anticipated by firms, parts of these cost may well be external. To my knowledge, there is no empirical evidence on external vs. internal adjustment costs for energy technologies. If one were to assume external effects in the adjustment costs of low-carbon technologies, the energy system would be more prone to lock-ins. Preliminary results beyond the research in chapter TECHNOLOGY POLICY indicate that the opportunity costs of climate policy without subsidies would consequently increase quite significantly compared to the case with an externality in LbD only.

Concerning modeling detail in endogenous technological change, one may want to separate R&D from the experience effects in LbD. The empirical findings on this topic are sparse though, and I do not expect a large change in the results, because the dynamics of LbD and R&D with finite patent life time are quite similar (Gerlagh u. a. 2009).

In the following, I point to two characteristics of REMIND that relate to fiscal policy, and the neoclassical modeling paradigm itself that may limit the scope of results obtained in the contributions relying on the model, chapters NASH REMIND, TECHNOLOGY POLICY, and MITIGATION IN SUB-SAHARAN AFRICA. The modeling of fiscal policy and political economy in the REMIND model is rather elementary: Lump sum taxation is assumed to be available to finance the low-carbon subsidies, as are lump sum returns to recycle the revenue from GHG pricing and energy taxes. Beyond that, there are no fiscal policy instruments in the model, and households, firms, and the government are not represented as separate actors. Scrutinizing these assumptions, Siegmeier u. a. (2015) argue that fiscal and climate policy should by studied together, and identify some beneficial interactions of fiscal and climate policy. Political economy is not reflected in the REMIND model, but is believed to cause large differences in efficiency of carbon taxes and technology subsidies, mostly due to rent-seeking (Helm 2010). Policy objectives other than climate change mitigation and according co-benefits are usually not reflected in EECMs endogenously, but instead assessed ex-post, for example by von Stechow u. a. (2015).

Finally, the results are obtained under the paradigm of neoclassical economics. In particular, the intertemporally optimizing growth model REMIND is rather close to what is usually called a first-best economy. The characteristics of a first-best economy are, according to Staub-Kaminski u. a. (2014): Representative consumers with standard utility functions, complete and free markets, perfect foresight, complete information, no transaction costs, price-taking behavior on all factor markets, full mobility and flexibility of production factors, and convex production technology. The REMIND model includes some second-best elements, such as emissions taxes, final energy taxes and subsidies, and some trade costs[1]. Beyond that, second-best scenarios include carbon lock-ins caused by imperfect anticipation of future climate policies (Bertram u. a. 2015), and restrictions in the availability of mitigation technologies (Kriegler u. a. 2014). Studies using reduced forms of the REMIND model also treat spillover effects in technological change (Hübler u. a. 2012), and embodied spillovers (Leimbach und Baumstark 2010), but in those cases the spillovers are anticipated and thus internalized in the model solution. My contribution in TECHNOLOGY POLICY is the first study that includes a non-internalized spillover externality in the REMIND model – the LbD spillovers in energy technologies.

One may think that inertia and path dependency involved in the energy system transformation pathways under stringent climate policy are underestimated by models close to the neoclassical ideal. In contrast to the REMIND model, other EECMs depict economies further away from first-best settings, for example operating under limited foresight (Crassous u. a. 2006). Emphasizing this point, Unruh (2000) argues "that industrial economies have become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale". He identifies economics of scale, learning effects, network externalities, and adaptive expectations as some possible reasons for increasing returns. For the adoption of renewable energy sources in particular, Lehmann u. a. (2012) provide an overview of the main technological, economic, and institutional barriers. IAMs regularly incorporate endogenous technological change, including externalities in LbD (Kohler u. a. 2006), but apart from that stay rather close to the neoclassical ideal.

By contrast, agent-based models take a starting point quite opposite to the neoclassical ideal, as they emphasize agent heterogeneity, bounded rationality[2] and adaptive expectations, local interactions, and non-equilibrium dynamics (Epstein 2006; Pyka und Fagiolo 2007). This allows for a much more detailed and involved modeling of techno-

[1] The formulation of the REMIND model is not strictly convex, but a unique equilibrium is always observed in the author's solution of the non-linear programming problem.

[2] Bounded rationality means that rational agents may have cognitive constraints in processing information, and is one of the main insights of behavioral economics – which challenges and modifies many of the assumptions of the rational actor paradigm of neoclassical economics based on observed human behavior (Simon 1986; Kahneman und Tversky 1979; McFadden 1999). Behavioral economics has strong implications for the design and effect of public polices (Chetty 2015); specifically for climate policy, the most important implications may be for social discounting (Brekke und Johansson-Stenman 2008), human cooperation and public good provision (Gowdy 2008), and energy demand responses and the public perception of climate policies (Pollitt u. a. 2013).

logical innovation and diffusion, network effects, and path dependencies (Dawid 2006; Pyka und Fagiolo 2007). For example, Axtell (2005) notes that agent-based modeling of markets yield history-dependent allocations of wealth that are not only determined by preferences and endowments. Some argue strongly for a more widespread adoption of agent-based models (Bankes 2002; Berry u. a. 2002; Farmer und Foley 2009). Janssen und Ostrom (2006) provide an overview of agent-based models for the governance of socio-economic systems, and there are initial attempts at using agent-based models to assess climate policy (Gerst u. a. 2013; Farmer u. a. 2015). While agent-based modeling is not a replacement for the general equilibrium concepts of neoclassics, which "provide a home for our intuitions and a point of departure for deeper exploration of market processes"(Axtell 2005), they may still be a useful complement. Whether, and how exactly, agent-based models can be of use in the analysis of public policy is by no means settled (Gaffard und Napoletano 2012). Lempert (2002) submits that agent-based models are particularly useful in finding robust policy in situations of deep uncertainty.

The consequences of climate stabilization policy for income distribution can be significant, as I demonstrate for Sub-Saharan Africa in the chapter MITIGATION IN SUB-SAHARAN AFRICA. The finding that Sub-Saharan Africa as a model region may have an incentive to join a global climate regime even before benefits from avoided damages – mainly due to emission permits allocated to the region by a burden sharing scheme under a global agreement – rests on two important premises: First, the international community must be willing and able to actually transfer ownership of these emission permits to the countries of Sub-Saharan Africa.

Second, the proceeds from the sales of a share of those permits on international markets by the receiving countries must be translated into as consumable income, and consequently raise welfare. One must doubt both premises: First, the Paris Agreement of the Conference of the Parties in late 2015 (UNFCCC Conference of the Parties 2015) did not decide on fixed effort sharing schemes, but rather adopts an iterative process to mitigation based on nationally determined contributions. One may see the failure to establish a global climate regime with a specific effort sharing scheme caused by the inability or unwillingness of countries to facilitate large transfers of wealth implied by the scheme. Second, suppose it were possible to transfer the permit wealth to the developing countries, these transfers may not be perfectly translated into consumption due to distortionary effect similar to resource curses (Kornek u. a. 2013).

Additionally, two other possibly adverse effects related to biomass trade are not included in the REMIND model: First, large-scale export of biomass may cause resource curses: While resources from high value point-sources, such as minerals or fossils are identified as more detrimental to economic growth than rents from agriculture (van der Ploeg 2011), high value biomass from plantations may well have characteristics of a high value point source in the future (Hvid 2015) – increasing the risk of resource curses. Second, the production of bioenergy crops may compete with food production for land and water, and consequently raise food prices and endanger food security (Wise u. a. 2009; Fargione u. a. 2010; Zilberman u. a. 2013).

Our results indicate that climate policy in countries in Sub-Saharan Africa can be very regressive due to the rise in liquid fuel prices, but our analysis is based on a partial equilibrium ex-post model. Rising prices of carbon intensive goods are only one of many distributional effects of climate policy, and a thorough assessment of the distributional effects of climate policy should account for general equilibrium effects (Fullerton 2011). Even if the direct incidence of a carbon price itself is regressive, the recycling of revenues is decisive for the regressivity: Klenert und Mattauch (2016) show in an analytical model with subsistence consumption of a carbon intensive good that carbon taxation can be regressive or progressive, only depending on the recycling scheme of tax revenue to households. Rausch u. a. (2011) make a similar point for carbon pricing in the United States using a detailed numerical computable general equilibrium model. These findings stress the need to consider the distributional consequences of climate policy in general equilibrium models with heterogeneous households and detailed fiscal policy. Furthermore, as climate impacts are commonly believed to be very regressive too, climate policy and climate impacts should be assessed jointly.

In sum, stringent mitigation action may pose too large a challenge for developing countries, considering the large-scale energy system transformation, accompanying distributional challenges, and possible adverse effects through climate rent curses, argue Jakob u. a. (2014). Instead, they propose policies that may be more feasible: reducing fossil-fuel subsidies, providing decentralized modern energy supply, and switching fuels in the power sector.

In chapter LAND IMPACTS I demonstrate two implications of land-biased damages for climate impacts, emphasizing that our contribution focuses on the economic mechanisms, and not on quantification. One premise of the model is that all land is traded on stock markets, but Caldecott u. a. (2013) suggest that, on the contrary, most agricultural land is owned by the operators of the land. On top of this, I assume perfect foresight and rational expectations on land and capital markets. Considering these caveats, one may choose to rather see the Portfolio effect between land and capital in our models as an abstract representation of what is happening at the micro scale, instead of as a rebalancing of investors' portfolios.

It would be desirable to model the impact of changing land rents for the decisions in the economy on a micro scale. To do so, one would need to account for sectoral differences in land use, differences in the quality of land, trade in agricultural products, and rent-seeking in the political economy. The literature on the resource curse suggests that natural rents have sizable effects on growth and economic efficiency, as discussed above. Beyond climate impacts, land is also important for climate change mitigation due to land-based mitigation options such as bioenergy or afforestation (Humpenöder u. a. 2014; Klein u. a. 2014; Wise u. a. 2009). The relevance of land for mitigation and impacts is an argument to treat both in together in a single coherent IAM framework.

Our results on fiscal policy and inequality in chapter FISCAL POLICY are based on a model that reflects household heterogeneity by distinguishing generations,and differences in preferences for bequests. It is desirable to extend this model by a social welfare framework to discuss optimal policies. So far, the most important implication of this work for *climate* policy is the non-neutrality of tax revenue recycling to households: There are efficiency consequences of different redistribution schemes, an effect that also has been shown for the recycling of carbon tax revenue by Rausch u. a. (2011) in a computable general equilibrium model with many heterogeneous households. In IAMs and EECMs, by contrast, heterogeneity of households is commonly modeled between countries only and governments are not reflected as distinct actors. Fiscal policy, along with its efficiency effects, can thus not be discussed in a meaningful way in these models.

In the introduction to this thesis I brought up that climate change and climate policy change natural rents and create new rents on a large scale. Contributions MITIGATION IN SUB-SAHARAN AFRICA and LAND IMPACTS reinforce this notion, and in this conclusion I presented several arguments for why current IAMs or EECMs do not deal with the consequences of changing rents in a satisfactory way. Chapter FISCAL POLICY emphasizes the role of rents for the distribution of wealth and income and for fiscal policy. Similarly, Mattauch (2015) holds that distinguishing rent income is important in evaluating two contrary views on capitalism itself: the view of capitalism as liberation, and capitalism as exploitation.

7.3 Prospects for Integrated Assessment

In the introduction of this thesis I started out to explore the frontiers of Integrated Assessment Modeling, and I would now like to suggest some prospects for future developments of IAMs and EECMs in the light of the contributions of this thesis.

Decades of development and scientific progress have pushed back the frontiers of Integrated Assessment, with the focus on: regional detail; technological detail in the energy, transport, and land-use sectors; and scenarios for socio-economic development. As a result, current EECM used in CEA of climate stabilization policy are very complex – and not only computationally demanding, but also very demanding in the organization of the scientific process itself. It is thus natural not only to ask where, but also whether at all, the frontiers of Integrated Assessment should be pushed further, or drawn in finer detail: Which processes should be included, and at what scale? What can be assess outside of the models themselves in an ex-post fashion?

Climate impacts can be assessed in IAMs to find socially optimal climate policy – the resulting marginal price of GHG emissions called the social cost of carbon. I argue in this thesis that aggregation of damages, and the aggregation of generations (which is implicit in ILA models) leads to an underestimation of climate impacts. In future research on quantitative impact modeling, it would per se be desirable to include climate damages on the level of (sectoral) factor inputs and their productivities to capture general equilibrium effects in the climate impacts, irrespective of the choice of an ILA or OLG model. It is helpful to better understand distortionary effects of natural rent income, as those may exacerbate the economic impact of climate damages. Additionally, modeling household heterogeneity between generations as in OLG models may have significance not only for the distribution, but also for the efficiency impact of climate damages, as demonstrated for example in chapter LAND IMPACTS.

Apart from heterogeneity across generations or countries, income heterogeneity within countries matters a lot for climate impacts: Dennig u. a. (2015) find that when climate damages are skewed towards the lower income classes, the social cost of carbon increase by an order of magnitude over the case where climate damages are just proportional to income, which is the usual assumption.

One recent strand of literature asserts that rather simple and aggregated global IAMs are good enough for the calculation of the social cost of carbon: Golosov u. a. (2014) present an analytical IAM, which Rezai und van der Ploeg (2015) extend somewhat. Both models find a simple formula for the social cost of carbon, which depends only on current GDP, and parameters for preferences on discounting and the carbon cycle. One may doubt the usefulness of these models in the determination of socially optimal climate policy: These models have one representative agent, the resulting *social* cost of carbon is thus by definition independent of the social preferences over inequality aversion across, and within countries. A meaningful model of the social cost of carbon should account for income differences at least across regions (Anthoff u. a. 2009), necessitating a regional model. Differentiating by region though, climate damages are highly nonlinear in the *regional* temperature changes (Burke u. a. 2015; Dell u. a. 2014), naturally leading to a rather complex model for the social cost of carbon.

To sum up my arguments and suggestions on climate impacts using IAMs: Disaggregation of physical damages, distinguishing households across time, and across income classes all seem to matter a great deal for the economic impacts, and in the determination of socially optimal policy.

In the following, I turn to discuss the prospects for EECMs for research on climate change mitigation. The modeling of energy technologies in EECMs is quite evolved already, there are rather gradual improvements to be found here: I conjecture that more detail in external effects may change the optimal balance between carbon pricing and complementary policies somewhat, but probably not dramatically.

I have argued that the possibility of distortionary effects caused by natural rents is not only relevant for the impact, but also for the mitigation side of climate change – but first of all a matter of empirics. Once empirical findings should be available, such effects may be included in EECMs, most probably parametrized and at a rather aggregate scale. Distortionary effects of natural resource exports may significantly change the national incentives for climate policy.

Siegmeier u. a. (2015) argue that the appraisal of climate policy should be embedded in a comprehensive public finance framework, and that failing to do so hides efficiency gains and reduces the flexibility in the intra- and intergenerational distribution of climate policy costs and benefits. Efficiency gains may stem from the revenue raising side of climate policy by indirectly taxing scarcity rents and redirecting them into productive capital investment, or from the revenue spending side by bringing the level and the structure of public investment, including public debt, closer to its optimum (Siegmeier u. a. 2015). Some of these effects are only visible in models with heterogeneous households, but also beyond these specific effects, models with heterogeneous household are in general needed for a meaningful representation of existing fiscal policy and public finance.

Another argument for including household heterogeneity explicitly in EECMs is that the recycling of climate policy revenue may have significant efficiency consequences: In OLG models, recycling of tax revenue has efficiency implications in general, as for example demonstrated in chapter FISCAL POLICY, or in models with climate policy (Rausch u. a. 2011; Stephan und Mueller-Fuerstenberger 1997). OLG models are a promising method to model household heterogeneity in IAMs, as not only the income distribution between generations is naturally included, but intragenerational heterogeneity can also be incorporated, as in chapter FISCAL POLICY, or the model of Rausch und Rutherford (2010). Furthermore, OLGs provide a clear separation of private preferences for life-cycle saving or for bequests, and social preferences on intergenerational discount rates for socially optimal policy[3].

The question of whether and how heterogeneity across individuals has to be accounted for in economic models is not only relevant for IAMs, but is a fundamental question in economics, and is by no means settled. The neoclassical mainstream in recent decades relied on representative agent models with rational expectations, which in many cases allows for a separate consideration of efficiency and distribution. This often lead the focus away from questions of distribution. Distribution has been brought back into the focus of economic scholarship recently, driven by rising inequality within many countries, and the seminal work of Piketty (2014). Piketty (2014) connects rising wealth inequality to some alleged general rules of capitalism (Piketty 2014; Piketty und Zucman 2014). This was criticized by many: Stiglitz (2015) emphasizes the role of rents and heterogeneous households in explaining wealth inequality. Acemoglu und Robinson (2015) criticize the neglect of the role of institutions and their endogenous evolution in the formation of inequality.

Piketty himself, in a reply, holds that studying inequality and institutions is complementary: Ïn order to put institutions back at the center of economics, I believe that it is also necessary to put the study of distribution back at the center of economics. Institutions do not arise out of harmonious societies populated by representative agents; they arise out of unequal societies and out of conflict"(Piketty 2015). Given the complex institutional challenges of climate stabilization policy, I think this stresses the point that studying distribution and distributional conflicts will be important.

Finally, after discussing the prospects for Integrated Assessment in the modeling of climate impacts and mitigation, there is the question of global versus national models: do detailed models of the national economies, including income heterogeneity and fiscal policy, have to be consolidated into global IAMs? Why isn't all that there is left to do after the Paris Agreement to sum up the national contributions to see how large the gap to the climate stabilization goal is, and consequently try to understand the incentives to strengthen national climate policy using much more flexible national models?

I think that a detailed global EECM is necessary for the evaluation of *socially optimal* climate policy. The 2015 Paris Agreement explicitly refers to socially optimal GHG emissions pathways, and those are most often calculated by EECMs (UNFCCC Conference of the Parties 2015).

I suggest that first of all then, EECMs may have to come clean with two common assumptions in their welfare economic concepts[4]: First, about the objective of socially optimal policy: The climate externality is commonly internalized by cooperative policy, while regional players in those models are assumed to behave non-cooperatively in all

[3] Karp und Traeger (2013) note that the social discounting in an OLG may naturally lead to non-constant social discount rates. Using non-constant social discount in public policy appraisal has been argued for by Arrow u. a. (2013) on the grounds of the inherent uncertainty of discount rates.

[4] The concerns discussed here are different, and in a sense more immediate than the serious fundamental concerns with the use of ILA models for socially optimal policy appraisal for intergenerational problems discussed in the introduction.

other respects[5]. In other words, in this 'socially optimal' solution, regions do not consider the welfare of individuals in other regions at all except for concerns related to climate policy. I would doubt that this is a good depiction of reality, as existing international and bilateral cooperation between countries, as well as development aid for foreign countries by private and public endeavours, expresses at least some concern for the welfare of individuals in other countries. Independent of those preferences, it would at least be very valuable to assess socially optimal policies under some degree of inequality aversion, for example following Anthoff u. a. (2009).

The second concern is about an assumption about the available means for climate policy: Often, the socially optimal pathway equalizes marginal costs of abating GHGs across countries, and it is assumed that countries could be compensated by transfer payments for their mitigation efforts under international agreements. After decades of climate negotiations, and in light of the Paris Agreement, one may doubt the feasibility of these transfers on both, the giving side and the receiving side: Rich countries seem quite reluctant to make such transfers, and one must doubt that such transfers could, without great losses, raise the well-being of the receiving countries. In the absence of viable transfer mechanisms, it is not socially optimal anymore to equalize marginal abatement costs across countries (Chichilnisky und Heal 1994). Instead, differentiated carbon prices then require increased efforts from richer countries.

Existing and announced climate policies as of 2015 are far from socially optimal though: The Paris Agreement notes the large gap between projected GHG emissions in 2030 under the intended nationally determined contributions, and socially optimal emission pathways for the 2°C target (UNFCCC Conference of the Parties 2015). In the iterative process of strengthening climate policy ambitions under the Paris Agreement, what is the role of complex global EECMs in research on the national incentives? Unilateral national incentives for climate policy will certainly be one active area of research: Edenhofer u. a. (2015) give an overview over unilateral incentives for climate policy. Some of these incentives, such as those related to fiscal policy or local air pollution, may not require a global model, except for effects due to, for example, international resource markets. Other incentives inherently require an international or global assessment, for example those related to international capital tax competition (Franks u. a. 2015) or trade sanctions. Furthermore, some policy objectives other than climate protection, such as biodiversity preservation or energy security, have global characteristics. Finally, calculating policies that internalize the domestic part of climate impacts may require an assessment in a global model. Taken together, detailed EECMs may be of good use in the research on national incentives for climate policy.

In very narrow conceptions of neoclassical economics, free riding on other countries' mitigation efforts is sometimes the only possible outcome in models of international climate policy. Beyond that, Schwerhoff (2016) discusses reasons for how leadership of countries in climate policy could motivate other countries to contribute to global mitigation efforts as well. Among them are reactions motivated by fairness, reciprocity, or norms (Schwerhoff 2016).

Looking ahead, EECMs will certainly continue to be indispensable in evaluating socially

[5] As, for example, in the Negishi solution in combination with climate change as the only externality (which is then cooperatively internalized), as used in some EECMs.

optimal climate policy, and integrating climate impacts into these models will prove valuable. There is a wealth of incentives for climate policy that has not been researched extensively, which may inspire a more positive outlook on climate policy in the coming decades. This should, however, not be a distraction from the backdrop of the large gap between socially optimal, and actually realized climate policy, but instead help building bridges towards stronger climate policy. In building this understanding for the various incentives for climate policy, Integrated Assessment may continue to prove a valuable concept.

Literatur

Acemoglu, D. und J. a. Robinson (2015). "The Rise and Decline of General Laws of Capitalism". *Journal of Economic Perspectives* 29.1, S. 3–28. DOI: 10.3386/w20766.

Anthoff, D., C. Hepburn und R. S. J. Tol (2009). "Equity weighting and the marginal damage costs of climate change". *Ecological Economics* 68.3, S. 836–849. DOI: 10.1016/j.ecolecon.2008.06.017.

Arrow, K, M Cropper, C Gollier, B Groom, G Heal, R Newell, W Nordhaus, R. Pindyck, W. A. Pizer, P. R. Portney, T. Sterner, R. S. J. Tol und M. L. Weitzman (2013). "Determining Benefits and Costs for Future Generations". *Science* 341.6144, S. 349–350. DOI: 10.1126/science.1235665.

Axtell, R. (2005). "The Complexity of Exchange". *The Economic Journal* 115.504, F193–F210. DOI: 10.1111/j.1468-0297.2005.01001.x.

Bankes, S. C. (2002). "Agent-based modeling: a revolution?" *Proceedings of the National Academy of Sciences* 99.Suppl 3, S. 7199–7200. DOI: 10.1073/pnas.072081299.

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

Berry, B. J. L., L. D. Kiel und E. Elliott (2002). "Adaptive agents, intelligence, and emergent human organization: capturing complexity through agent-based modeling." *Proceedings of the National Academy of Sciences of the United States of America* 99.3, S. 7187–7188. DOI: 10.1073/pnas.092078899.

Bertram, C., G. Luderer, R. C. Pietzcker, E. Schmid und E. Kriegler (2015). "Complementing carbon prices with technology policies to keep climate targets within reach". *Nature Climate Change* 5, S. 235–239. DOI: 10.1038/NCLIMATE2514.

Brekke, K. A. und O. Johansson-Stenman (2008). "The behavioural economics of climate change". *Oxford Review of Economic Policy* 24.2, S. 280–297. DOI: 10.1093/oxrep/grn012.

Burke, M., S. M. Hsiang und E. Miguel (2015). "Global non-linear effect of temperature on economic production". *Nature* 527, S. 235–239. DOI: 10.1038/nature15725.

Caldecott, B., N. Howarth und P. McSharry (2013). *Stranded Assets in Agriculture : Protecting Value from Environment-Related Risks.*

Casillas, C. E. und D. M. Kammen (2010). "The Energy-Poverty-Climate Nexus". *Science* 330.6008, S. 1181–1182. DOI: 10.1126/science.1197412.

Chetty, R. (2015). "Behavioral Economics and Public Policy". *NBER Working Paper* 20928. DOI: 10.3386/w20928.

Chichilnisky, G. und G. Heal (1994). *Who should abate carbon emissions? An international viewpoint.* DOI: 10.1016/0165-1765(94)90119-8.

Crassous, R., J.-c. Hourcade und O. Sassi (2006). "Endogenous Structural Change and Climate Targets Modeling experiments with Imaclim-R". *The Energy Journal* 27, S. 259–276.

Dawid, H. (2006). "Agent-based models of innovation and technological change". *Handbook of Computational Economics: Agent-Based Computational Economics*. Hrsg. von K. Judd und L. Tesfatsion. Bd. 2. North-Holland, S. 1235–1272. DOI: 10.1016/S1574-0021(05)02025-3.

Dell, M., B. F. Jones, B. a. Olken und M. Gates (2014). "What Do We Learn from the Weather? The New Climate-Economy Literature". *Journal of Economic Literature* 52.3, S. 740–798. DOI: 10.3386/w19578.

Dennig, F., M. B. Budolfson, M. Fleurbaey, A. Siebert und R. H. Socolow (2015). "Inequality, climate impacts on the future poor, and carbon prices". *Proceedings of the National Academy of Sciences* 20, S. 201513967. DOI: 10.1073/pnas.1513967112.

Doupé, P. (2014). "Reduced deforestation and economic growth". *Crawford School of Public Policy - Centre for Climate Economic & Policy Working Paper* 1402.

Edenhofer, O., M. Jakob, F. Creutzig, C. Flachsland, S. Fuss, M. Kowarsch, K. Lessmann, L. Mattauch, J. Siegmeier und J. C. Steckel (2015). "Closing the emission price gap". *Global Environmental Change* 31, S. 132–143. DOI: 10.1016/j.gloenvcha.2015.01.003.

Epstein, J. M. (2006). "Remarks on the Foundations of Agent-Based Generative Social Science". *Handbook of Computational Economics*. Hrsg. von L. Tesfatsion und K. Judd. Bd. 2. 05. Elsevier B.V., S. 1585–1604. DOI: 10.1016/S1574-0021(05)02034-4.

Fargione, J. E., R. J. Plevin und J. D. Hill (2010). "The Ecological Impact of Biofuels". *Annual Review of Ecology, Evolution, and Systematics* 41.1, S. 351–377. DOI: 10.1146/annurev-ecolsys-102209-144720.

Farmer, J. D. und D. Foley (2009). "The economy needs agent-based modelling." *Nature* 460.7256, S. 685–6. DOI: 10.1038/460685a.

Farmer, J. D., C. Hepburn, P. Mealy und A. Teytelboym (2015). "A Third Wave in the Economics of Climate Change". *Environmental and Resource Economics* 62.2, S. 329–357. DOI: 10.1007/s10640-015-9965-2.

Franks, M., O. Edenhofer und K. Lessmann (2015). "Why finance ministers favor carbon taxes , even if they do not take climate change into account". *Environmental and Resource Economics*, S. 1–28. DOI: 10.1007/s10640-015-9982-1.

Fullerton, D. (2011). "Six distributional effects of environmental policy." *Risk analysis* 31.6, S. 923–9. DOI: 10.1111/j.1539-6924.2011.01628.x.

Gaffard, J. und M Napoletano, Hrsg. (2012). *Agent-based models and economic policy*. Paris: Revue de l'OFCE.

Gerlagh, R., S. Kverndokk und K. E. Rosendahl (2009). "Optimal Timing of Climate Change Policy: Interaction Between Carbon Taxes and Innovation Externalities". *Environmental and Resource Economics* 43.3, S. 369–390. DOI: 10.1007/s10640-009-9271-y.

Gerst, M. D., P. Wang, A. Roventini, G. Fagiolo, G. Dosi, R. B. Howarth und M. E. Borsuk (2013). "Agent-based modeling of climate policy: An introduction to the ENGAGE multi-level model framework". *Environmental Modelling and Software* 44, S. 62–75. DOI: 10.1016/j.envsoft.2012.09.002.

Golosov, M., J. Hassler, P. Krusell und A. Tsyvinski (2014). "Optimal Taxes on Fossil Fuel in General Equilibrium". *Econometrica* 82.1, S. 41–88. DOI: 10.3982/ECTA10217.

Gowdy, J. M. (2008). "Behavioral economics and climate change policy". *Journal of Economic Behavior & Organization* 68.3-4, S. 632–644. DOI: 10.1016/j.jebo.2008.06.011.

Helm, D. (2010). "Government failure, rent-seeking, and capture: The design of climate change policy". *Oxford Review of Economic Policy* 26.2, S. 182–196. DOI: 10.1093/oxrep/grq006.

Hübler, M., L. Baumstark, M. Leimbach, O. Edenhofer und N. Bauer (2012). "An integrated assessment model with endogenous growth". *Ecological Economics* 83, S. 118–131. DOI: 10.1016/j.ecolecon.2012.07.014.

Humpenöder, F., A. Popp, J. P. Dietrich, D. Klein, H. Lotze-Campen, M. Bonsch, B. L. Bodirsky, I. Weindl, M. Stevanovic und C. Müller (2014). "Investigating afforestation and bioenergy CCS as climate change mitigation strategies". *Environmental Research Letters* 9, S. 064029. DOI: 10.1088/1748-9326/9/6/064029.

Hvid, A. (2015). "Increasing Natural Resource Rents from Farmland: A Curse or a Blessing for the Rural Poor?" *Peace Economics, Peace Science and Public Policy* 21.1, S. 59–78. DOI: 10.1515/peps-2014-0004.

International Energy Agency (2014). *World Energy Outlook 2014*. World Energy Outlook. Paris. DOI: 10.1787/weo-2014-en.

Jakob, M., J. C. Steckel, S. Klasen, J. Lay, N. Grunewald, I. Martínez-Zarzoso, S. Renner und O. Edenhofer (2014). "Feasible mitigation actions in developing countries". *Nature Climate Change* 4.11, S. 961–968. DOI: 10.1038/nclimate2370.

Janssen, M. a. und E. Ostrom (2006). "Governing Social-Ecological Systems". *Handbook of Computational Economics*. Hrsg. von L. Tesfatsion und K. Judd. Bd. 2. Elsevier B.V., S. 1465–1509. DOI: 10.1016/S1574-0021(05)02030-7.

Kahneman, D. und A. Tversky (1979). "Prospect Theory: an Analysis of Decision Under Risk". *Econometrica* 47.2, S. 263–292.

Karp, L und C Traeger (2013). "Discounting". *Encyclopedia of Energy, Natural Resource, and Environmental Economics*. Hrsg. von J. F. Shogren. Bd. 2. Amsterdam: Elsevier, S. 286–292. DOI: 10.1016/B978-0-12-375067-9.00150-9.

Karp, L. und A. Rezai (2014a). "Asset prices and climate policy". *mimeo*.

– (2014b). "The political economy of environmental policy with overlapping generations". *International Economic Review* 55.3, S. 711–733.

Klein, D., G. Luderer, E. Kriegler, J. Strefler, N. Bauer, M. Leimbach, A. Popp, J. P. Dietrich, F. Humpenöder, H. Lotze-Campen und O. Edenhofer (2014). "The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE". *Climatic Change* 123.3, S. 705–718. DOI: 10.1007/s10584-013-0940-z.

Klenert, D. und L. Mattauch (2016). "How to make a carbon tax reform progressive: The role of subsistence consumption". *Economics Letters* 138, S. 100–103. DOI: 10.1016/j.econlet.2015.11.019.

Kohler, J., M. Grubb, D. Popp und O. Edenhofer (2006). "The Transition to Endogenous Technical Change in Climate-Economy Models: A Technical Overview to the Innovation Modeling Comparison Project". *The Energy Journal* SI2006.01, S. 17–55. DOI: 10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI1-2.

Kornek, U., J. Steckel, K. Lessmann und O. Edenhofer (2013). "The climate rent curse: new challenges for burden sharing". *mimeo*.

Kriegler, E., J. P. Weyant, G. J. Blanford, V. Krey, L. Clarke, J. Edmonds, A. Fawcett, G. Luderer, K. Riahi, R. Richels, S. K. Rose, M. Tavoni und D. P. van Vuuren (2014). "The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies". *Climatic Change* 123.3-4, S. 353–367. DOI: 10.1007/s10584-013-0953-7.

Lehmann, P., F. Creutzig, M.-H. Ehlers, N. Friedrichsen, C. Heuson, L. Hirth und R. Pietzcker (2012). "Carbon Lock-Out: Advancing Renewable Energy Policy in Europe". *Energies* 5.12, S. 323–354. DOI: 10.3390/en5020323.

Leimbach, M. und L. Baumstark (2010). "The impact of capital trade and technological spillovers on climate policies". *Ecological Economics* 69.12, S. 2341–2355. DOI: 10.1016/j.ecolecon.2010.06.023.

Lempert, R. (2002). "Agent-based modeling as organizational and public policy simulators." *Proceedings of the National Academy of Sciences of the United States of America* 99 Suppl 3.90003, S. 7195–6. DOI: 10.1073/pnas.072079399.

Lessmann, K., R. Marschinski und O. Edenhofer (2009). "The effects of tariffs on coalition formation in a dynamic global warming game". *Economic Modelling* 26.3, S. 641–649.

Lessmann, K., U. Kornek, V. Bosetti, R. Dellink, H.-P. Weikard, J. Emmerling, J. Eyckmans, M. Nagashima und Z. Yang (2014). "The Stability and Effectiveness of Climate Coalitions: A Comparative Analysis of Multiple Integrated Assessment Models". DOI: 10.1007/s10640-015-9886-0.

Mattauch, L. (2015). "Rent and redistribution". PhD thesis. Technical University of Berlin. DOI: 10.14279/depositonce-4905.

McFadden, D. (1999). "Rationality for Economists?" *Journal of Risk and Uncertainty* 19.1, S. 73–105. DOI: 10.1017/CBO9781107415324.004.

Nordhaus, W. (2015). "Climate Clubs: Overcoming Free-riding in International Climate Policy". *American Economic Review* 105.4, S. 1339–1370. DOI: 10.1257/aer.15000001.

Piketty, T. (2014). *Capital in the Twenty-First Century*. Belknap Press.

– (2015). "Putting Distribution Back at the Center of Economics: Reflections on Capital in the Twenty-First Century". *Journal of Economic Perspectives* 29.1, S. 67–88. DOI: 10.1257/jep.29.1.67.

Piketty, T. und G. Zucman (2014). "CAPITAL IS BACK: WEALTH-INCOME RATIOS IN RICH COUNTRIES 1700-2010". *Quarterly Journal of Economics* 129.3, S. 1255–1310. DOI: 10.1093/qje/qju018.

Pollitt, M. G., I. Shaorshadze, M. G. Pollitt und I. Shaorshadze (2013). "The Role of Behavioral Economics in Energy and Climate Policy". *Handbook on Energy and Climate Change*. Hrsg. von R. Fouquet. Edward Elgar, S. 523–546.

Pyka, A. und G. Fagiolo (2007). "Agent-based modelling: A Methodology for neo-Schumpeterian Economics". *Elgar Companion to Neo-Schumpeterian Economics*. Hrsg. von H. Hanusch und A. Pyka. Cheltenham, UK: Edward Elgar.

Rausch, S. und T. F. Rutherford (2010). "Computation of Equilibria in OLG Models with Many Heterogeneous Households". *Computational Economics* 36.2, S. 171–189. DOI: 10.1007/s10614-010-9229-8.

Rausch, S., G. E. Metcalf und J. M. Reilly (2011). "Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households". *Energy Economics* 33.202, S20–S33. DOI: 10.1016/j.eneco.2011.07.023.

Rezai, A. und F. van der Ploeg (2015). "Robustness of a simple rule for the social cost of carbon". *Economics Letters* 132, S. 48–55. DOI: 10.1016/j.econlet.2015.04.007.

Schwerhoff, G. (2016). "The economics of leadership in climate change mitigation". *Climate Policy* 16.2, S. 196–214. DOI: 10.1080/14693062.2014.992297.

Siegmeier, J., L. Mattauch, M. Franks, D. Klenert, A. Schultes und O. Edenhofer (2015). "A Public Finance Perspective on Climate Policy: Six Interactions That May Enhance Welfare". *FEEM working paper series* 031.2015. DOI: 10.2139/ssrn.2596604.

Simon, H. A. (1986). "Rationality in Psychology and Economics". *The Journal of Business* 59.4, S. 209–224. DOI: 10.1086/296363.

Staub-Kaminski, I., A. Zimmer, M. Jakob und R. Marschinski (2014). "Climate Policy in Practive: A Typology Of Obstacles And Implications For Integrated Assessment Modeling". *Climate Change Economics* 5.1. DOI: 10.1142/S2010007814400041.

Stephan, G. und G. Mueller-Fuerstenberger (1997). "Overlapping Generations or Infinitely-Lived Agents". *Environmental and Resource Economics* 10, S. 27–40.

Stiglitz, J. E. (2015). "New Theoretical Perspectives on the Distribution and Wealth among Individuals: Part I. The Wealth Residual". *NBER Working Paper* 21189. DOI: 10.3386/w21189.

UNFCCC Conference of the Parties (2015). *Adoption of the Paris Agreement. Proposal by the President.*

Unruh, G. C. (2000). "Understanding carbon lock-in". *Energy policy* 28, S. 817–830. DOI: 10.1016/S0301-4215(00)00070-7.

Van der Ploeg, F. (2011). "Natural Resources: Curse or Blessing?" *Journal of Economic Literature* 49.2, S. 366–420. DOI: 10.1257/jel.49.2.366.

Von Stechow, C., D. McCollum, K. Riahi, J. C. Minx, E. Kriegler, D. P. van Vuuren, J. Jewell, C. Robledo-Abad, E. Hertwich, M. Tavoni, S. Mirasgedis, O. Lah, J. Roy, Y. Mulugetta, N. K. Dubash, J. Bollen, D. Ürge-Vorsatz und O. Edenhofer (2015). "Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis". *Annual Review of Environment and Resources* 40.1, S. 363–394. DOI: 10.1146/annurev-environ-021113-095626.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-lamberty, R. Sands, S. J. Smith, A. Janetos und J. Edmonds (2009). "Implications of Limiting CO2 Concentrations for Land Use and Energy". *Science* 324.May, S. 1183–1186. DOI: 10.1038/ncb2099.

World Bank (2015). *State and Trends of Carbon Pricing*.

Zilberman, D., G. Hochman, D. Rajagopal, S. Sexton und G. Timilsina (2013). "The impact of biofuels on commodity food prices: Assessment of findings". *American Journal of Agricultural Economics* 95.2, S. 275–281. DOI: 10.1093/ajae/aas037.

Acronyms

GHG greenhouse gas

CO_2 carbon dioxide

IAM Integrated Assessment Model of Climate Change

ILA infinitely-lived agent

OLG overlapping generations

EECM Energy-Economy-Climate Model

CBA cost-benefit analysis

CEA cost-effectiveness analysis

RCP Representative Concentrations Pathway

BAU business-as-usual

GDP Gross Domestic Product

UNFCCC United National Framework Convention on Climate Change

AR5 Fifth Assessment Report of the IPCC

BECCS bioenergy with carbon capture and storage

REMIND Regional Model of Investments and Development

MAGICC6 Model for the Assessment of Greenhouse Gas Induced Climate Change Version 6 (Meinshausen u. a. 2011), `http://www.magicc.org`

R&D research and development

LbD learning-by-doing

Tools and Resources

Chapters NASH REMIND, TECHNOLOGY POLICY, and MITIGATION IN SUB-SAHARAN AFRICA use and build on the REMIND model. The REMIND model has been developed as a joint effort of many people at Research Domain 3 at the Potsdam Institute for Climate Change Impact. It is described in full detail in Luderer u. a. (2015). The model is formulated in GAMS (GAMS Development Corporation 2013), available at `https://www.gams.com`. The resulting non-linear optimization problem is solved in GAMS using the CONOPT solver (Drud 1994), described at `http://www.conopt.com`.

All chapters except FISCAL POLICY make use of the R programming language for data analysis and plotting routines (R Core Team 2015), available at `https://www.r-project.org/`. The R packages dplyr (Wickham und Francois 2015), and ggplot2 (Wickham 2009) are used extensively throughout the thesis.

Data analyses in this thesis is strongly influenced by the tidy data concept of Wickham (2014).

For chapter LAND IMPACTS I used the Python language (`https://www.python.org`), and the packages SciPy (SciPy: Open source scientific tools for Python), and SymPy for symbolic computation in Python (`http://www.sympy.org`).

I used LaTeX(`https://www.latex-project.org/`) to typeset this thesis. Chapter MITIGATION IN SUB-SAHARAN AFRICA was produced using Microsoft Word.

I used the Linux operating system for most of my work and thus profited a lot from many other open source software packages not explicitly acknowledged here. Thanks!

Literatur

Drud, A. S. (1994). "CONOPT - A Large-Scale GRG Code". *ORSA Journal on Computing* 6.2, S. 207–216. DOI: 10.1287/ijoc.6.2.207.

GAMS Development Corporation (2013). *General Algebraic Modeling System (GAMS)*. Washington, DC.

Jones, E., T. Oliphant, P. Peterson und Others. *SciPy: Open source scientific tools for Python*.

Luderer, G., M. Leimbach, N. Bauer, E. Kriegler, L. Baumstark, C. Bertram, A. Giannousakis, J. Hilaire, D. Klein, A. Levesque, I. Mouratiadou, M. Pehl, R. Pietzcker, F. Piontek, N. Roming, A. Schultes, V. J. Schwanitz und J. Strefler (2015). "Description of the REMIND model (Version 1.6)". *SSRN Electronic Journal* 2697070.

R Core Team (2015). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria.

Wickham, H. (2009). *ggplot2: elegant graphics for data analysis*. Springer New York.

– (2014). "Tidy Data". *Journal of Statistical Software* 59.10. DOI: `10.18637/jss.v059.i10`.

Wickham, H. und R. Francois (2015). *dplyr: A Grammar of Data Manipulation*.

Statement of Contribution

Chapters Introduction and Conclusion
The author is responsible for the drafts of these two chapters. Helpful and thorough comments on the drafts by Marian Leimbach, Linus Mattauch, Max Franks, David Klenert, and Lisa Schneider are gratefully acknowledged.

Chapter Nash REMIND
Marian Leimbach, Gunnar Luderer, and the author of this thesis designed the research. The decentralized solution concept developed in the paper was conceived by Gunnar Luderer, and refined and implemented by Marian Leimbach and the author with contributions from Lavinia Baumstark and Anastasis Giannousakis. Marian Leimbach and the author wrote the paper with contributions from all other authors.

Chapter Technology Policy
The author of this thesis, Marian Leimbach, Gunnar Luderer, and Ottmar Edenhofer designed the research. Gunnar Luderer conceived the algorithm for the internalization of the spillover externality, which was implemented and refined by the author with input from Marian Leimbach, Gunnar Luderer, Robert Pietzcker, and Lavinia Baumstark. The author analyzed data and wrote the paper with contributions from all authors.

Chapter Mitigation in Sub-Saharan Africa
Marian Leimbach led the research project, and conceived of the research question in close collaboration with all other authors. Marian Leimbach and the author of this thesis conducted the model runs with help from Niklas Roming. The author and Marian Leimbach contributed the analysis of the mitigation costs. Niklas Roming contributed the decomposition analysis, and the analysis of the energy system results in collaboration with Marian Leimbach. Gregor Schwerhoff contributed the ex-post analysis of the distributional effects and wrote the corresponding section; the author supplied the relevant analysis of REMIND results to this section.Marian Leimbach wrote the paper with contributions and refinements from all authors.

Chapter Land Impacts
The research question was conceived by the author of this thesis and Ottmar Edenhofer. All calculations, the model implementation, and data analysis was performed by the author with support from Marian Leimbach and Ottmar Edenhofer. The author interpre-

ted and discussed the results in close collaboration with Ottmar Edenhofer and Marian Leimbach. The author wrote the chapter, and both co-authors contributed revisions.

Chapter FISCAL POLICY
The conception of the research question and the method to address it are due to the joint effort of Max Franks, David Klenert, and Kai Lessmann, with additional support by Ottmar Edenhofer. All calculations, the model implementation, data analysis and visualization were conducted by Max Franks, with support by David Klenert and the author of this thesis. Interpretation, discussion, and conclusions were done in close collaboration with David Klenert, Kai Lessmann, and the author. The text of the chapter was written by Max Franks, all co-authors contributed refinements.

Acknowledgements

I thank Ottmar Edenhofer for the supervision of my PhD research. His leadership made Research Domain 3 at the Potsdam Institute a very rewarding place to work for me. His energy and openness to discussion despite the noise of everyday life were truly valuable to me.

Marian Leimbach was very thorough in day-to-day guidance, and was of great help in navigating the challenges of my PhD time at PIK – I am very grateful for that. My work profited much from the REMIND group, and I am thankful for the cooperative and cheerful spirit among their members and their open doors no matter what.

I am indebted to Gunnar Luderer for supporting me and helping me in seeing and solving problems differently in cases my thinking and work got stuck.

Working with my coauthors was a great pleasure. The work with the PROFITs – Linus Mattauch, Jan Siegmeier, David Klenert, and Max Franks – was always most inspirational and productive.

Inhabitants and good friends of A26, I count myself very lucky having spend so much time with you up there under that roof – thanks for the friendship, support, and fun we had.

I thank the members of my PhD committee Dieter Scherer, Ottmar Edenhofer, Massimo Tavoni, and Christian von Hirschhausen. I was very fortunate to have the support of Dorothe Ilskens, Ina Baum, Susanne Stundner, Nicole Reinhardt, Kristiyana Neumann, and Marcel Meistring in all administrative and procedural issues during my PhD – thank you very much.

Marian Leimbach, Linus Mattauch, Max Franks, David Klenert, and Lisa Schneider proofread and commented on drafts of this thesis – thanks very much.

Studying physics and writing my Diplom thesis under Patrik Recher and Björn Trauzettel was joyful, and taught me fundamentals I value much.

On a personal note, I am lucky to have such good friends in Berlin and around the globe, who made the last years so much fun. Without them, I would have run around like a headless chicken.

Above all, nothing of this would have been possible without my family. I am most grateful to my parents Ingrid and Günter, and my sisters Alina and Lara, for the unyielding support and love. Growing up in an atmosphere full of curiosity was the most valuable thing to me, making it joyful to learn to think for myself and question authority.